Bounding SEL Threshold Using Saturation Cross-Section Data

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Outline

- Why Single-Event Latchup (SEL)* is Difficult…and Important
- Latchup: What Doesn't Work
- Trying "Big" Data: Jeepers…This Kind of Works
  - And What Different Types of Data Work For
- Correlations: From Characterization to Modeling
- When Correlation Isn't Quite Enough
- A Workable Bounding Strategy
  - Caveats and Gaps

*In CMOS=Complementary Metal-Oxide-Semiconductor

Abbreviations

ADC-Analog-to-Digital Converter
ADI-Analog Devices, Incorporated
CENV—Environment Coefficient figure of merit
CERN-Conseil European de Recherche Nucleaire
CL-Confidence Level
CMOS-Complementary Metal-Oxide-Semiconductor
DAC-Digital-to-Analog Converter
Epi-Epitaxial
FOM-Figure of Merit
GEO-Geostationary Equatorial Orbit
JPL-Jet Propulsion Laboratory
LET-Linear Energy Transfer
LET_0-Onset LET
LSI-LSI Logic Corporation
LTC-Linear Technology Corporation (now part of ADI)
Maxim-Maxim Integrated (now part of ADI)
MIEL-International Conference on MIcroELectronics
NSREC-Nuclear and Space Radiation Effects Conference
ON Semi—ON Semiconductor Corporation
Op Amp-Operational Amplifier
QCOM-Qualcomm Incorporated
REDW-Radiation Effects Data Workshop
SEL-Single-Event Latchup
σ_S-Saturated cross section
s-Weibull shape parameter
TI-Texas Instruments
TNS-Transactions on Nuclear Science
w-Weibull width parameter
WC-Worst Case

“What’s the most you’ve ever lost on the toss of a coin?”

SEL Is Ubiquitous, Potentially Catastrophic and Can Be Limiter of System Lifetime

How Common is it?
Unhardened CMOS: 50%
--of which 50% are destructive

~4 % of SEL rates >1 per month (GEO)
~20% of SEL rates>1 per year (GEO)
~43% of SEL rates>1 per 10 year (GEO)

Part-Level Consequences
Nondestructive—power cycle needed

Latent Damage

Catastrophic failure

Parts/Technology Affected
Any Bulk/Epi CMOS unless Specifically hardened to SEL

Even if CMOS is only in control logic or input/output

System Consequences
Nondestructive—disruptive

Latent Damage-reduces reliability

Catastrophic failure—that’s bad, right?

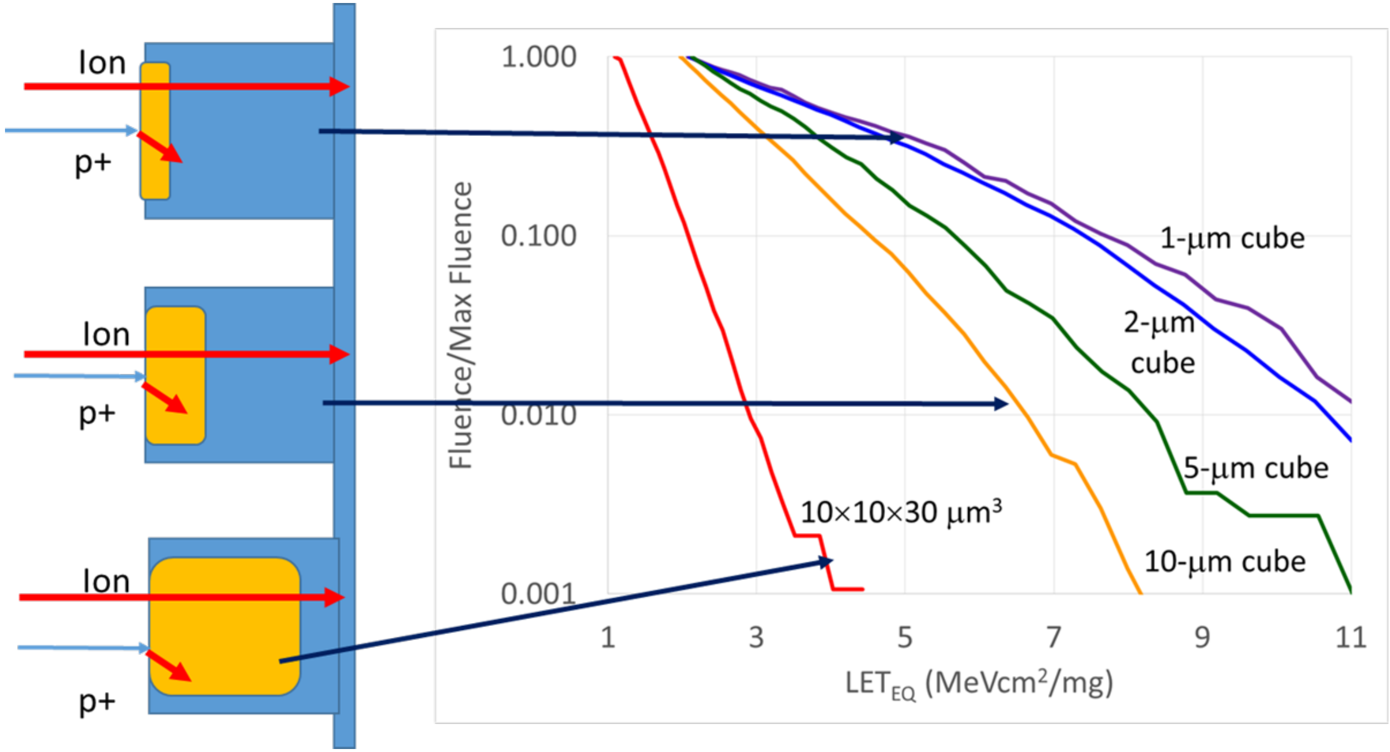
A Priori Risk Prediction

Usual criteria show no predictive power

SEL: What Doesn't Work

- Conventional similarity criteria do not improve predictive power
- %parts susceptible does not depend on:
  - Vendor
  - Process—limited
    - BiCMOS less likely to latch up
  - Fabrication Facility
  - Feature size
  - Part Function—limited
    - 70% of Analog-to-Digital/Digital-to-Analog Converters (ADC/DAC) susceptible
    - Amplifiers/comparators maybe slightly <50%
- None of these criteria improve prediction
  - They also dilute statistics and may obscure trends for the technology

- Proton recoil ions range short; SEL sensitive volumes are deep
  - Significantly reduces effectiveness of protons as SEL screen
- Heavy-ions: only sure way to identify SEL susceptibility
  - Not all heavy-ion accelerators have sufficient range



What About Big (or At Least Bigger) Data?

- Problem with SEL data
  - Severe SEL consequences mean testing often abandoned when part found to be susceptible
  - Many single-LET go/no-go tests
    - LET varies depending on requirements
  - Relatively few allow determination of both onset (LET_0)and saturation (σ_s)
  - Few full Weibull fits to data
    - Caveat: Many fits are bounding, not “best-fit”
    - Many datasets are proprietary/unavailable
- Several recent efforts
- Rudenkov et al.—2017 MIEL Proceedings
- Allen et al.—2017 NSREC REDW
- Ladbury et al. 2021 IEEE TNS (May 2021)
- Coronetti et al., CERN Database, published in full in Ladbury, IEEE TNS (April 2024)

What Different Datasets Give Us

Large Go/No-Go Dataset ⇒

% of parts that latch up
-Overall
-Time series?
-By part type?
-By vendor?
-etc.

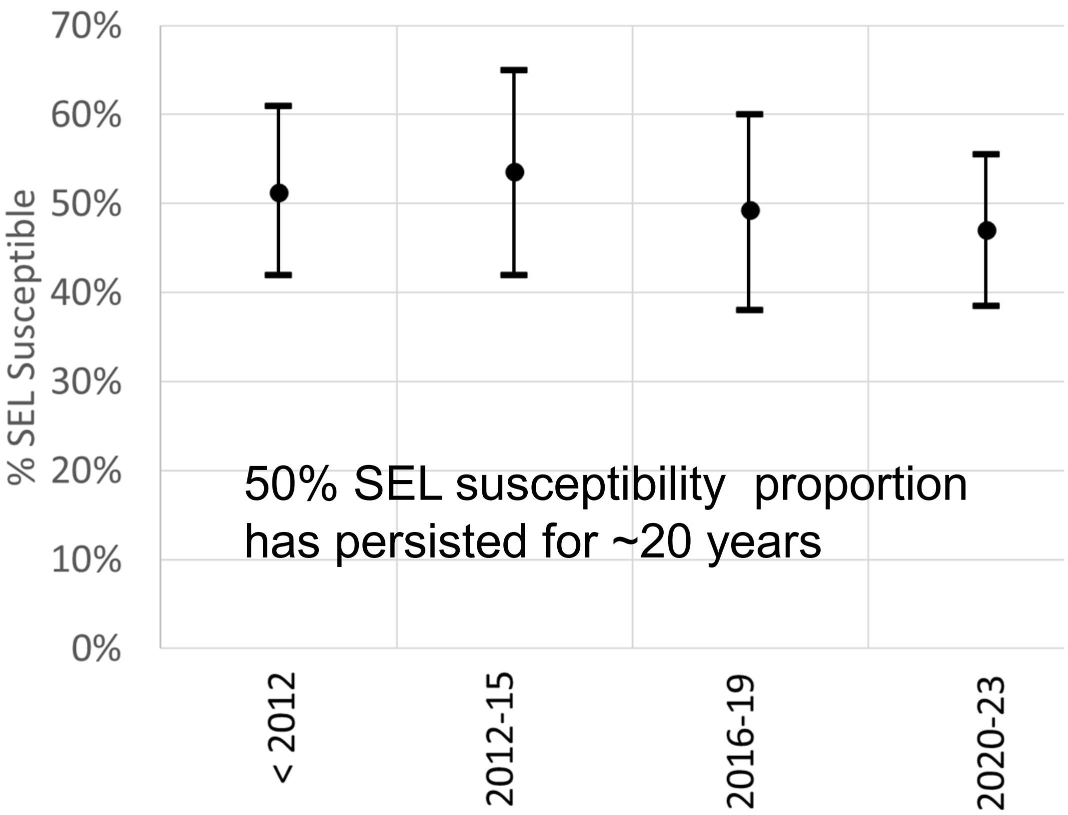
Full/Partial Fit to σ vs. LET ⇒

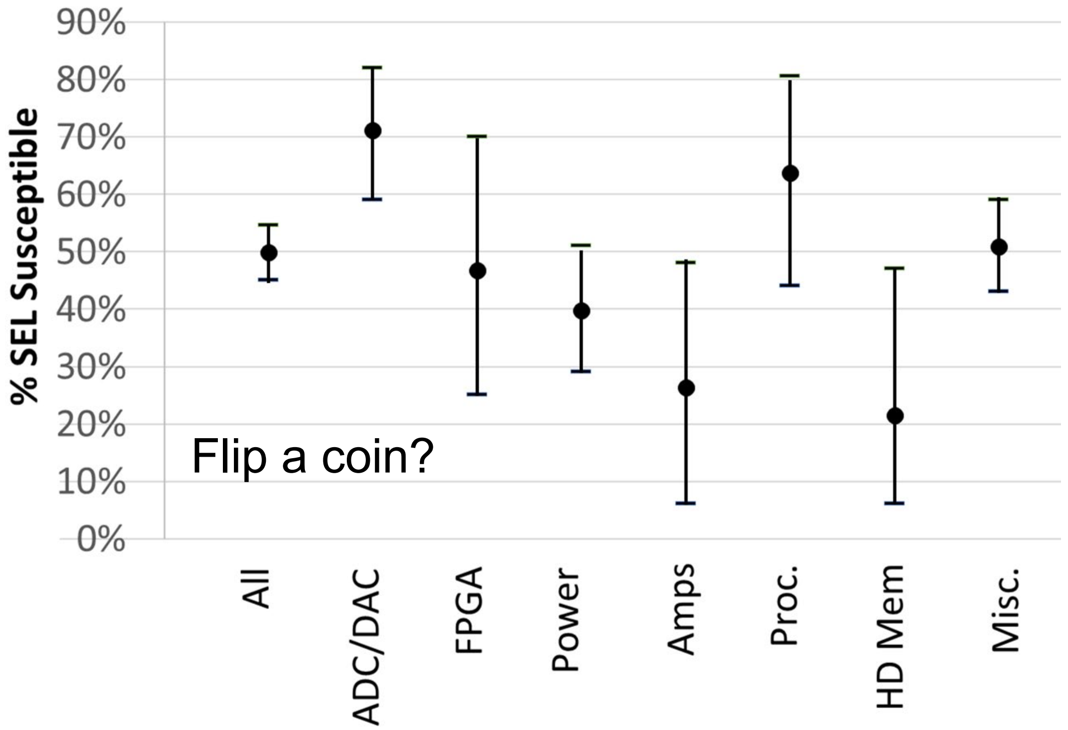
Fit Parameter Relations
-Distributions
-Correlations
-Parameter Models
-Bayesian Priors
-Limiting Rates

Special ⇒

e.g. Rudenkov et al. normalize σ_s to die area—useful for system-level studies bounding SEL risk

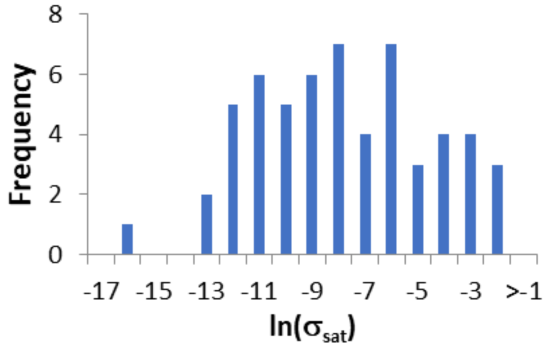
Update of Allen et al. 2017

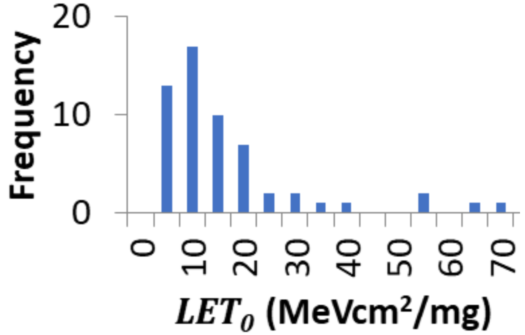


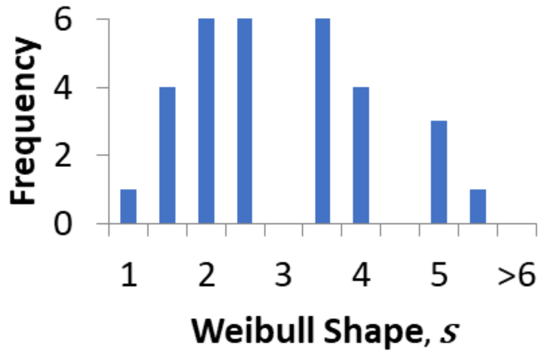


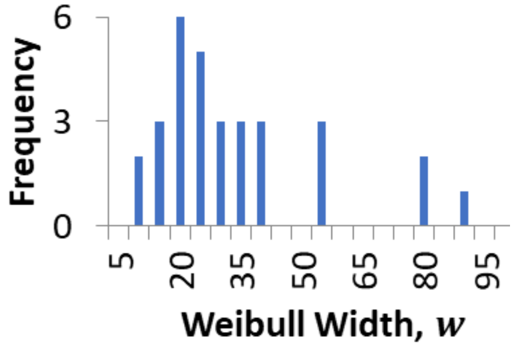
Recent analysis of JPL database for SEL susceptible parts analyzed ~200 part types. Statistics are sufficient that data can be divided into rough categories of part time or test date to look for trends. Conclusions remain the same: Unhardened CMOS is ~50% likely to latch up at some LET.

What Do Parameter Distributions Tell Us?



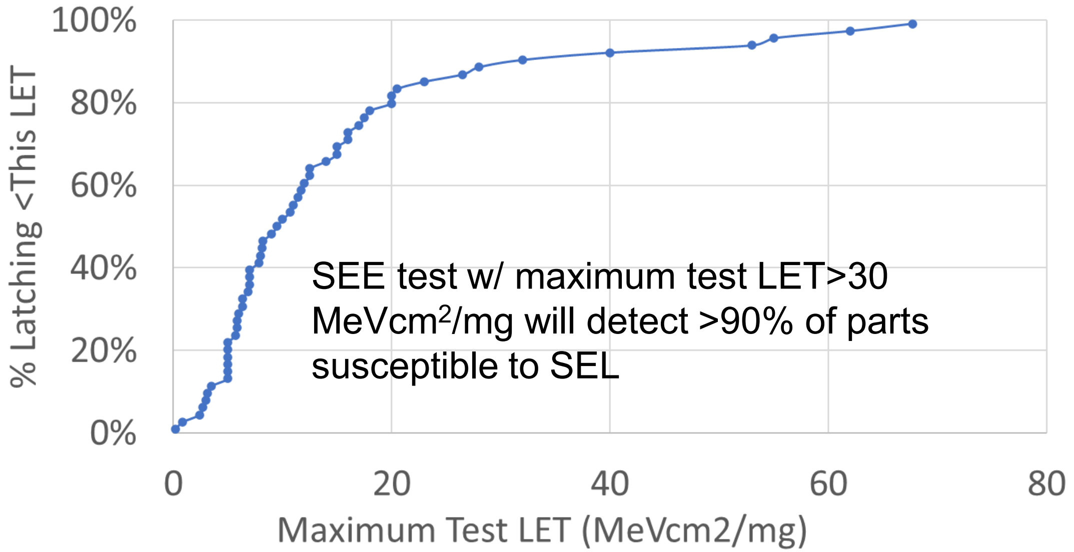






57 of 81 parts in CERN SEL database provide estimates of both onset (LET_0) and saturation (σ_{sat})

- σ_{sat} spans >6 orders of magnitude, LET_0 2 orders



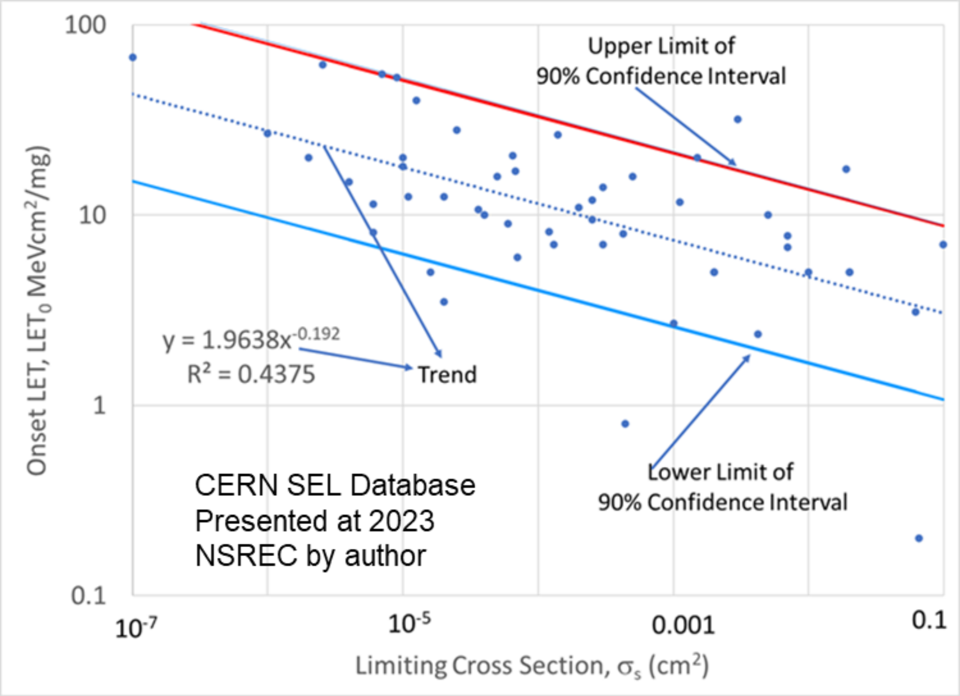
31 of 81 parts in CERN SEL database provide estimates of all Weibull fit parameters

- ~80% of parts have s≥2; ~80% have w<40

Weibull (4 parameter)→ 6 correlation coefficients

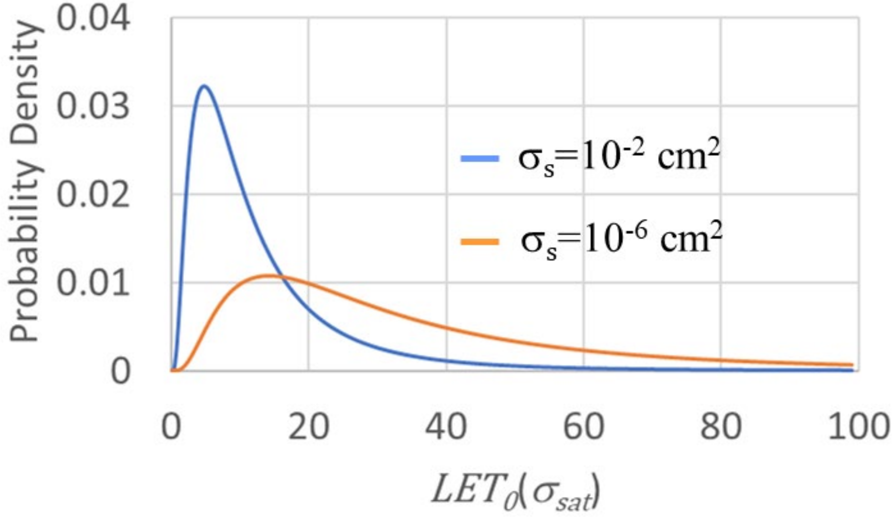
- Only 2 are significant
  - Correl(σ_{sat}, LET_0)=-0.27
  - Correl(w,s)=-0.43
- Correlations have important implications for how data can be used to model a priori SEL susceptibility

SEL Rate Can Be Bounded



- Subset of CERN database for which LET_0 and σ_s can be determined independently
  - LET_0 and σ_s related by a power-law trend
  - Variability about trend~lognormal distribution w/ constant lognormal standard deviation

Measuring σ_s yields LET_0 distribution



Can express LET_0 as function of σ_{sat}, or vice versa

- Best fit to CERN data yields m_{ln}=1.96*$(\sigma_s)^{-0.192}$, s_{ln}=0.82

$R_{FOM}=C_{ENV}*\sigma_s/(LET_{0.25})^2=C_{ENV}*\sigma_s/(LET_0+w*0.288^{1/s})^2$

$R_{FOM}<C_{ENV}*\sigma_s/(LET_0(CL))^2=R_B$ (CL=Confidence Level)

$=C_{ENV}*\sigma_s/(\exp(\mathrm{NORMINV}(1-CL,\ m_{ln},s_{ln})))^2$

Should bound rate conservatively at >CL confidence

- Valid for both measured and upper limit σ_s
- Remember: What we predict here is really LET_0

Cross validation of Datasets

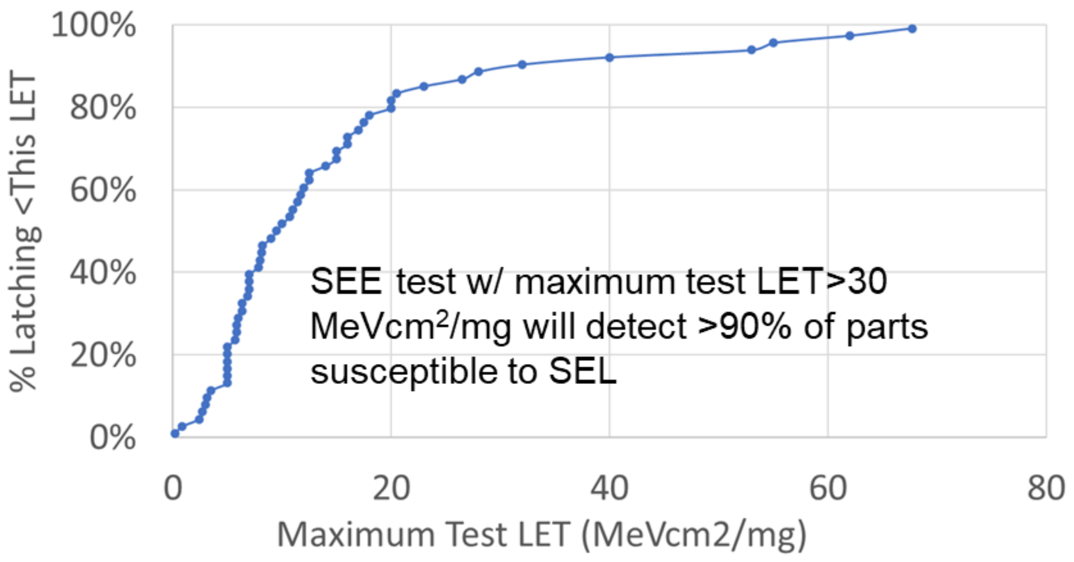
	σ_{obs}	Mfg.	Func.	Obs. LET_0	Med. LET_0	90%WC LET0	P($LET_0 \leq$ Obs.)
AD9283	5.0E-07	ADI	ADC	>29.8	31.70	11.10	47%
Blackjack	1.0E-02	LSI	ASIC	>5	4.47	1.66	53%
NB3N2304NZ	2.5E-04	ON Semi	Buffer	8	15.10	5.20	22%
AD7760	5.0E-04	ADI	ADC	8	8.43	2.95	47%
LTC1864	8.0E-05	LTC	ADC	8.5	11.99	4.19	34%
LMG1210	5.0E-05	TI	Driver	12	13.12	4.59	45%
ADP195	8.0E-07	ADI	Switch	>20.3	29.03	10.15	>33%
CC1200	5.0E-04	TI	XCVR	2.7	8.43	2.95	8%
Snapdragon LPDDR5	1.0E-03	QCOM	Emb. DDR	<14.3	7.38	2.58	<79%
MAX2982	9.0E-03	Maxim	XCVR	5	4.84	1.69	49%
MAX2981	1.0E-05	Maxim	FE Line Drvr.	16	17.88	6.25	45%

Look at parts tested by JPL with sufficient data to estimate both LET_0 and σ_s over past ~5 years

- Use only parts not already in CERN SEL database
- 90% WC bounds all but 1 of the parts
  - Expected for 90% CL given 11 parts

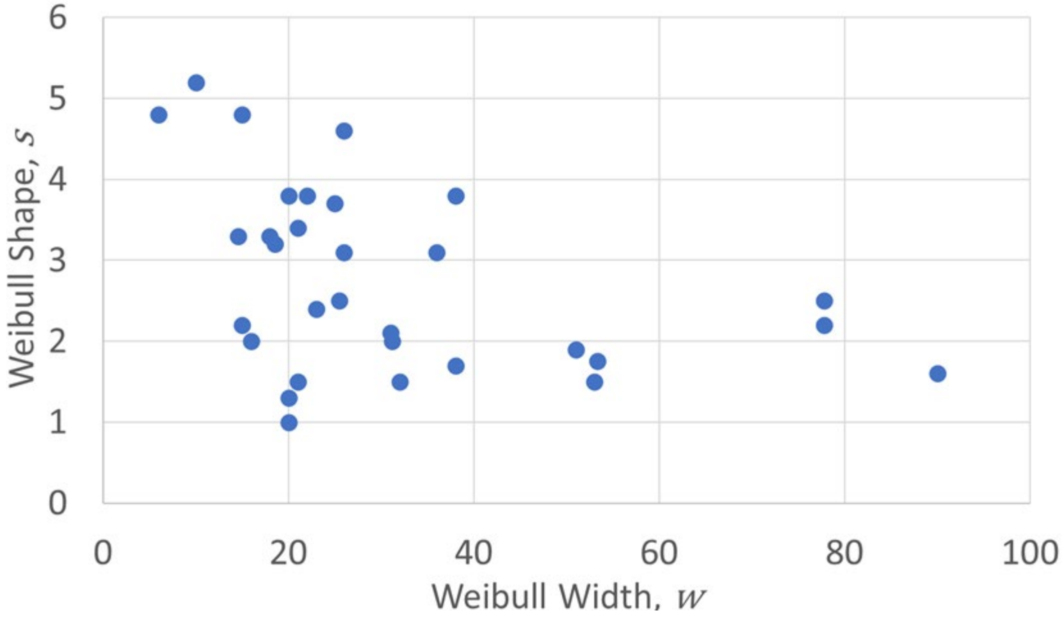
Median predicted LET_0 comes close for most parts!

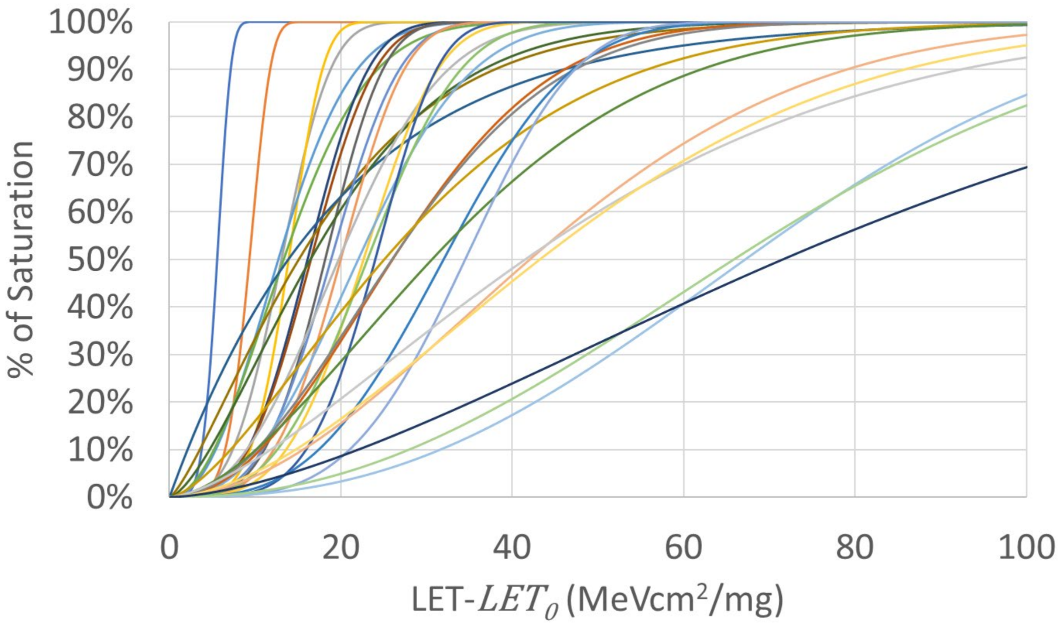
*See Abbreviations page for Vendors



- Can use quantile distribution of LET_0 to correct for bias introduced by limited test LET
  - Changes results for JPL database <3.5%
- Also useful for test planning, especially testing at board level when overburden varies with part

Effect of Weibull w, s—and How Do We Treat Them?

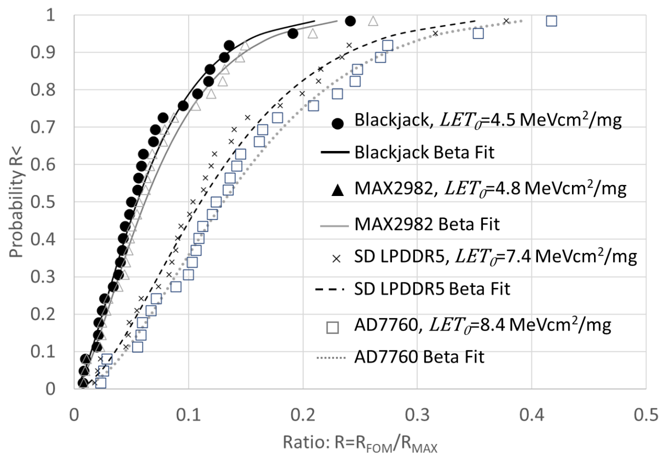


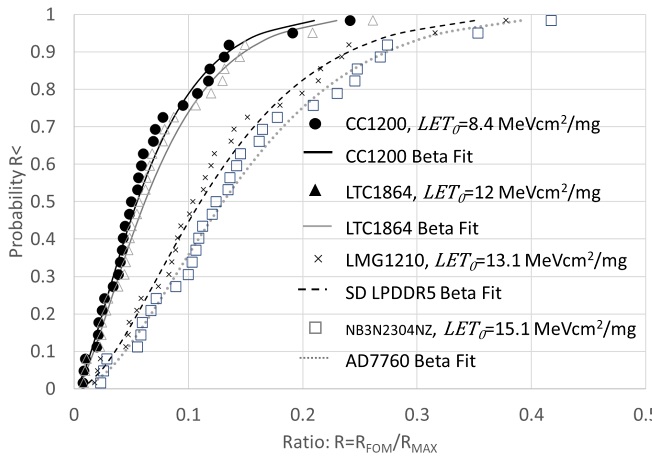


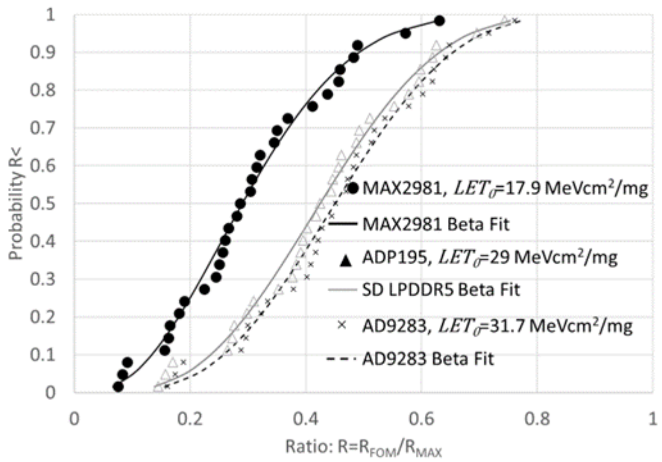
- Correlation w-s cannot be modeled simply
- Does mean cannot treat w and s independently
- w-s pairs represent broad range of behaviors

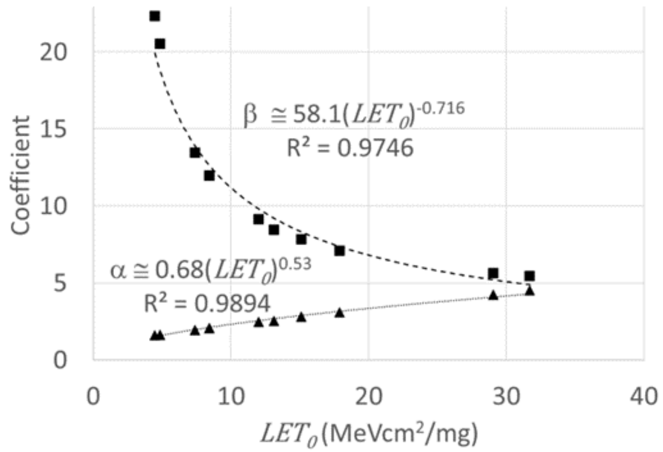
- Assume the 31 w-s pairs representative of the rising behavior of σ vs. LET

Making SEL Rate Bounds Less Conservative



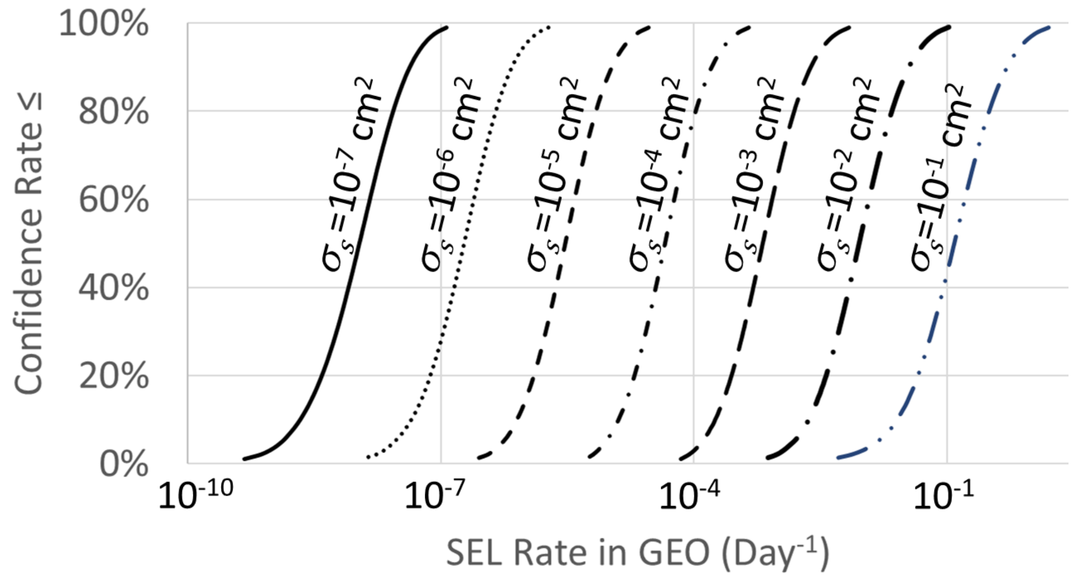


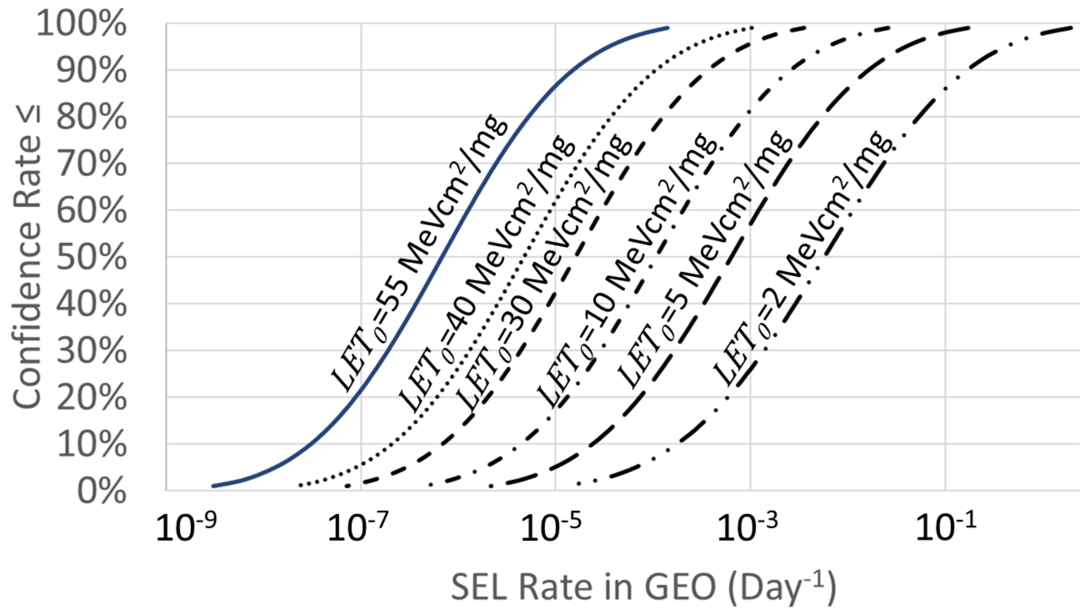




- Estimate bounding rate (R_B from slide 8) for all parts in table based on LET_0 and σ_s
- Estimate FOM rate (R_{FOM}) pairing each LET_0 and σ_s pair with each w-s pair
- Take ratio: $r = R_{FOM}/R_B \leq 1$, plot vs. quantile (note: r distribution depends on LET_0)
- Since $0 \leq r \leq 1$, can also plot best fit of data to a β distribution:
- $\beta(r,\alpha,\beta) = {}^{\Gamma(\alpha)\Gamma(\alpha)}/_{\Gamma(\alpha+\beta)}\, r^{\alpha}(1-r)^{\beta}$
- Goodness of fit suggests r well behaved
- This means conservatism of bounding rate can be relaxed: R(CL)=R_B (CL1)x r((CL_2), such that only 10% of rates in sample space exceed R(CL)
- β distribution yields sufficiently good fit, can use it or r -quantiles nonparametrically

Bounding SEL Rates to a Desired Confidence





- What this means is if we know either LET_0 or σ_s, we can bound rate to any desired confidence
  - Contingent on CERN dataset being sufficiently representative for parts susceptible to SEL
    - Have 57 parts defining relationship between LET_0 and σ_s, and 31 defining w-s behavior of σ vs. LET
    - JPL dataset provides 11 more part types supporting relationship between LET_0 and σ_s
- Got data? (full Weibull best fits to σ vs. LET or raw data (counts, fluences, LETs, etc.) for SEL)

Current Gaps and Future Work

- Heavy-ion SEL testing
  - If data are sufficient to estimate σ_s, LET_0, and SEL rate can be bounded for any designed confidence
    - Could be one measurement at very high LET, fluence (how high an LET will be discussed at NSREC)
    - Or sufficient σ vs. LET to determine saturation, but maybe not onset.
- Laser SEL testing is fairly good (and getting better) at estimating LET_0, but not σ_s.
  - May be possible to bound SEL rate and σ_s to desired confidence with laser testing
- Latent damage remains troubling gap in knowledge
  - ~50% of latchable parts will fail due to SEL at some LET
  - Remaining 50% may experience only nondestructive SEL-OR- may experience latent damage
  - Detecting latent damage remains more an art than a science
  - Current NESC/HLS effort underway to improve latent damage risk assessment and detection
- Finally: Analysis is predicated on how representative the datasets are of current parts of interest
  - Viewing parts as belonging/not-belonging (binomial) to trend, 57 parts$\rightarrow$<4% don't belong 2/ at 90% CL
    - Adding in 11 more parts from JPL database: 68 parts $\rightarrow$<3.4% in the "don't belong" mode
  - Your data are welcome and key to validating and improving the model—especially full σ vs. LET best fits

Conclusions

- SEL in unhardened CMOS remains a persistent and difficult obstacle to use of modern devices
  - Conventional risk reduction methods (e.g. analysis of data for similar parts, proton testing) do not work
- Big (or at least bigger) data is a promising approach for improving SEL risk analysis
  - Large datasets of go/no-go testing reveal proportion of SEL susceptible parts
    - If large enough, reveal trends over time, vendor, part type, process…(Spoiler alert: flip a coin)
  - Large datasets of σ vs. LET allow investigation of fit parameter distributions, correlations, etc.
- Model built on CERN dataset can bound LET_0 in terms of σ_s, or σ_s in terms of LET_0
  - Can be used to bound SEL rate conservatively above a desired confidence
  - If 31 CERN database w-s pairs fully representative of likely σ vs. LET behavior, can bound rate for desired CL
  - Also offers possibility of bounding SEL rates with laser data—still to be investigated
  - Model is supported independently by 11 more part types in JPL database
- Efforts to better understand SEL risks still ongoing
  - NESC/HLS effort to better understand incidence of and identify latent damage
  - Still collecting more data
- And this represents just one SEE mode. Can we apply big data approaches to others?