Jet Propulsion Laboratory
California Institute of Technology

Data Analysis and Interpretation

Module 09a: You went to the trouble of getting this data. Don’t you want to understand what it means?

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Acronyms and Abbreviations

- CAD—Computer Aided Design
- CL—Confidence Level
- DDR/2/3/4—Double-Data Rate (as in SDRAM)
- DRAM—Dynamic Random Access Memory
- DSEE—Destructive Single-Event Effect
- EDA—Exploratory Data Analysis
- EDAC—Error Detection And Correction
- LET—Linear Energy Transfer
- MBU—Multi-Bit Upset (multiple bits in same word)
- MC—Monte Carlo
- MCU—Multi-Cell Upset (Multibit not in same word)
- ND—NonDestructive
- RPP—Rectangular ParallelePiped
- SDRAM—Synchronous DRAM
- SEB—Single-Event Burnout
- SEE—Single-Event Effect
- SEFI—Single-Event Functional Interrupt
- SEGR—Single-Event Gate Rupture
- SEL—Single-Event Latchup
- SET—Single-Event Transient
- SEU—Single-Event Upset
- WC—Worst-Case
- Z—Atomic Number of an Element

Agenda

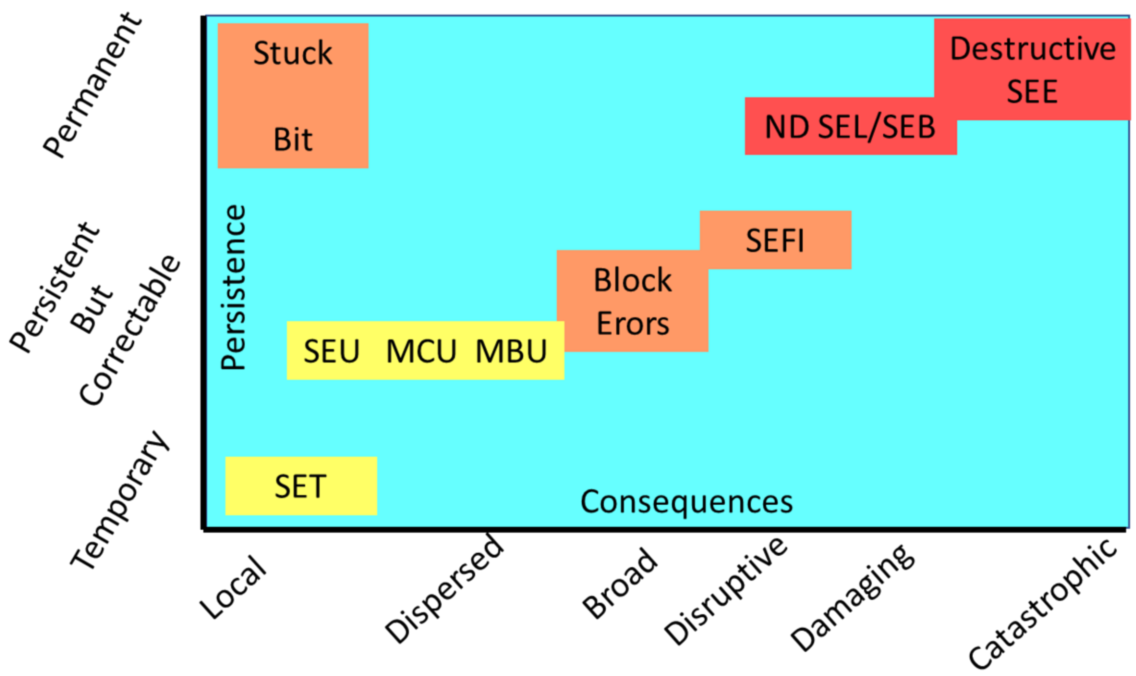
I. Introduction: Purposes and Goals of SEE Data Analysis
II. Part types, types of SEE—challenges and data structure
III. The Tug of War: Purifying SEE data and maintaining statistics
IV. Good Data? Good for What? Bounding SEE risk, rates probability and consequences
V. Interpreting SEE analysis results—requirements and performance
VI. Exploratory Data Analysis—Making the data make sense for special problems

Introduction: Goals and Purposes of Analysis

- Structure and methodology of analysis dictated by its goals/purpose
- Purpose: To ensure **PART'S** SEE susceptibilities will not prevent the **SYSTEM** from meeting its **PERFORMANCE REQUIREMENTS**
- Things to remember:
  - SEE occur at the part level (there may be multiple modes requiring separation)
  - Consequences of SEE that matter are those at the system level (including mitigation)
  - Different SEE modes affect various **Performance Requirements** differently
    - Reliability—main threats are destructive SEE or nondestructive SEE from which system cannot recover (e.g. SEFI requiring power cycle in a system unable to power cycle)
    - Availability—applies to systems where faults can be repaired (repair could include ground intervention or even a servicing mission); reparable faults usually nondestructive—but servicing mission could repair DSEE
    - Survivability—Is system capable of functioning after a severe event (Solar Particle Event, Man-made event…
    - Precision, Accuracy, Fidelity—can all be compromised permanently or temporarily by any SEE

SEE Modes and Their Characteristics

MODE	Symptom	Recovery	Data looks like?
SET	Disturbed output	Self-recovering for device	Waveforms or {Amp. and width}
SEU	1 or a few Flipped bits	Correct by Rewrite	Series of errors/ addresses
Block Error	Many Flipped bits	Correct by Rewrite	Coincident errors and addresses
SEFI	Lost function; Data errors	Reset or Power-On/Reset	Onset of lost function, errors
DSEE	High current; Lost function	N/A (usually)	Onset high I and loss of function
Stuck Bit	Unprogram-mable bit	Uncorrectable (may anneal)	Addresses w/ recurrent errors



Challenges For SEE Modes and Different Part Types

Challenges for SEE Modes

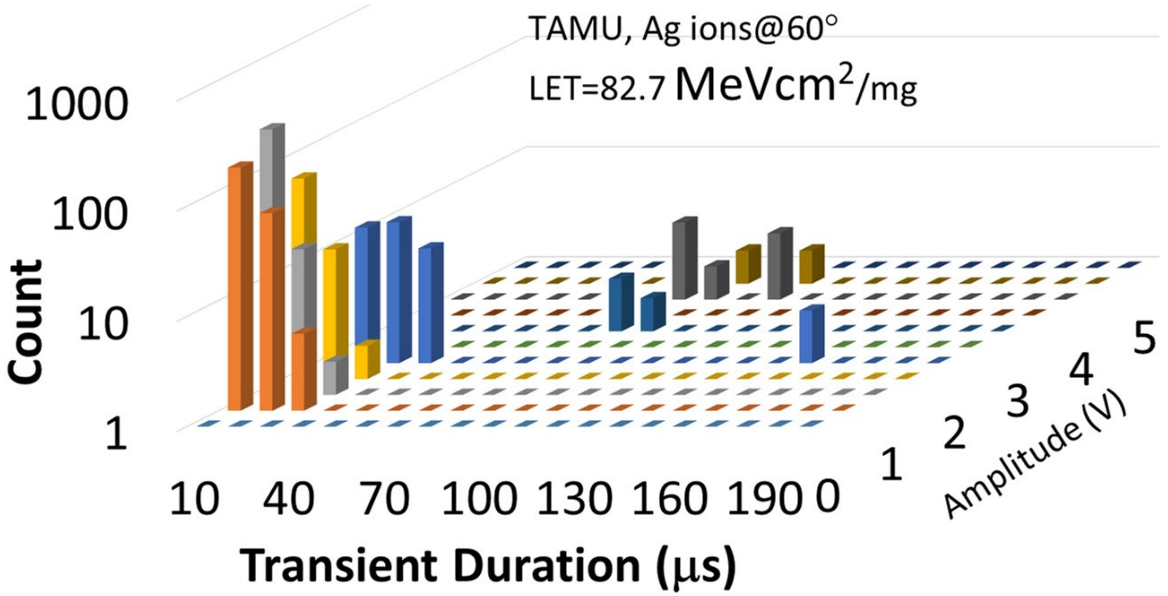
- SET test challenges
  - Test-condition dependence; propagation of SET mode
- SEU test challenges
  - Test-condition dependence
- Block Errors, SEFI mainly upsets in control logic
  - Disruptive, rare events; hard to gather enough statistics
- Destructive SEE
  - SEL depends on supply voltage, temperature
    - Disruptive, so accumulating statistics challenging
  - SEGR and SEB dependencies on angle, ion, energy and voltages so complex rate estimation not feasible
    - Every SEGR is destructive, so cannot even accumulate statistics/cross section on each device
    - Part-to-part variation and Poisson errors are confounding

Challenges for Part Types

- Bipolar linear devices (op amps, comparator, etc.)
  - Multiple SET modes; strong application dependence
- Analog-to-digital and digital-to-analog converters
  - Multiple SEE modes + more likely SEL susceptible
- FLASH, DRAM and other complex memories
  - Complex SEE response: SET, SEU, SEL stuck bits, SEFI…
  - High SEFI susceptibility disruptive to testing, limits statistics
- Other Complex parts (FPGA, processors, etc…)
  - Very limited insight into causes/mechanisms of SEE
  - Errors manifest as either SEFI or “silent”
- Power Transistors and related devices
  - Complex dependence on ion species, energy, angle, voltages
  - SEGR always destructive; complicates assessing variability

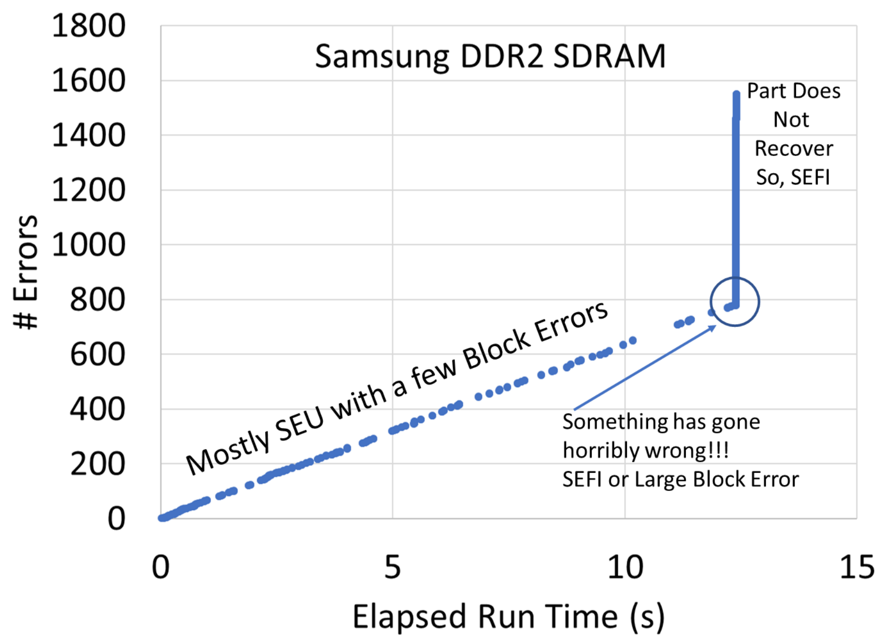
Single-Event Transients—Specificity vs. Statistics

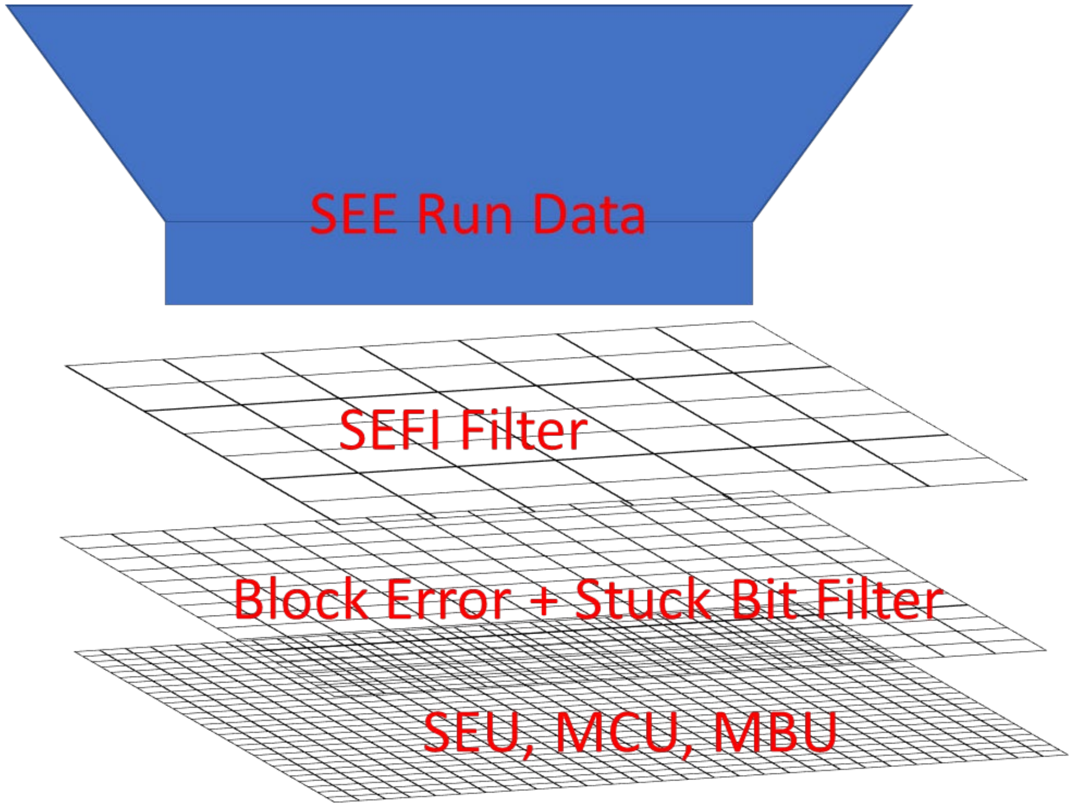
- Many SEE depend strongly on application conditions
- SET are a particularly vexing example
  - SET rates and waveforms depend on part configuration, input voltages, supply voltages, loads/fan-out…
    - Gathering data for all application conditions limits statistics for any one configuration
- In some cases, a rare mode poses higher risk, and it may be useful to combine data for different conditions if the condition doesn't affect susceptibility
  - Example: If waveforms and σ vs. LET are similar for different supply voltages, may consider combining data
- Similar situation I: Competing SEFI modes
  - SEFI are very disruptive to testing process, so gathering statistics is challenging even under best of circumstances
  - SEFI requiring power-on/reset may be serious issue
    - Even if it is rare, it may drive design
- Similar situation II: Rare destructive SEL mode competing with more common nondestructive SEL



- Analog Devices OP293 Op amp has mostly short transients
- ~4% of SETs in OP293 op amp last longer than 100 μs
  - May last up to 500 μs (hard to filter capacitatively)
- Statistics extremely limited for long transients making rate determination difficult
- Although long transients seen during beam run, the run was not long enough to gather large sample

Some Parts Exhibit Bewildering SEE Behavior





- Errors from 1 SEFI may be > all SEU during beam run
  - Ignore error tallies after SEFI occurs, block errors, etc.
  - Need to find and eliminate stuck bits
  - SEU cross sections must use data before SEFI and purified of block errors and stuck bits (as they occur)
  - Test: Fluence between upsets should be~ exponential

- Process is like running gravel through a sieve
  - Must remove large-impact events to avoid contamination
  - Important to bin events having similar impact

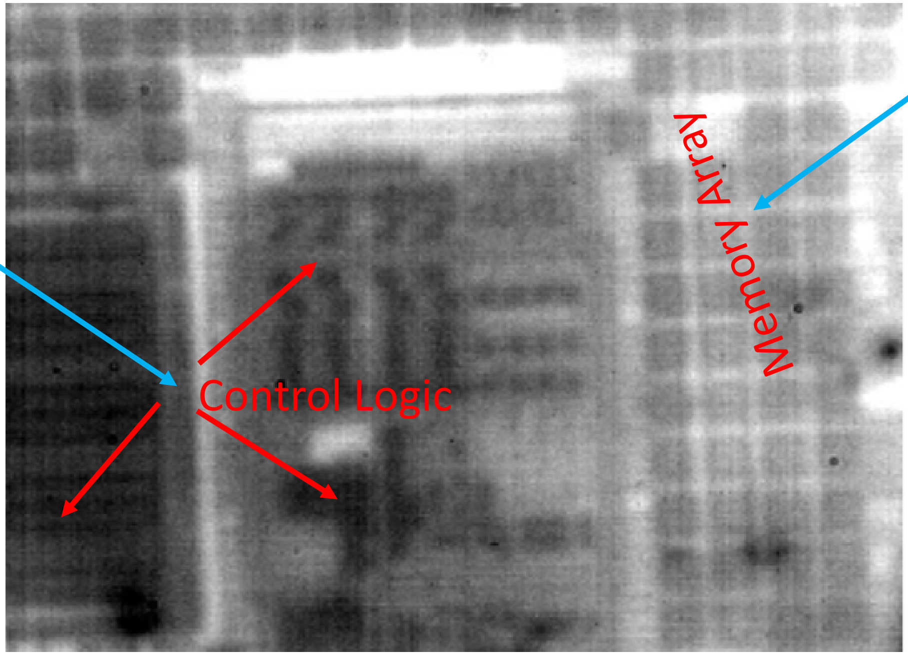
Binning Events In An Ideal World

Ideally, we would know which chip features cause which faults and bin like events together. Not possible for broadbeam

Photomicrograph of Elpida 256 Mbit SDRAM
Taken at NRL during laser SEL testing

Likely source of SEFI, block error, SEL

Likely source of SEU, MCU, MBU and stuck bits



SEL susceptible features in the control logic. Sequential stimulation caused stair-step current rise.

- Ideally, effects repeatable
  - Events accumulate as each feature stimulated until boundaries found
  - Similar events from similar features can be combined to increase cross section statistics

- Even if features causing events are known, surprises possible
  - Laser test of ASIC showed SEL on a voltage supply not present in the part of chip being irradiated!

- Broadbeam testing yields less info about which features cause particular events
- Approaches are complementary

Binning Events In The Real World

- When is an upset more than an upset, a SEFI more than a SEFI…?
  - Goal is to bound system-level risk—binning often done with respect to system consequences

Low Risk

Limited Impact
Easy recovery

- Event has little impact or system recovers easily with available resources/design

Example I: Short transient that is filtered w/o impact

Example II: Short transient in high-rate data stream

Example III: SEU in a system that already has EDAC

Example IV: Block errors at low rate in system that already has EDAC

Moderate Risk

Non-negligible impact;
Recovery impacts operations

- Event or recovery impact operations, perhaps causing degraded service or a short outage

Example I: Fault results in loss of an observation in a science mission

Example II: Fault causes pointing error, resulting in a few dropped phone calls

High Risk

Significant Impact;
Recovery drives design or causes outage

- Event or recovery result in significant outage or degradation of capability or performance
- System may not already include needed recovery ability, necessitating redesign.

Example: Linear bipolar part found to have extremely long SETs

Example II: SEFI in part requires power cycle for recovery, but system precludes cycling power

Unacceptable

Catastrophic impact
or
Unrecoverable

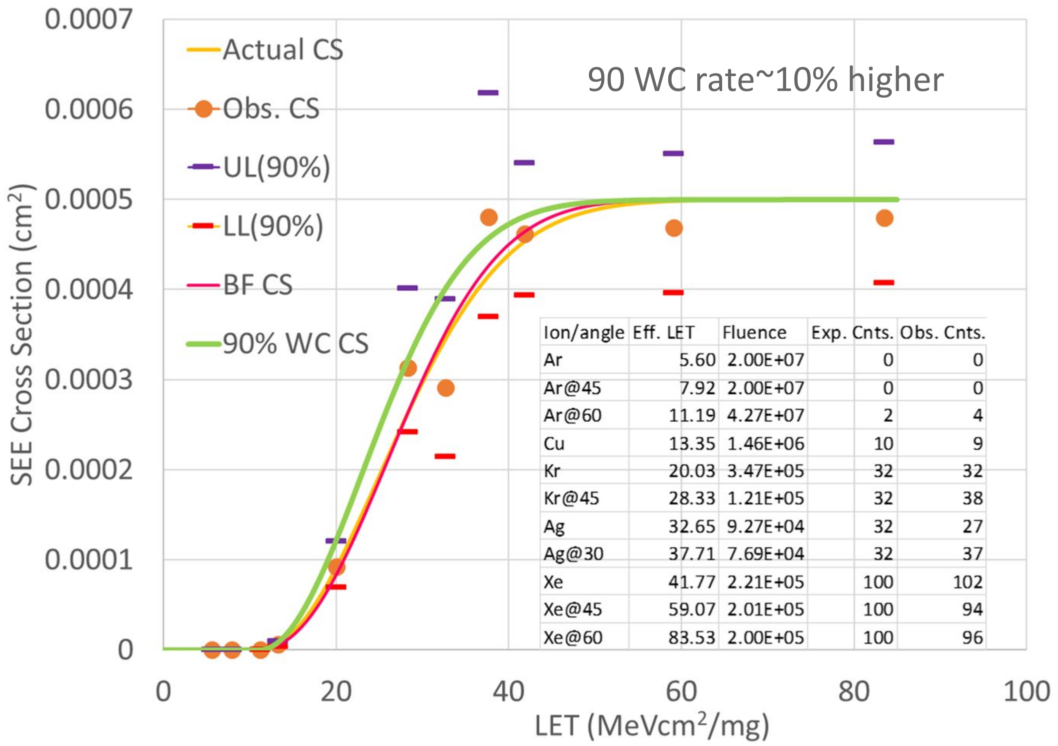
- Event drives reliability and/or availability to unacceptably low levels.

Example I: Destructive SEE with unacceptably high rate

Example II: Potential for stuck bits in Boot-Up nonvolatile memory

Example III: inability to cycle power to recover from SEFI.

Good Datasets Bound Risk



Ion/angle	Eff. LET	Fluence	Exp. Cnts.	Obs. Cnts.
Ar	5.60	2.00E+07	0	0
Ar@45	7.92	2.00E+07	0	0
Ar@60	11.19	4.27E+07	2	4
Cu	13.35	1.46E+06	10	9
Kr	20.03	3.47E+05	32	32
Kr@45	28.33	1.21E+05	32	38
Ag	32.65	9.27E+04	32	27
Ag@30	37.71	7.69E+04	32	37
Xe	41.77	2.21E+05	100	102
Xe@45	59.07	2.01E+05	100	94
Xe@60	83.53	2.00E+05	100	96

- Data should reveal structures similar to those of fit
  - LET_0—Should have 0 events for lowest LET
  - σ_{sat}--No increase in σ w/ LET for ≥2 highest LETs
  - w, s—≥3 LETs on rising portion of σ vs. LET

- Bounding risk→bounding probability + consequences
- Understanding/Bounding Consequences:
  1) SEE can happen any time during mission
  2) To assess consequences, must observe mode
  3) SEE directly affect only part in which it occurs
     a) Should understand how error and recovery affect system
     b) Survivability? Reliability? Availability? Performance?
- Probability=Rate Estimations
  1) “Pure” σ vs. LET data for each SEE mode
     a) Doesn’t change whether goal is rate estimation or bound
  2) Need Weibull fit to each dataset (see figure to left)
     a) Best fit→ actual rate; bounding rate ensures performance
  3) Environment model(s) based on purpose of rate
     a) Galactic Cosmic Rays (usually WC—Solar Minimum)
     b) Solar or trapped protons (WC or at the desired confidence)

Rate Estimation Techniques and Data Requirements

General Rule: If your model has n parameters, you generally need at least n+2 data points for a meaningful fit

Buchner's Rule

- Only two SEE rates matter—zero and nonzero
  - All you need is one high-LET, high-Fluence run.

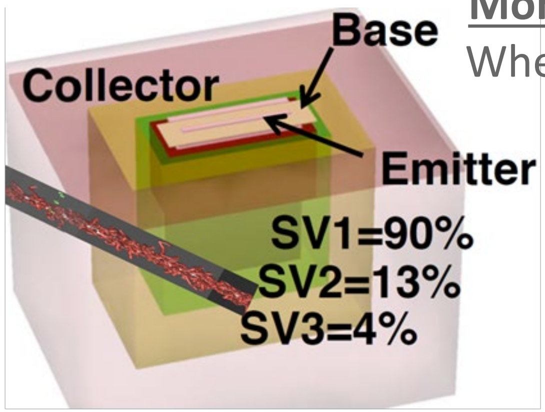
Rectangular Parallelepiped

- Still the predominant estimate
  - See next slide
- Minimum of 4 parameters: LET_0, σ_{sat}, Weibull w and s
- Ought to have ≥6 cross section data points for meaningful rate
- Weibull (or other) fit determines rate
  - Fitting SEE data can be challenging (see next presentation)

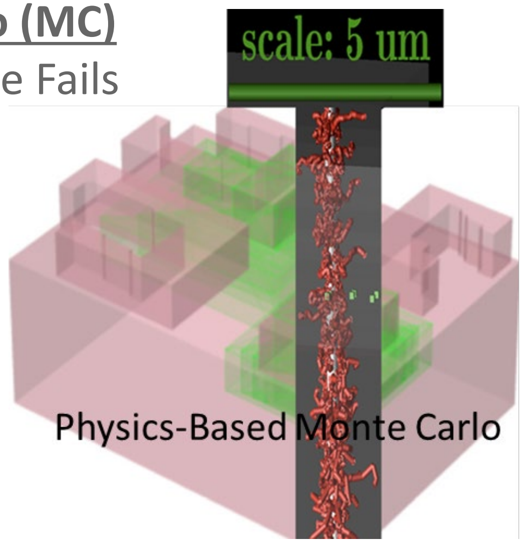
- Figure of Merit (FOM) (an underrated technique)
- $C_E \times FOM = C_E \times \sigma_{sat}/LET_{0.25}^2 = C_E \times \sigma_{sat}/(LET_0 + w \times (0.288)^{1/s})^2$
- 2 parameters, so need ~4 LETs for meaningful rate

Monte Carlo (MC)

When All Else Fails



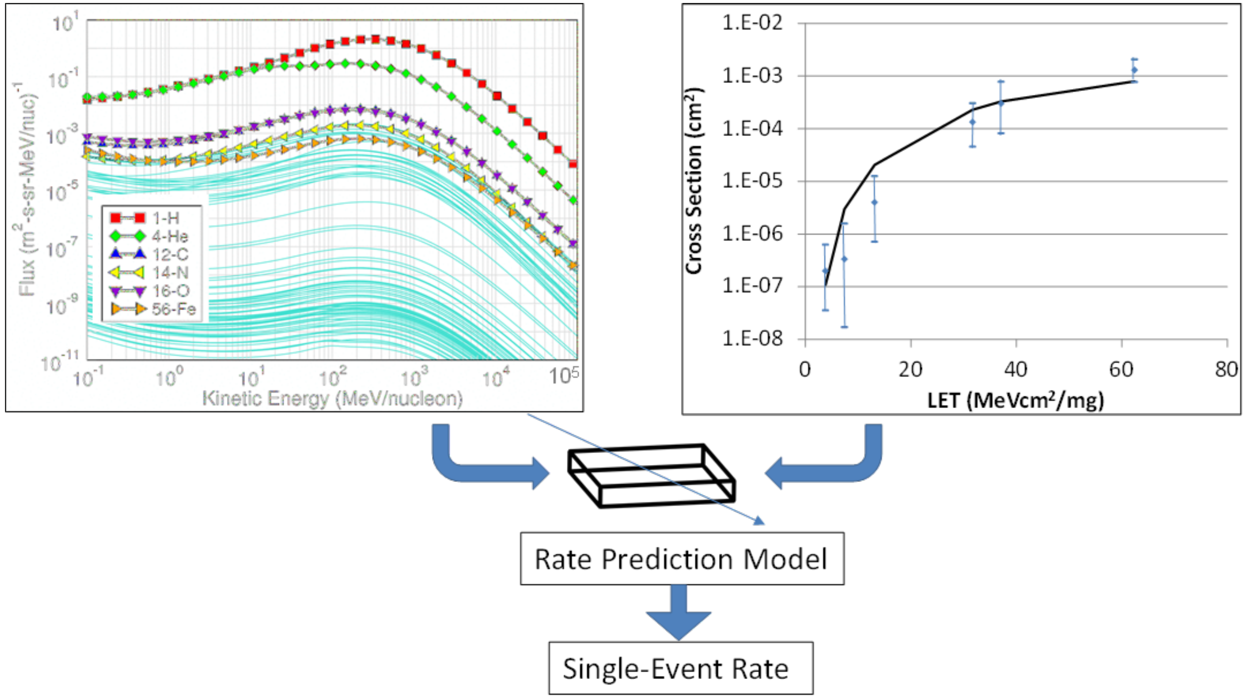
Nested-Volume Monte Carlo



Physics-Based Monte Carlo

- MC models can be complex and require lots of data

From SEE Cross Section vs. LET to SEE Rate



- SEE rate estimation involves combining for each mode in part
  - part susceptibility data (σ vs. LET—same for all environments)
  - Environmental model(s) (proton, heavy ion, same regardless of part)
  - Simplified sensitive volume model (Rectangular Parallelepiped (RPP))
  - σ vs. LET usually w/ 4 Weibull fitting parameters, LET_0, σ_{sat}, w and s

- LET_0 related to minimum charge needed to cause SEE (given RPP dimensions)
- σ_{sat} related to sensitive area for effect on chip due to all sensitive features (# not known for broadbeam testing, so conventionally set as 1)
- w and s determine how quickly cross section rises form onset to saturation with LET
- Cross section error decrease w event count, n
  - Errors are Poisson, decrease ~$n^{1/2}$
- Fit should be bounding given error bars
- σ vs. LET fitting methods discussed next
  - Eyeball Mark IV—qualitative, subjective
  - Least-squares—does poor job w/ LET_0
  - Generalized Linear Model—allows determination not just of best fit, but also confidence contours
- Fits/rates especially sensitive to poorly determined LET_0 and σ_{sat}

Interpreting SEE Data& Analyses: Requirements

Test Results for Each SEE Mode

Fault Symptoms/Identification | Data: LET, Counts, Fluences, σ | Consequences | Rates | Recovery

Analysis, Including Propagation of SEE Effects to All Relevant Levels

Requirements May Take Many Forms and May Be Implemented At/For Many Levels

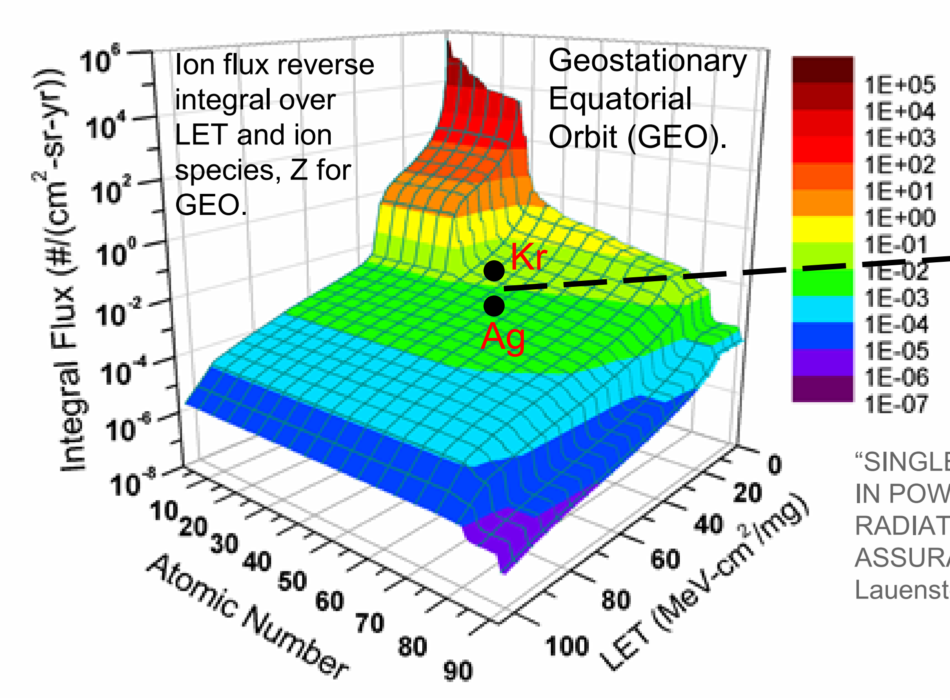
- Often parts-level radiation requirements can be verified entirely based on test results or limited analysis
  - Example I: No destructive SEE shall be observed for fluence of 10^7 ions/cm2 with LET$\geq$75 MeVcm^2/mg
  - Example II: SEE modes must be self-recovering, without external intervention.
  - Usually, these requirements are conservative—ensuring impact of SEE mode will be negligible
- Higher-level requirements often require understanding propagation of SEE consequences and recovery at system level
  - May require significant analysis, modeling and simulation to verify compliance
  - Often these requirements phrased in terms of reliability, availability, accuracy, precision…

Not All Radiation Requirements Include The Word "Radiation"

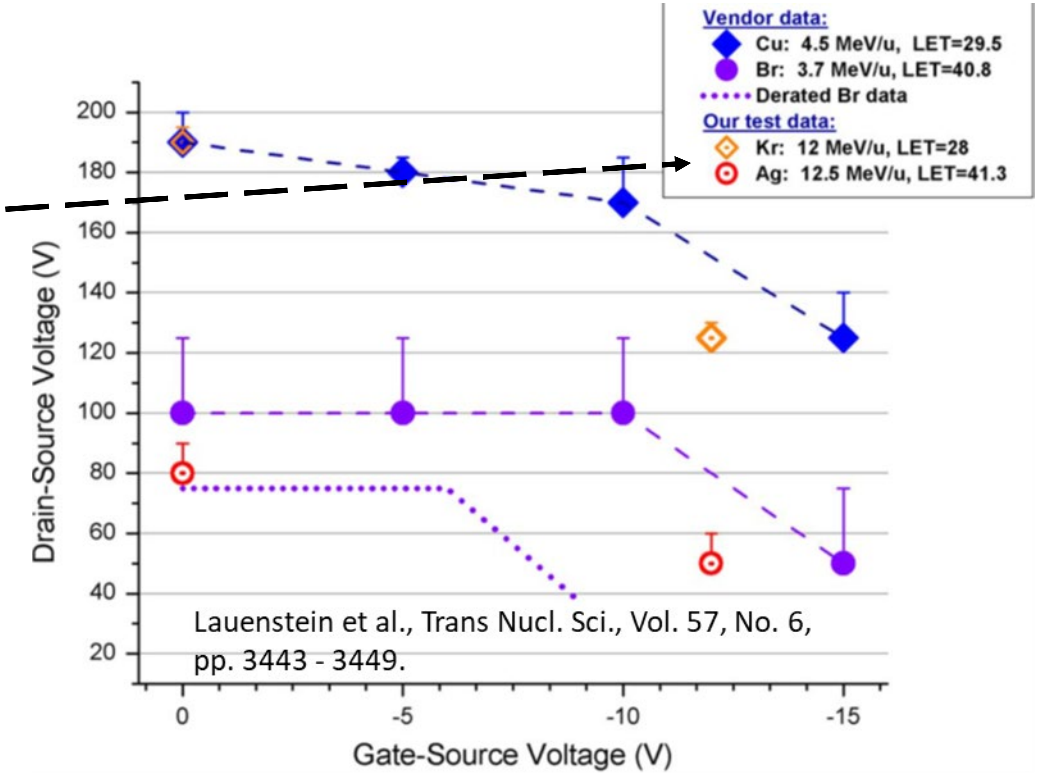
Examples

SEE Mode	SEE Mode	Requirements Affected
SET	Read Sensor	Accuracy, Precision…
SET	Turn on/off Hardware	Availability, Reliability…
Destructive SEE	Regardless of Application	Reliability…
SEFI	Recovery Requires Reinitialization of Part	Data Accuracy, Availability (slight)…
SEFI	Recovery Requires Reinitialization of Part	Data Accuracy, Availability, Reliability Could also require hardware redesign

Risk Avoidance: Response to Uncertainty



"SINGLE-EVENT GATE RUPTURE IN POWER MOSFETS: A NEW RADIATION HARDNESS ASSURANCE APPROACH," J.-M. Lauenstein, PhD Dissertation.

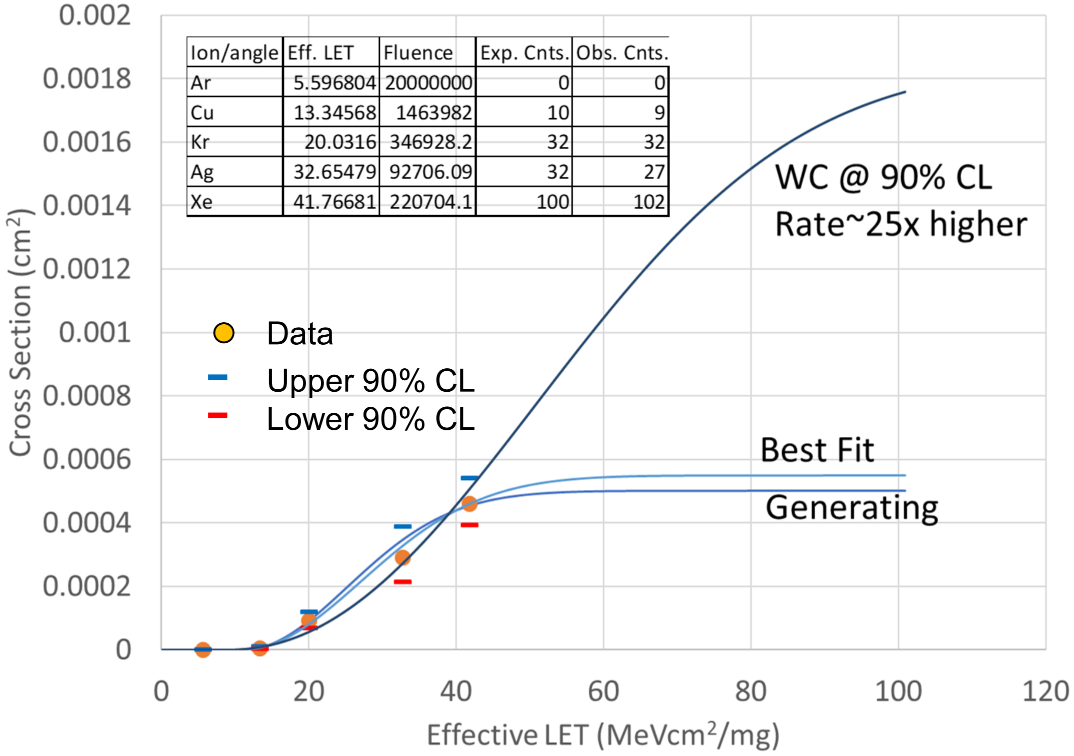


- Inability to estimate rates means testing seeks to identify operating voltages where failure probability negligible
  - Choose test with ions having LET, Z high enough to be improbable
  - Such approaches do not estimate rates, but rather potentially "lethal" ions in the environment incident on the device
  - Especially for SEGR, response is variable, caution is advised

- SEB/SEGR mechanisms too complicated for reliable rate estimation
  - Susceptibility depends on applied voltages, ion angle, energy and species Z, not just LET
- Consequences can be severe

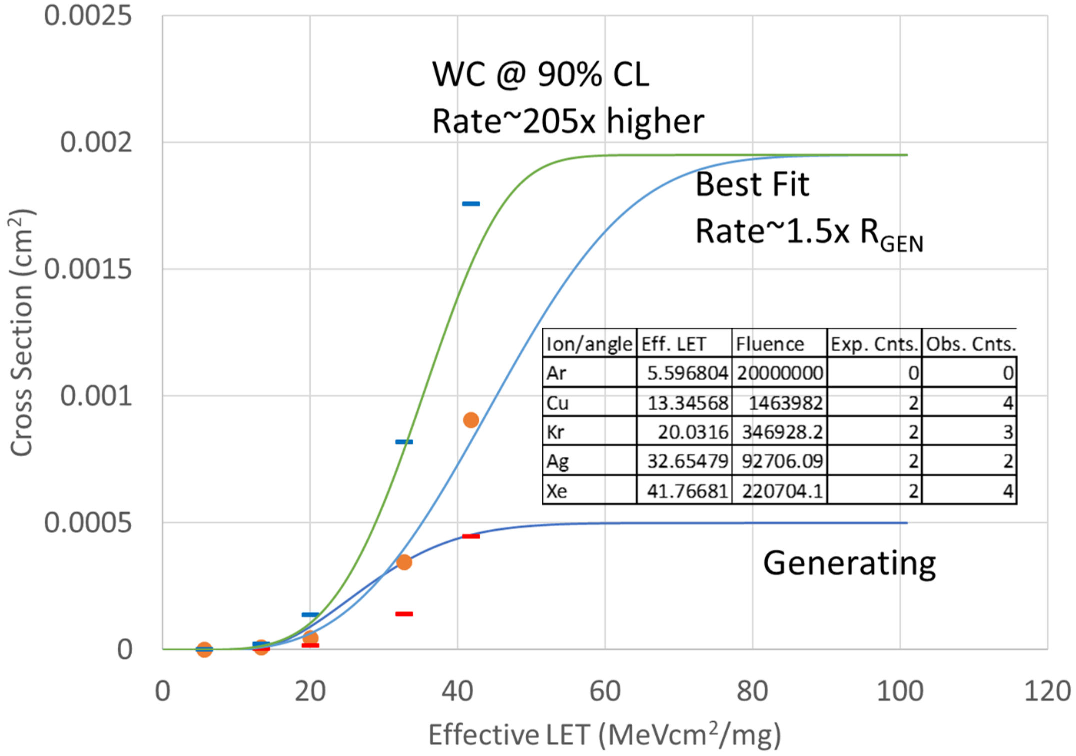
Lousy Data II: Poor Saturation and Statistics

Statistics good, but poor saturation constraint



Ion/angle	Eff. LET	Fluence	Exp. Cnts.	Obs. Cnts.
Ar	5.596804	20000000	0	0
Cu	13.34568	1463982	10	9
Kr	20.0316	346928.2	32	32
Ag	32.65479	92706.09	32	27
Xe	41.76681	220704.1	100	102

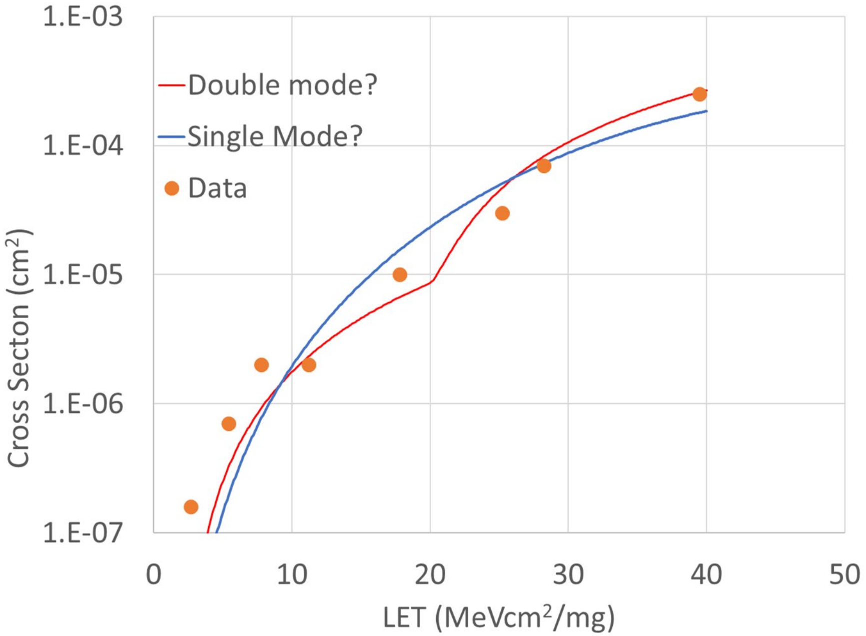
Poor statistics and poor saturation constraint



Ion/angle	Eff. LET	Fluence	Exp. Cnts.	Obs. Cnts.
Ar	5.596804	20000000	0	0
Cu	13.34568	1463982	2	4
Kr	20.0316	346928.2	2	3
Ag	32.65479	92706.09	2	2
Xe	41.76681	220704.1	2	4

- Data quality determines possible fits--# of cross sections, SEE counts/error bars both important
  - Onset, saturation clearly defined—at least 1 LET with 0 events and high fluence, >1 LET w/ no cross section increase
  - Ratio of 90% WC rate to best-fit rate provides a good measure of data quality: If <<2x, data quality is good

Lousy Data II: Mixed Modes

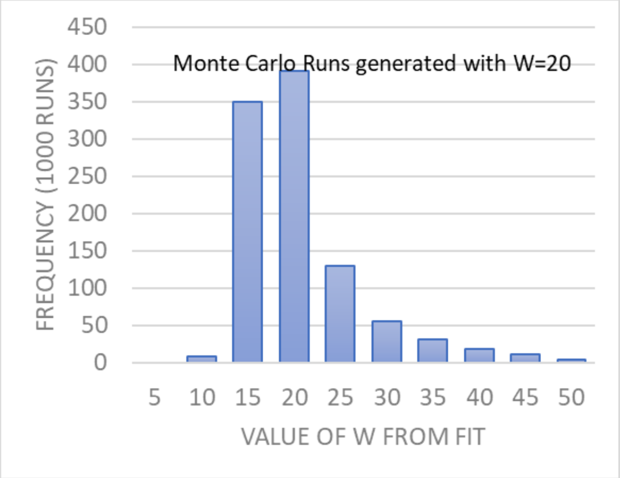


- Early on, we focused on getting "clean" data
  - What happens if we don't?
- This fake data generated w/ 2 different modes
  - Could you tell?
  - SEU—one bit at a time; burst errors can be multi-bit
- Can be difficult to detect

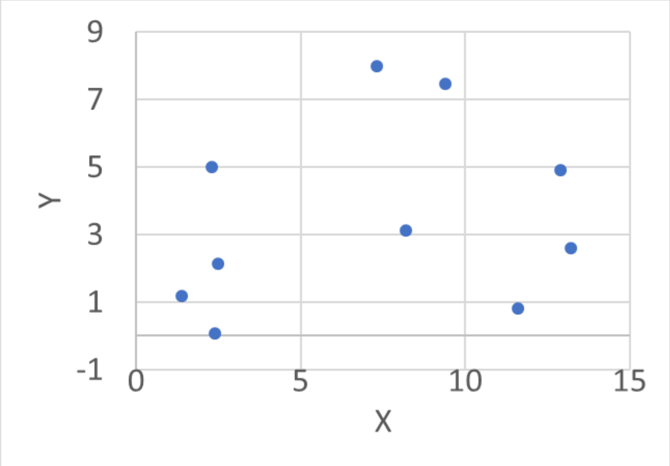
- Mixing SEE modes in introduces 2 types of errors
  - Consequences of two modes may be very different
    - Makes errors of interpretation likely
  - Distorts σ vs. LET and therefore fit and rate
- Examples of mixed modes I've seen
  - Destructive and nondestructive SEL
    - Only way to tell is to see failure
  - Nondestructive SEL and High-current SEFI
    - SEL high-current is self-sustaining
  - SEB and SEGR
    - Gate can fail during SEB as well as SEGR
- SEU and block error/burst error
  - Block/Burst errors can dwarf error count due to SEU even if they occur at lower rates.

Some Data Analysis Tools

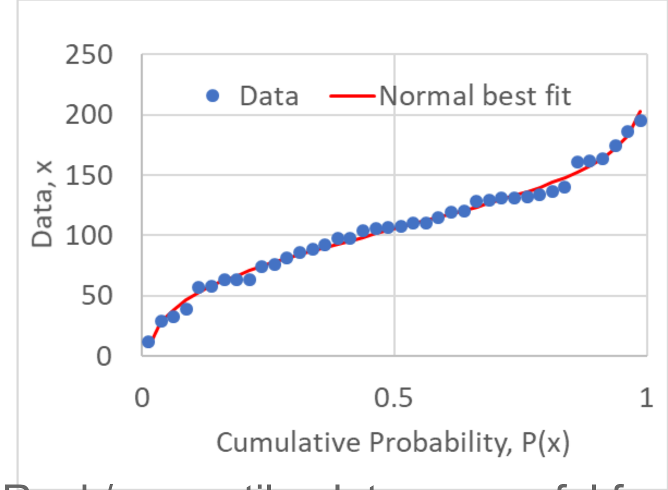
This is NOT a class on Exploratory Data Analysis(EDA)—but these plots very useful in exploring relationships in datasets



- Histograms good for examining distributions of parameters
- Examples
  - Transient widths, daily upsets
- Suggests ways to model errors or look for biases
  - Above: w is skewed right



- Scatter plots good for looking for relations between quantities
- Examples
  - Transient widths vs. amplitudes
- Suggests ways to model data
  - Fit above for w tends to be skewed right



- Rank/percentile plots are useful for
  - Extracting confidence intervals from data
  - Nonparametric but can examine distributions
- Rank data smallest to largest (n entries)
  - Rank plot plots data vs. its rank
  - Percentile plot— percentile=(Rank-0.5)*1/n

See https://www.itl.nist.gov/div898/handbook/eda/eda.htm for more info on EDA

Conclusions

- SEE data is about as simple as data can get—all you do is watch what happens and count
- Each SEE data analysis driven by project requirements and challenges peculiar to SEE mode and part type
- Cross section vs. LET determines SEE rates for the part—same curve in any environment
  - Good data is a tug-of-war between getting a “pure” cross section for a SEE mode and retaining adequate statistics
    - Often “purification” involves segregating events by their system consequence; Laser testing can inform analysis based on physics
    - Adequate statistics are those that allow rate estimation/bounding with required accuracy and assurance
- Options for “rate” estimation range from go/no-go to full-blown Monte Carlo CAD calculations
  - Each demands different amounts and types of data
- Interpretation of SEE analysis can be in terms of requirements verification or system performance
  - Radiation can have bearing on requirements that do not mention radiation explicitly
  - If rate estimation impractical—risk avoidance (safe operating conditions, part rejection etc.) are often only viable option
- Special problems—there is a lot more data that is lousy than good, so be prepared to identify shortcomings
  - For challenging data, EDA techniques in https://www.itl.nist.gov/div898/handbook/eda/eda.htm are useful