Applied SEE Test Data: Modern NAND Flash

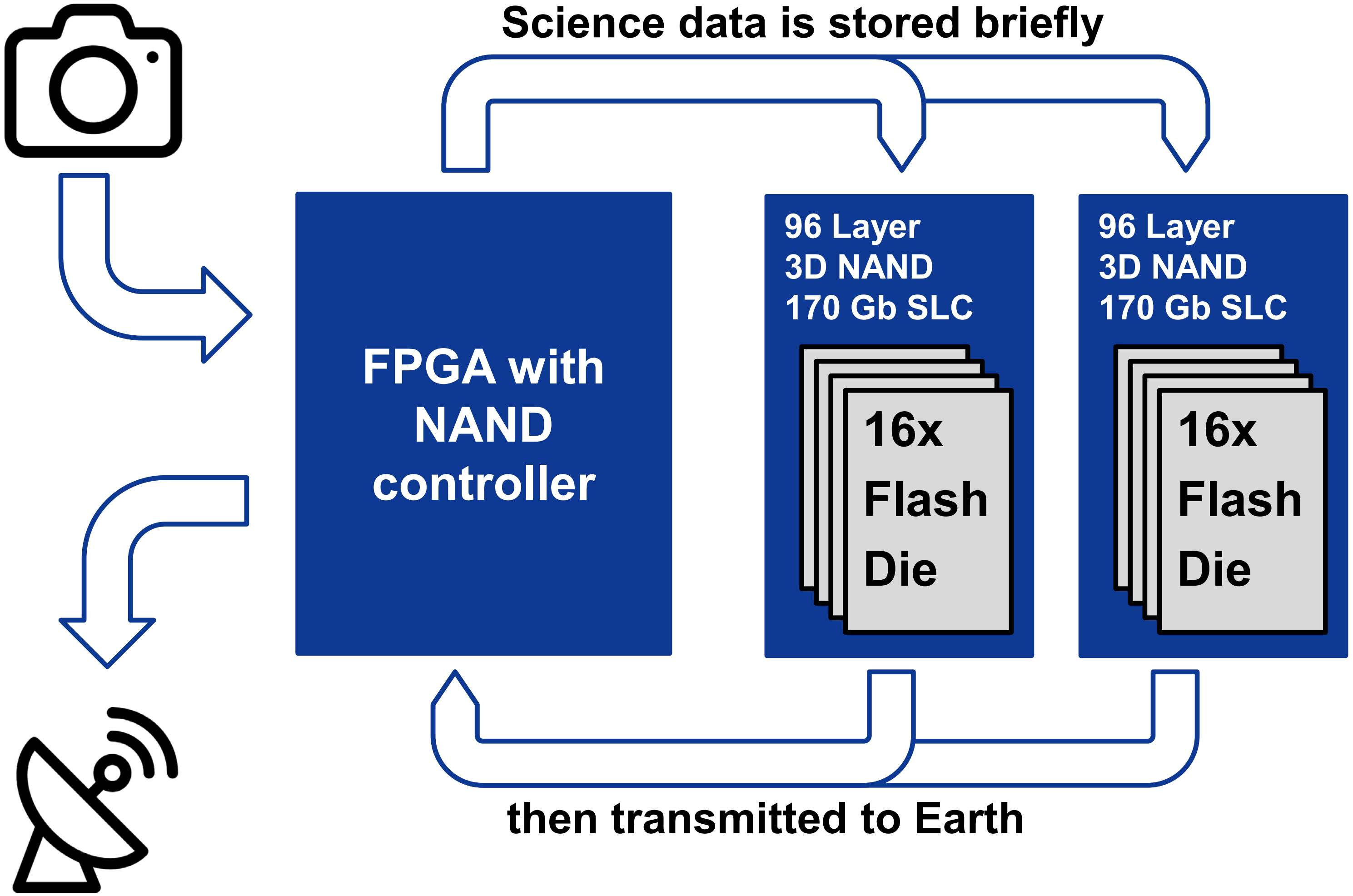
Ted Wilcox & Rebekah Austin
NASA Goddard Space Flight Center

Overview

- **SEEMAPLD 2022**: “Risk-Driven and Mitigation-Focused SEFI Testing of NAND Flash Devices”
- **Lesson**: Test the things that really matter, and test them well enough to inform your decision making
- **Example**: NAND flash SEFI criticalities and recoverability

- This talk covers the *application* of data for useful system-level analyses

Consider a Notional Data Storage System



Science data is stored briefly

FPGA with NAND controller

96 Layer
3D NAND
170 Gb SLC

16x Flash Die

96 Layer
3D NAND
170 Gb SLC

16x Flash Die

then transmitted to Earth

Total Memory Available:
32 x 170 Gb = 680 GB
Purely commercial 3D NAND flash

Radiation Questions Arise:
Is the system sufficiently radiation tolerant?

Ask the right questions

The real purpose of all this:

Is the system sufficiently radiation tolerant?

Partial answers:

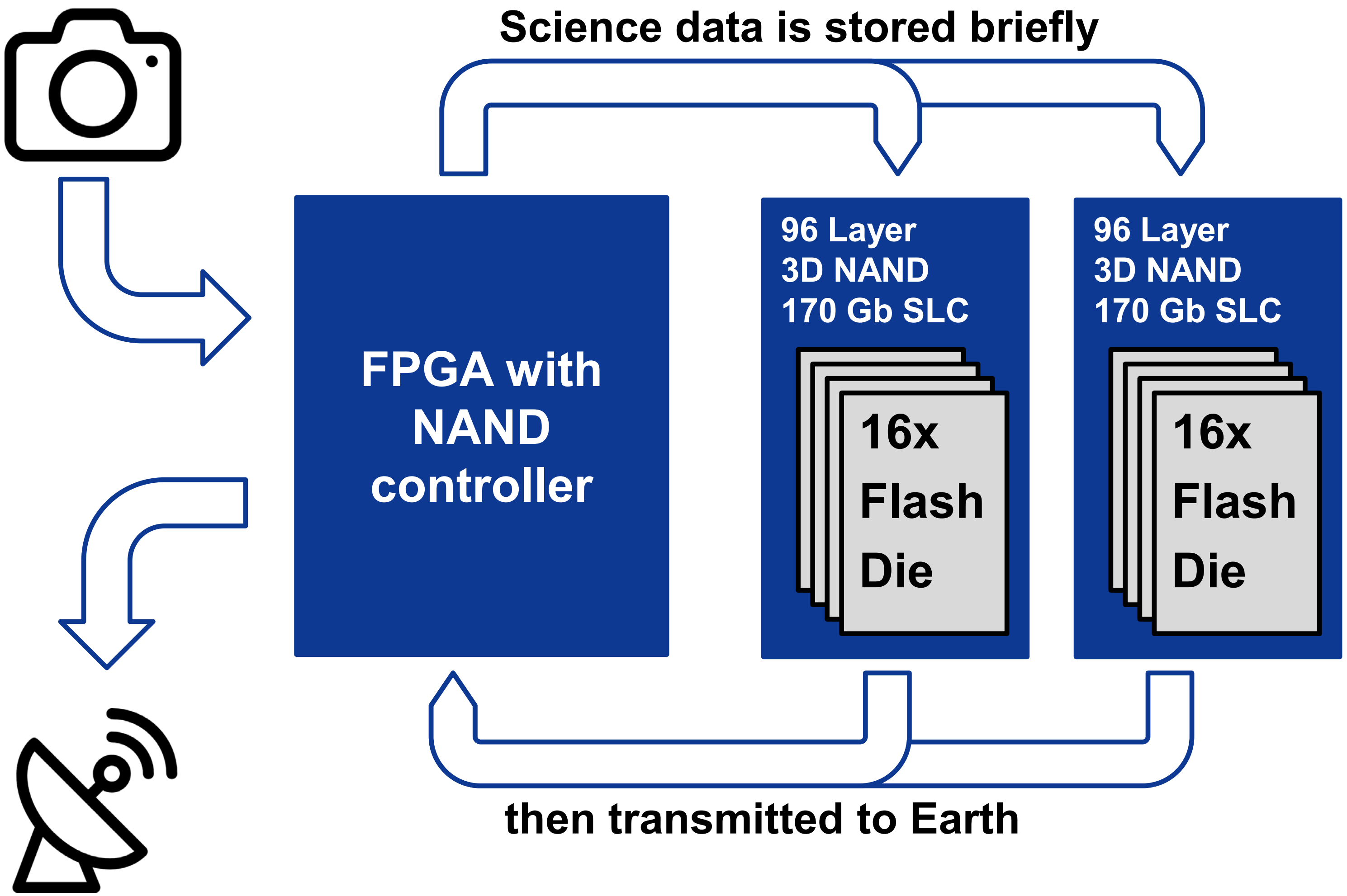
- 12 bit errors per day
- 1.3 SEFIs per week
- $LET_{th} > 20$ $MeV \cdot cm^2/mg$
- The data storage is redundant

These are informative, but lead to deeper questions:

Is it good enough?

How should we have designed the system in the first place?

Identification of Susceptibilities



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Sensor:

- Pixel errors (SEU)
- Row errors (SEFI)
- Destructive (SEL)

FPGA:

- Configuration (SEU)
- RAM / DFF (SEU)
- Logic Circuits (SET)

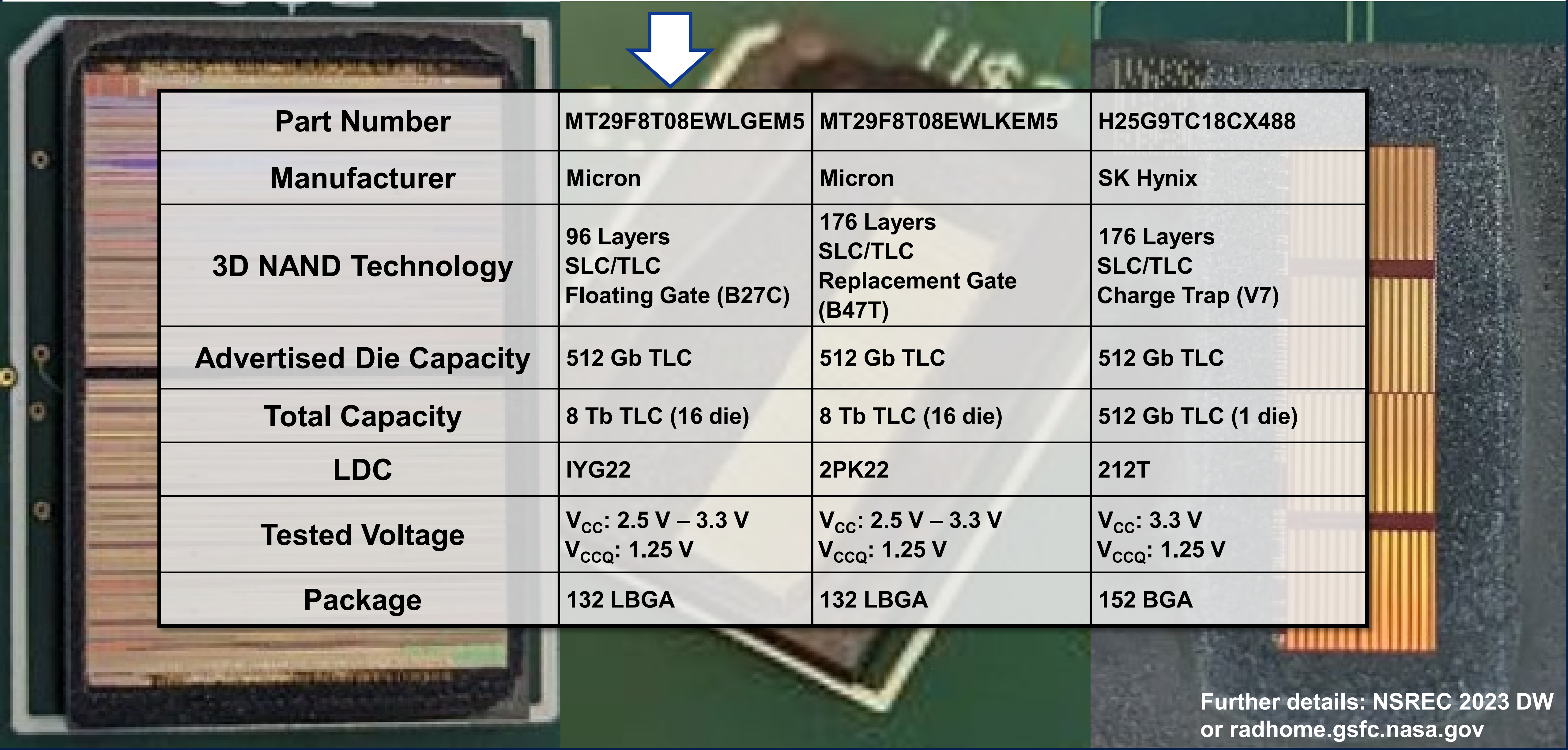
Flash:

- Bit errors (SEU)
- Block failures (SEFI)
- Destructive (SEL)

Transmitter System:

- Bit errors (SEU)
- System Hangups (SEFI)
- Destructive (SEL)

Recent SEE Data for Analysis

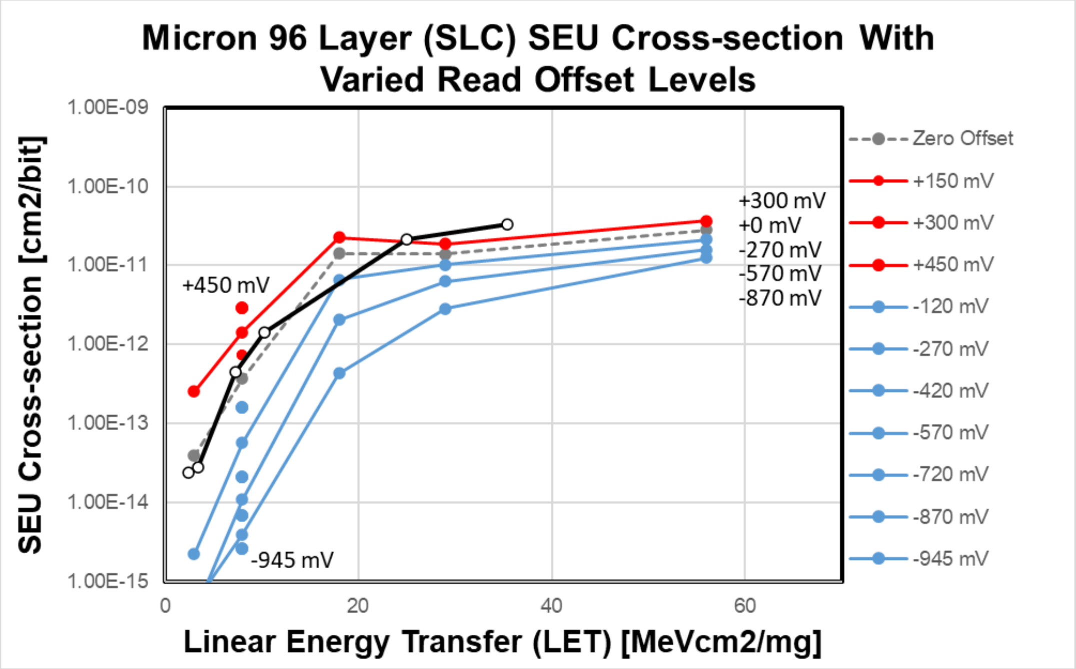


Part Number	MT29F8T08EWLGEM5	MT29F8T08EWLKEM5	H25G9TC18CX488
Manufacturer	Micron	Micron	SK Hynix
3D NAND Technology	96 Layers SLC/TLC Floating Gate (B27C)	176 Layers SLC/TLC Replacement Gate (B47T)	176 Layers SLC/TLC Charge Trap (V7)
Advertised Die Capacity	512 Gb TLC	512 Gb TLC	512 Gb TLC
Total Capacity	8 Tb TLC (16 die)	8 Tb TLC (16 die)	512 Gb TLC (1 die)
LDC	IYG22	2PK22	212T
Tested Voltage	V_{CC}: 2.5 V – 3.3 V V_{CCQ}: 1.25 V	V_{CC}: 2.5 V – 3.3 V V_{CCQ}: 1.25 V	V_{CC}: 3.3 V V_{CCQ}: 1.25 V
Package	132 LBGA	132 LBGA	152 BGA

Further details: NSREC 2023 DW or radhome.gsfc.nasa.gov

Data Available is Purely Part-Level

SEU data


Micron 96 Layer (SLC) SEU Cross-section With Varied Read Offset Levels

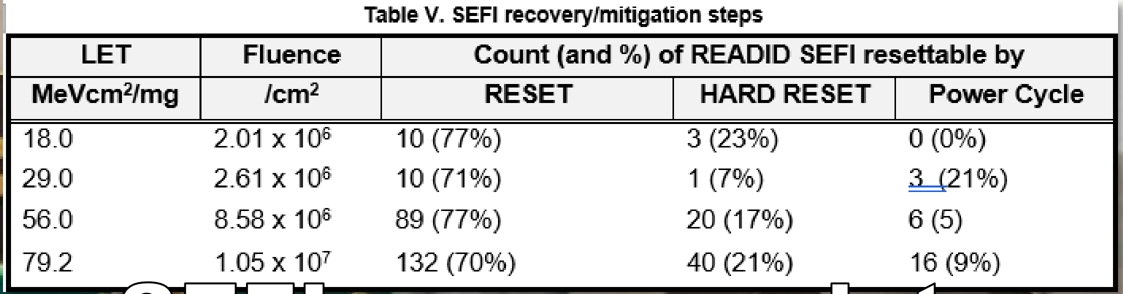


Table V. SEFI recovery/mitigation steps

LET	Fluence	Count (and %) of READID SEFI resettable by		
MeVcm^2/mg	/cm^2	RESET	HARD RESET	Power Cycle
18.0	2.01 x 10^6	10 (77%)	3 (23%)	0 (0%)
29.0	2.61 x 10^6	10 (71%)	1 (7%)	3 (21%)
56.0	8.58 x 10^6	89 (77%)	20 (17%)	6 (5)
79.2	1.05 x 10^7	132 (70%)	40 (21%)	16 (9%)

SEFI recovery data

SEL immunity

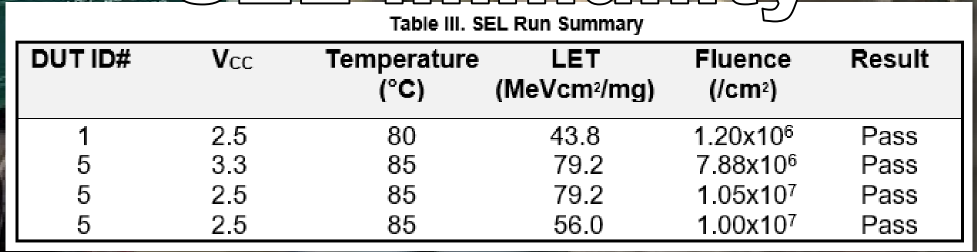
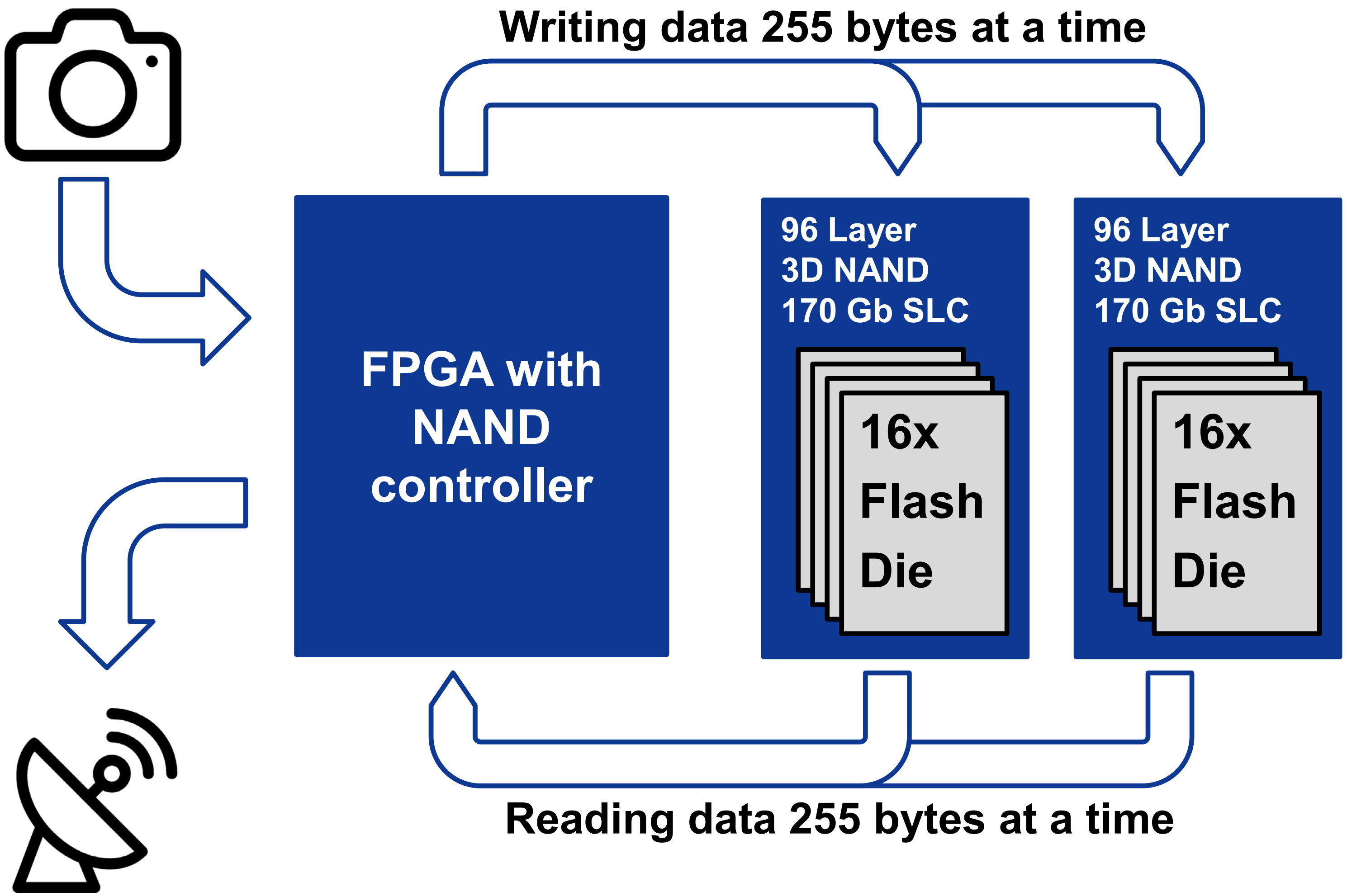


Table III. SEL Run Summary

DUT ID#	V_{CC}	Temperature (°C)	LET (MeVcm^2/mg)	Fluence (/cm^2)	Result
1	2.5	80	43.8	1.20x10^6	Pass
5	3.3	85	79.2	7.88x10^6	Pass
5	2.5	85	79.2	1.05x10^7	Pass
5	2.5	85	56.0	1.00x10^7	Pass

Applying Part Data to Notional Architecture



Writing data 255 bytes at a time

FPGA with NAND controller

96 Layer 3D NAND 170 Gb SLC

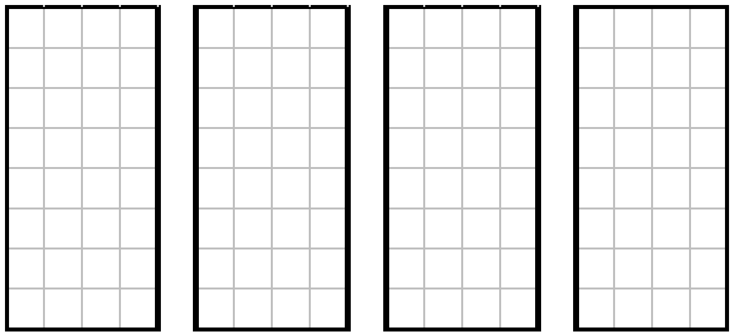
16x Flash Die

96 Layer 3D NAND 170 Gb SLC

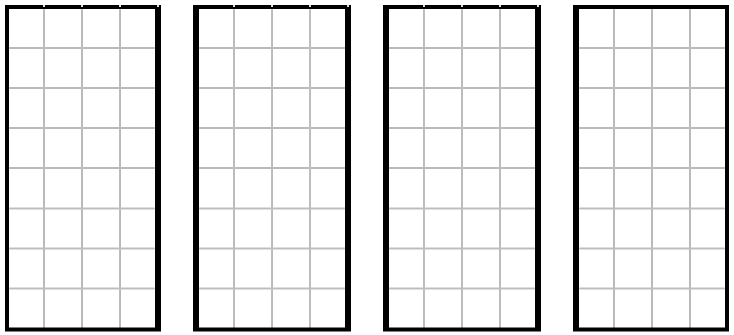
16x Flash Die

Reading data 255 bytes at a time

Implementation #1:
Write EDAC codewords to a single flash block, filling each flash die sequentially



Implementation #2:
Spread EDAC codewords across memory, interleaved among 32 die



Probabilistic System Analysis

Define Mission Parameters

Mission Timeline
- 5 Years
- Steps: 1 day

Error Rates (Any Source)
- Background: Solar Min
- Peak: Worst Day

System Components
- (32) Micron 96L Die

Operations
- Rewrite every 14 days and power cycle every 60 days

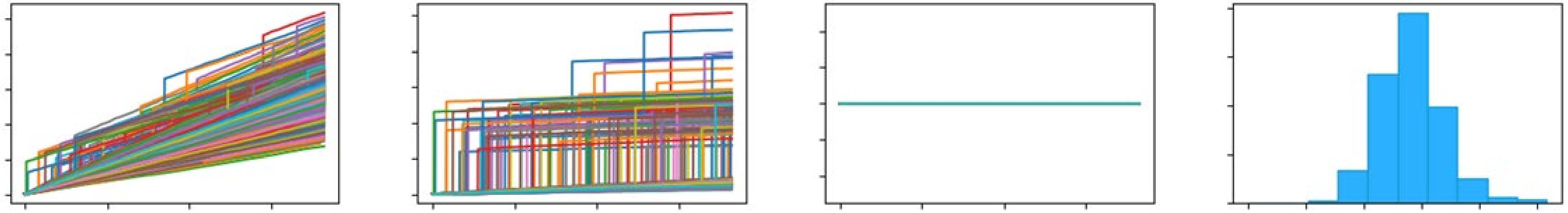
Setup Analysis

- 1000 independent Monte Carlo simulations
- Background Variability: +/- 3x
- Peak Events: 1 per 50 years
- Part Response Uncertainty: +/- 2x

Iterative Monte Carlo Simulations

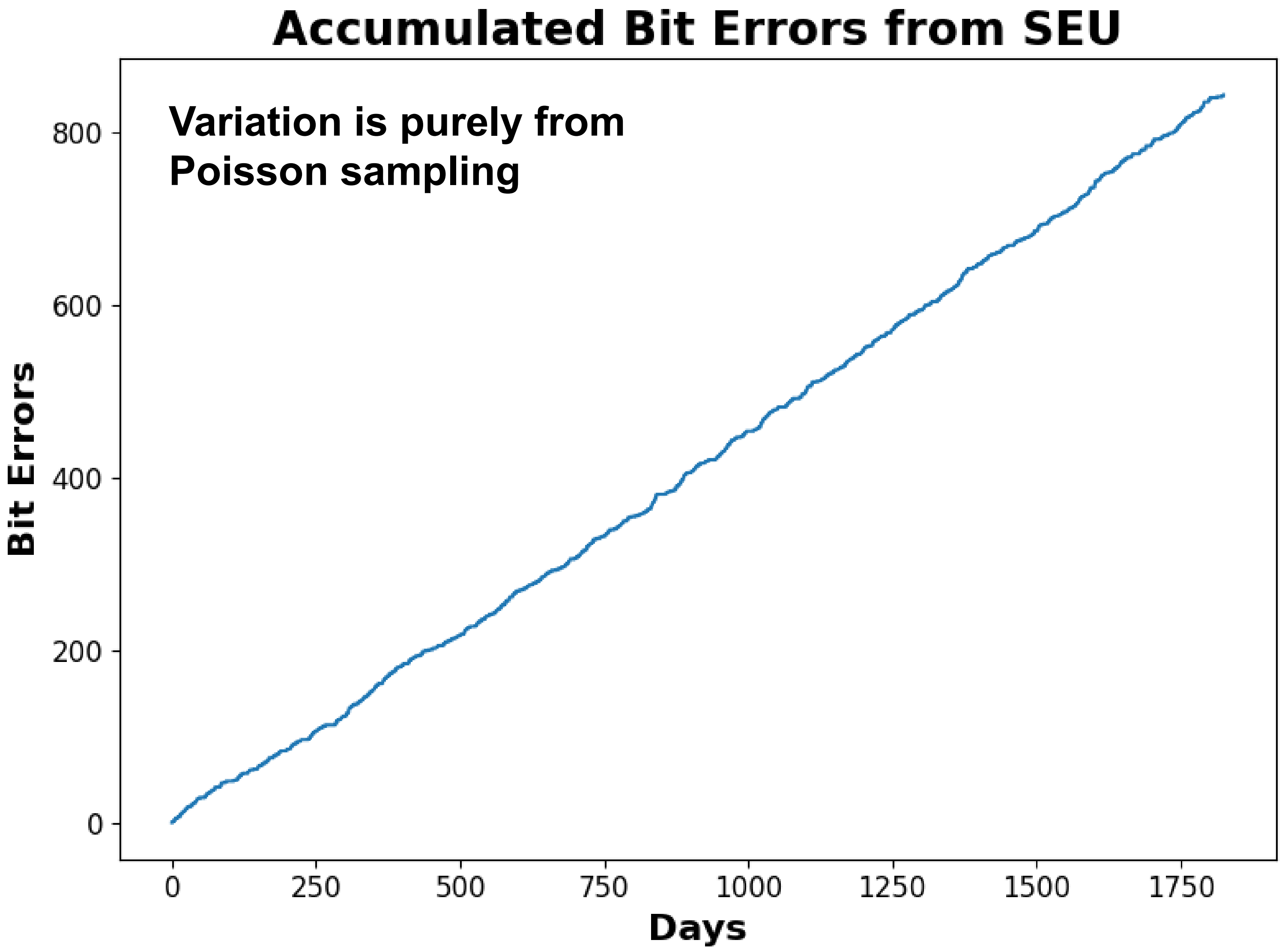

Random SEU / SEFI Errors Occur → Check for Uncorrectable Errors → Perform Any Scheduled Tasks → Update Results

Collect and Summarize Data



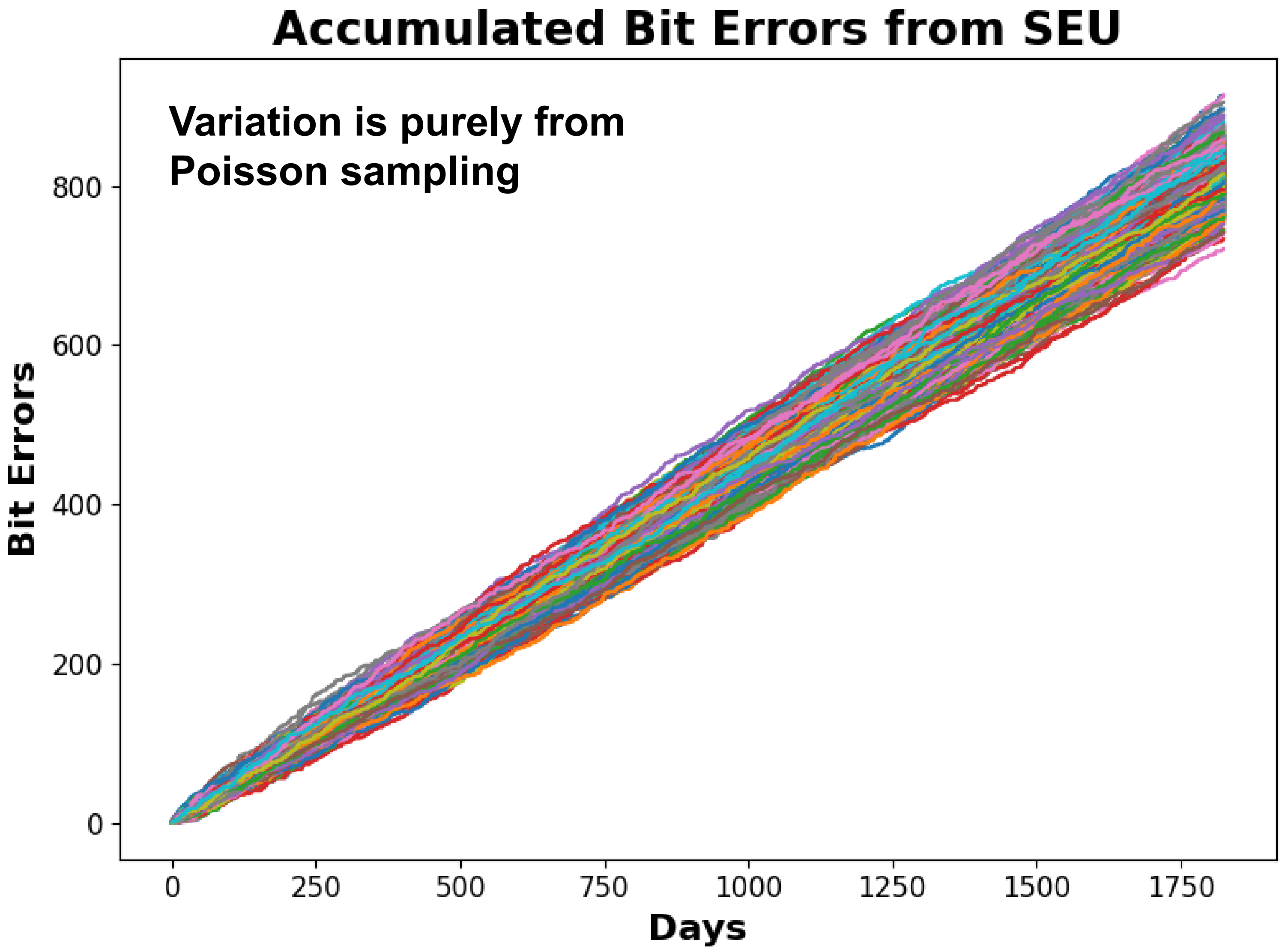
Monte Carlo SEE Analysis (Die Level)

- Die-level SEU



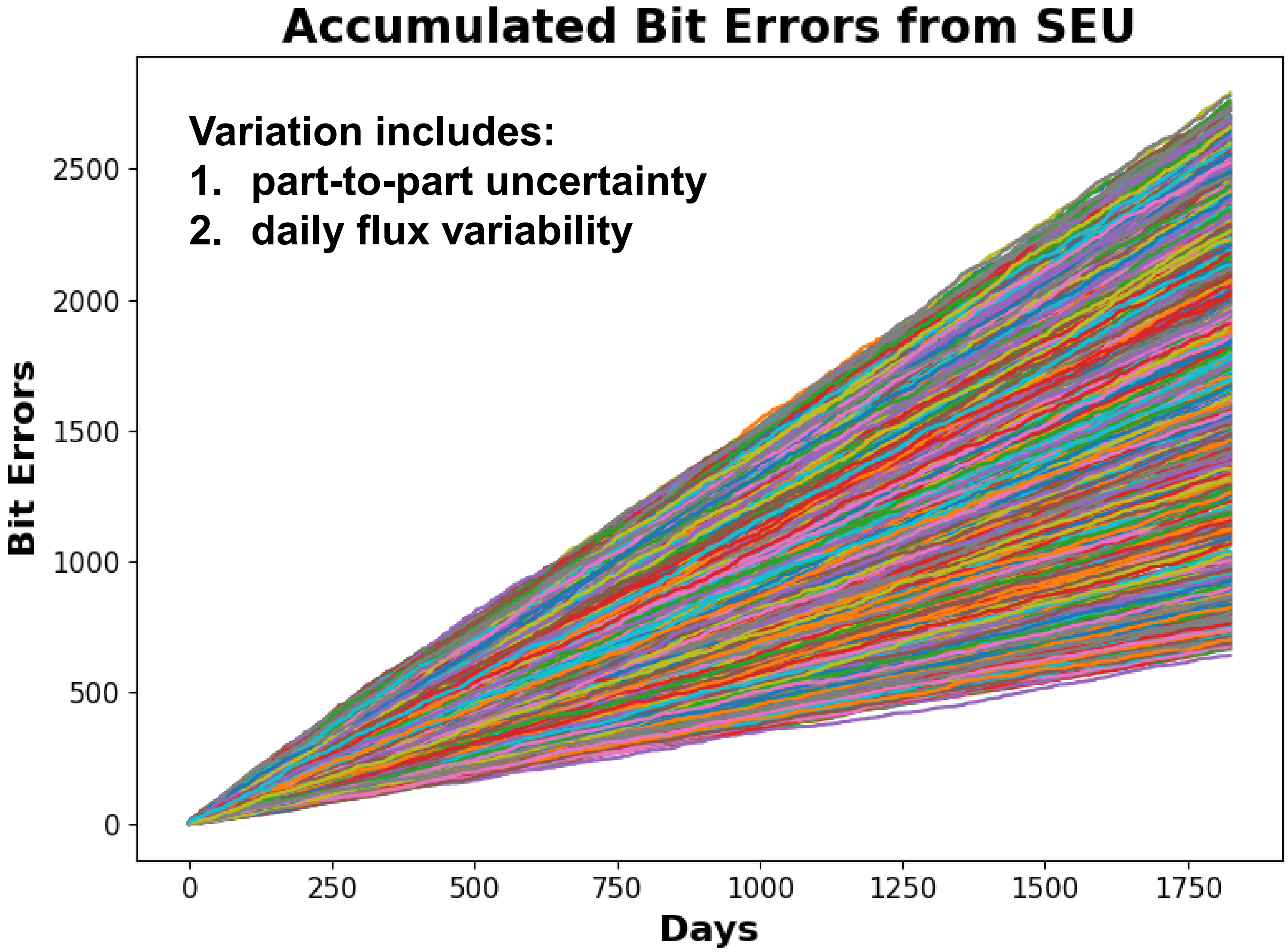
Monte Carlo SEE Analysis (Die Level)

- Die-level SEU
- 1000 Monte Carlo Runs



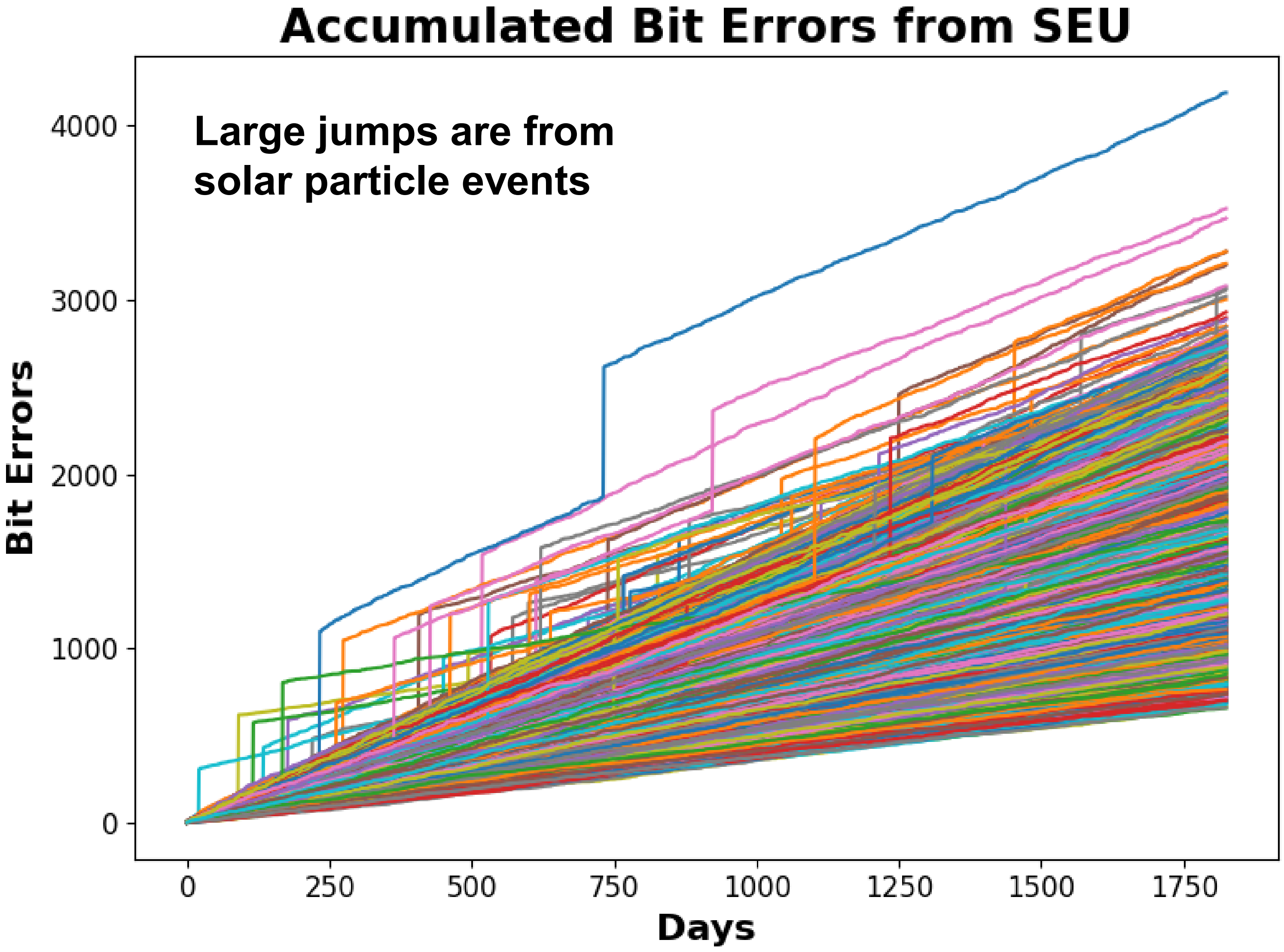
Monte Carlo SEE Analysis (Die Level)

- Die-level SEU
- 1000 Monte Carlo Runs
- Layer In:
    - Rate Uncertainty and Environmental Variation



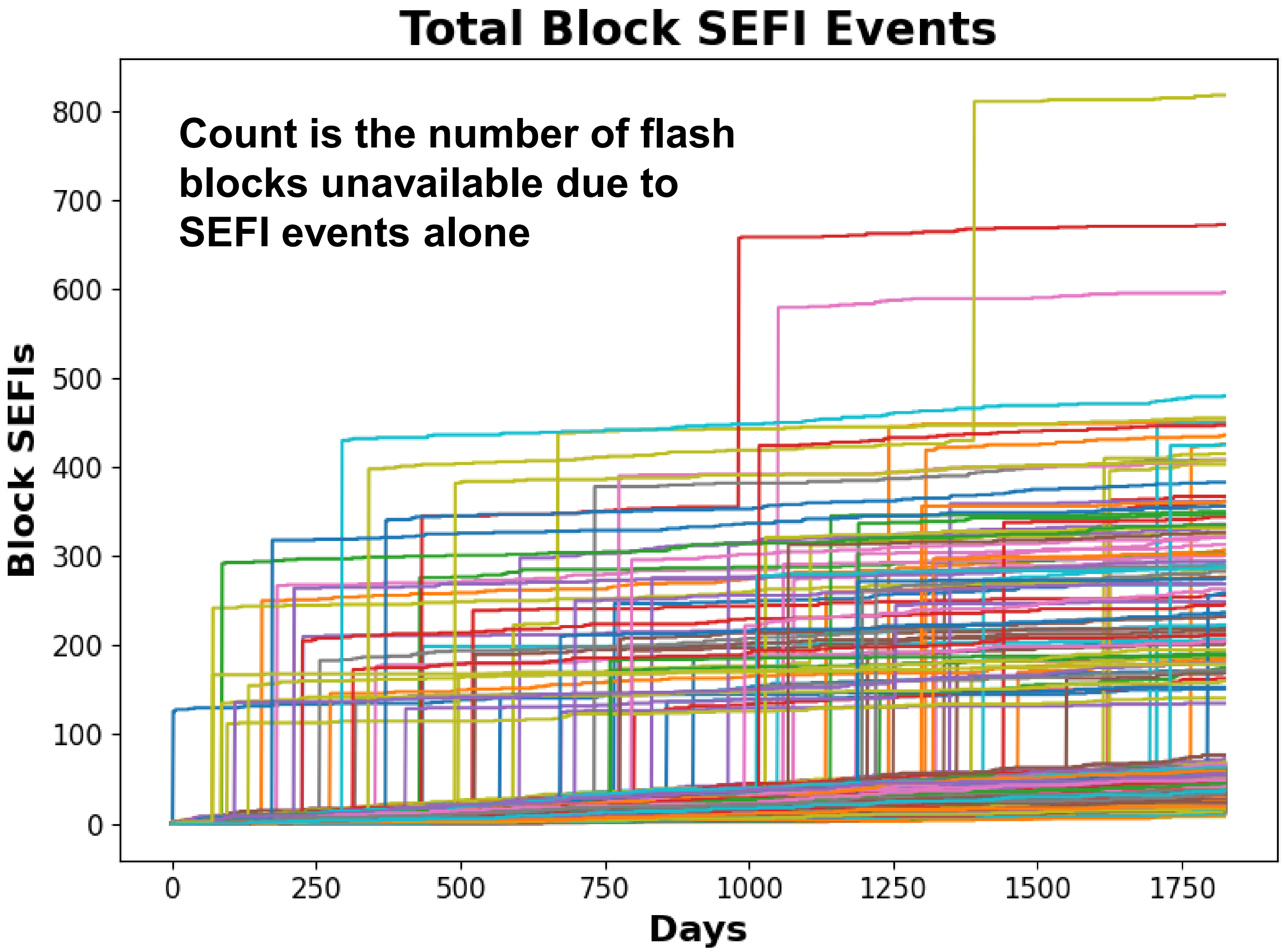
Monte Carlo SEE Analysis (Die Level)

- Die-level SEU
- 1000 Monte Carlo Runs
- Layer In:
  - Rate Uncertainty and Environmental Variation
  - Random SPE



Monte Carlo SEE Analysis (Die Level)

- Die-level SEU
- 1000 Monte Carlo Runs
- Layer In:
  - Rate Uncertainty and Environmental Variation
  - Random SPE
- SEFI



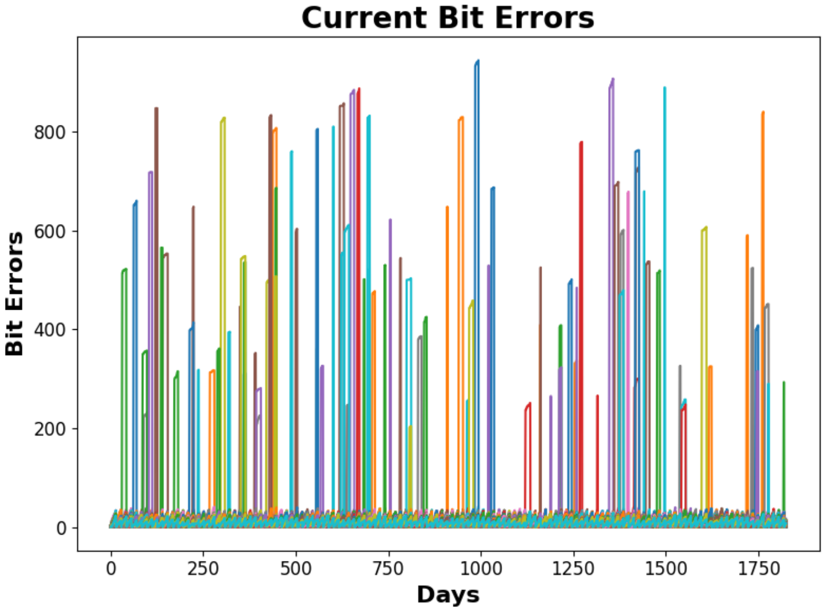
Monte Carlo SEE Analysis (Die Level)

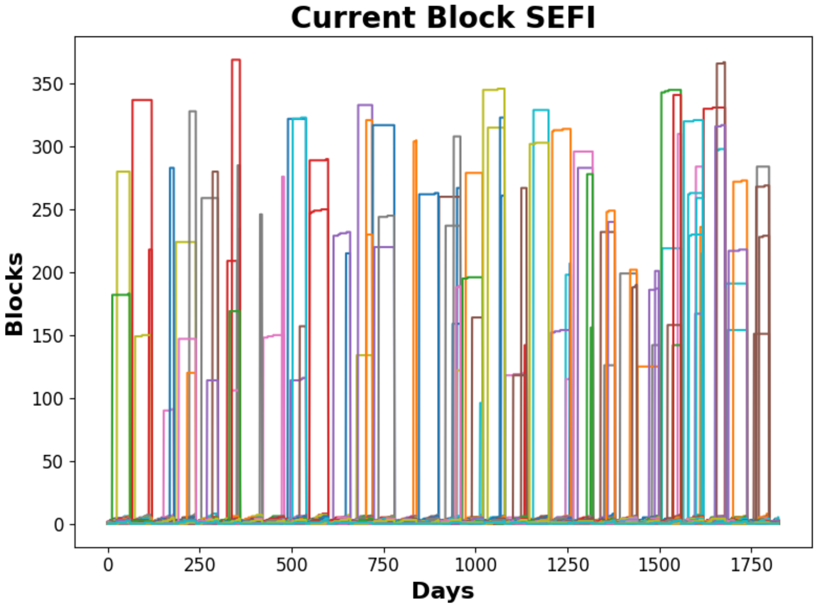
- Die-level SEU
- 100 Monte Carlo Runs
- Layer In:
  - Rate Uncertainty and Environmental Variation
  - Random SPE
- SEFI
- Operational Plans

Including mission operations gives us a “telemetry” point-of-view: How is the system affected *right now*?

SEU cleared every 14 days as data cycles through the system

SEFI cleared every 60 days* with scheduled power cycling





***or after uncorrectable errors**

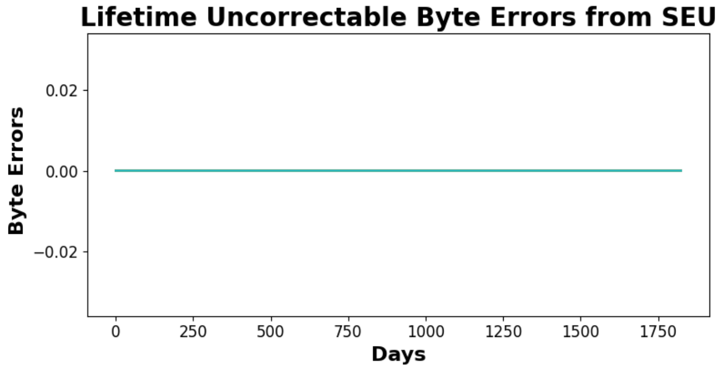
Monte Carlo SEE Analysis (System Level)

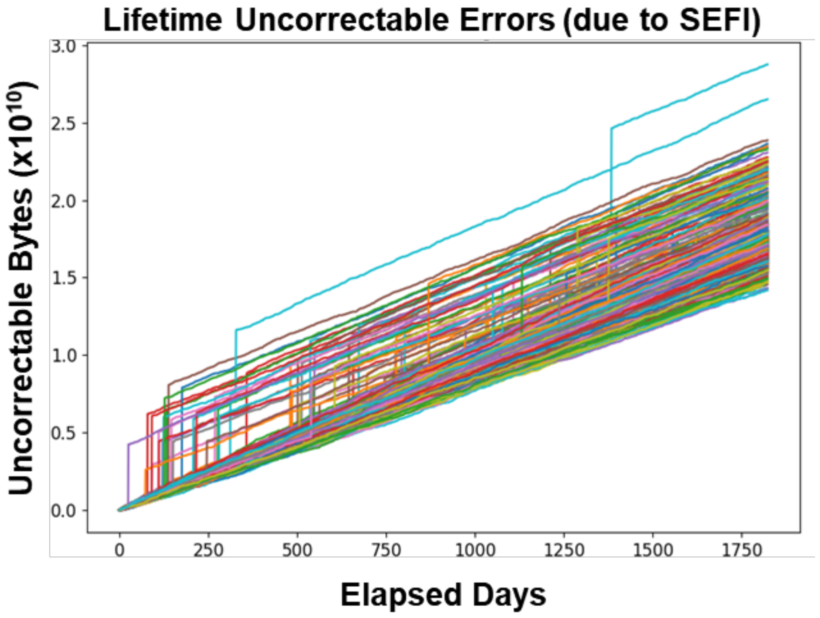
- Die-level SEU
- 100 Monte Carlo Runs
- Layer In:
  - Rate Uncertainty and Environmental Variation
  - Random SPE
- Die-Level SEFI
- Operational Plans
- **System-Level Effects**

(EDAC implementation is arbitrary – here it is capable of correcting 16 errors in 255 symbols)

Implementation #1:

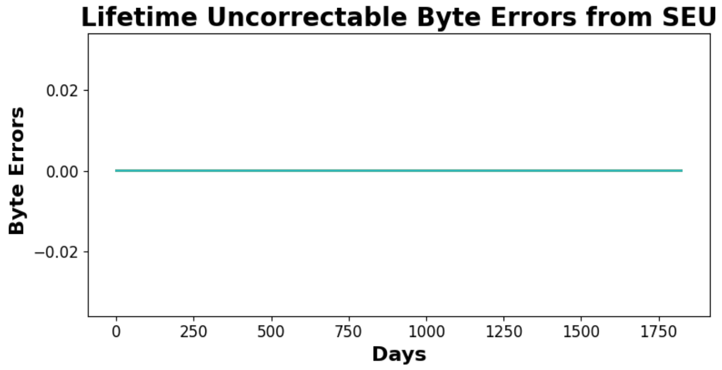
EDAC codewords stored in single die

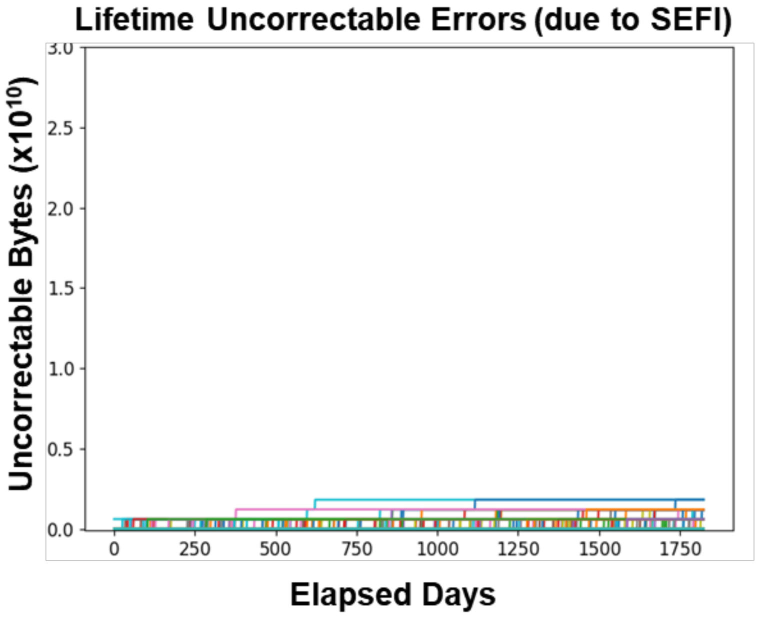

Lifetime Uncorrectable Byte Errors from SEU


Lifetime Uncorrectable Errors (due to SEFI)

Implementation #2:

EDAC codewords spread across all die


Lifetime Uncorrectable Byte Errors from SEU


Lifetime Uncorrectable Errors (due to SEFI)

Applied SEE Data: Final Delivered Products

- Probabilistic deliverables to system stakeholders:

Monte Carlo Results	**Implementation #1**	**Implementation #2**
Any uncorrectable errors?	100% of missions	25% of missions
90th Percentile Data Loss	• 17.3 GB (.0020%) Loss • SEFI on 972 of 1824 days • Data lost on 972 days	• 563 MB (.000065%) Loss • SEFI on 865 of 1824 days • Data lost on 1 day
99th Percentile Data Loss	• 21.1 GB (.0024%) Loss • SEFI on 850 of 1824 days • Data lost on 850 days	• 1.12 GB (.00013%) Loss • SEFI on 844 of 1824 days • Data lost on 2 days

- Observe that SEFI “rate” is similar in all cases
- System-level results vary significantly (99th percentile: loss of 25 MB every other day, vs loss of 560 MB twice in five years)
- Time-dependent factors (operations, current state, and environmental conditions) provide context that a purely statistical evaluation struggles to incorporate

Summary

- SEE evaluation can use part data to estimate system response
- Robust system evaluation includes variability, uncertainty, system-level mitigations and operational details to deliver probabilistic analyses
- Monte Carlo strategy performed here is just one example
  - Easily extend to effects beyond SEE (e.g., TID, retention, and wafer lot variability)
  - Time-dependent or random effects and device-specific characteristics
- Future work: incorporating application duty cycle and recovery steps
  - Criticality of Read vs. Write mode events → whether data is *unrecoverably* lost or simply uncorrectable *for now*
  - Minimum recovery steps → how much downtime is incurred for an uncorrectable event

Design strategically: Drastically different data loss behavior for two EDAC implementations using same hardware

Test strategically: SEU cross-section error bars may be totally irrelevant to this system; spend your time elsewhere