A New Approach to System-Level Single Event Survivability Prediction

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Acronyms

- Combinatorial logic (CL)
- Commercial off the shelf (COTS)
- Complementary metal-oxide semiconductor (CMOS)
- Device under test (DUT)
- Edge-triggered flip-flops (DFFs)
- Electronic design automation (EDA)
- Error rate (λ)
- Error rate per bit(λ_{bit})
- Error rate per system(λ_{system})
- Field programmable gate array (FPGA)
- Global triple modular redundancy (GTMR)
- Hardware description language (HDL)
- Input – output (I/O)
- Intellectual Property (IP)
- Linear energy transfer (LET)
- Mean fluence to failure (MFTF)
- Mean time to failure (MTTF)
- Number of used bits (#Usedbits)
- Operational frequency (fs)
- Personal Computer (PC)
- Probability of configuration upsets ($P_{configuration}$)
- Probability of Functional Logic upsets ($P_{functionalLogic}$)
- Probability of single event functional interrupt (P_{SEFI})
- Probability of system failure (P_{system})
- Processor (PC)
- Radiation Effects and Analysis Group (REAG)
- Reliability over time (R(t))
- Reliability over fluence ($R(\Phi)$)
- Single event effect (SEE)
- Single event functional interrupt (SEFI)
- Single event latch-up (SEL)
- Single event transient (SET)
- Single event upset (SEU)
- Single event upset cross-section (σ_{SEU})
- System on a chip (SoC)
- Windowed Shift Register (WSR)
- Xilinx Virtex 5 field programmable gate array (V5)
- Xilinx Virtex 5 field programmable gate array radiation hardened (V5QV)

Problem Statement and Abstract

- **The process for application of single event upset (SEU) data used to characterize system performance in radiation environments needs improvement.**
- **We are investigating the application of classical reliability performance metrics combined with standard SEU analysis data to improve system survivability prediction.**

This presentation is a simplified approach for SEU data extrapolation to complex systems. Future work will incorporate additional details.

Background (1) : FPGA SEU Susceptibility

SEU Cross Section (σ_{SEU})

- σ_{SEU}s (per category) are calculated from SEU test and analysis.
- σ_{SEU}s are calculated per particle linear energy transfer (LET).
- Most believe the dominant σ_{SEU}s are per bit (configuration or flip-flops (DFFs)). However, global routes are significant (more than DFFs).

σ_{SEU}s are measured by bit!

σ_{SEU}s are measured by bit???

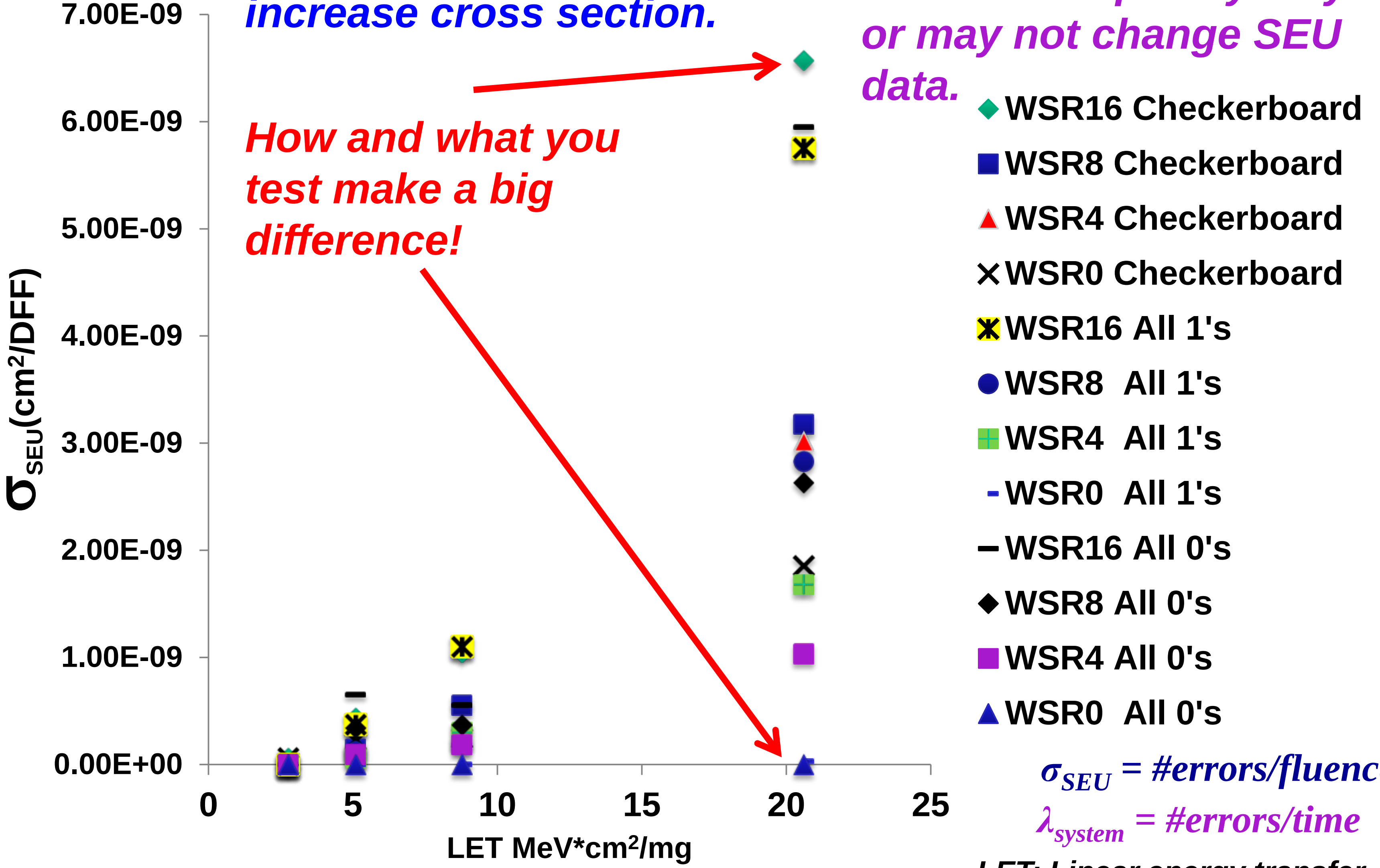
$$\underbrace{P(fs)_{system}}_{\text{Design } \sigma_{SEU}} \propto \underbrace{P_{Configuration}}_{\text{Configuration } \sigma_{SEU}} + \underbrace{P(fs)_{functionalLogic}}_{\text{Functional logic } \sigma_{SEU}} + \underbrace{P_{SEFI}}_{\text{SEFI } \sigma_{SEU}}$$

Functional logic σ_{SEU}: Sequential and Combinatorial logic (CL) in data path

SEFI σ_{SEU}: Global Routes and Hidden Logic

For a system, should σ_{SEU}s be measured by bit????

Window Shift Register (WSR) Microsemi σ_{SEU}s: Design and Stimulus Dependencies to SEUs



Add combinatorial logic, increase cross section.

How and what you test make a big difference!

Increase frequency may or may not change SEU data.

σ_{SEU} = #errors/fluence

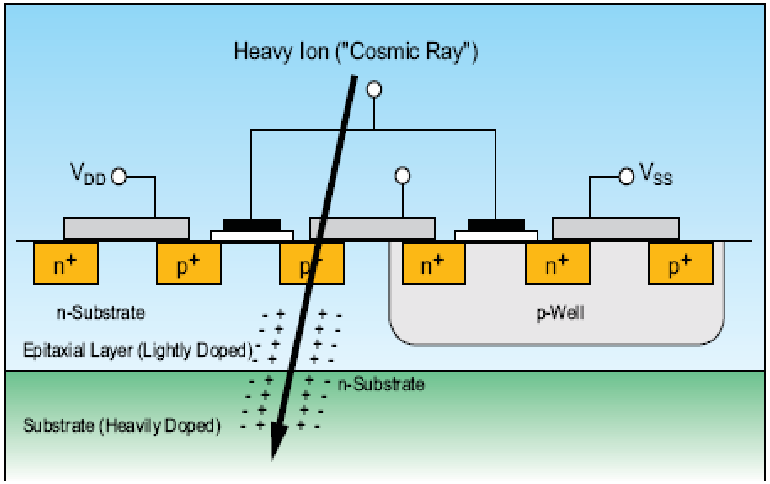
λ_{system} = #errors/time

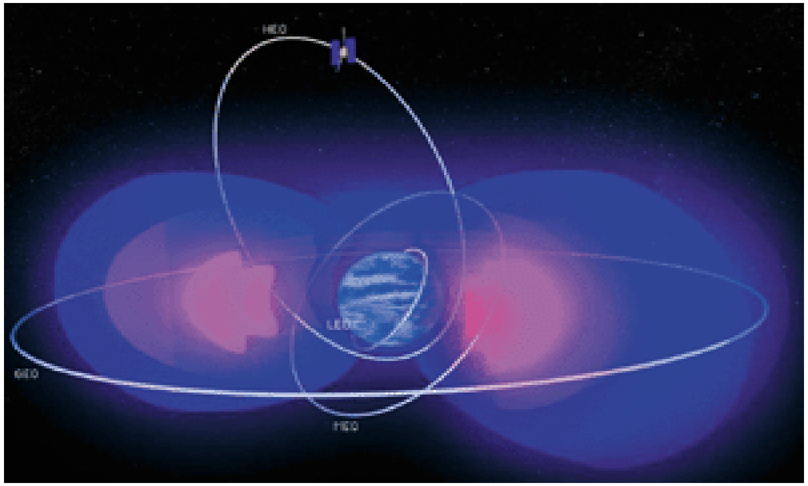
LET: Linear energy transfer

Background (2)

Conventional Conversion of SEU Cross-Sections To Error Rates for Complex Systems Next Step

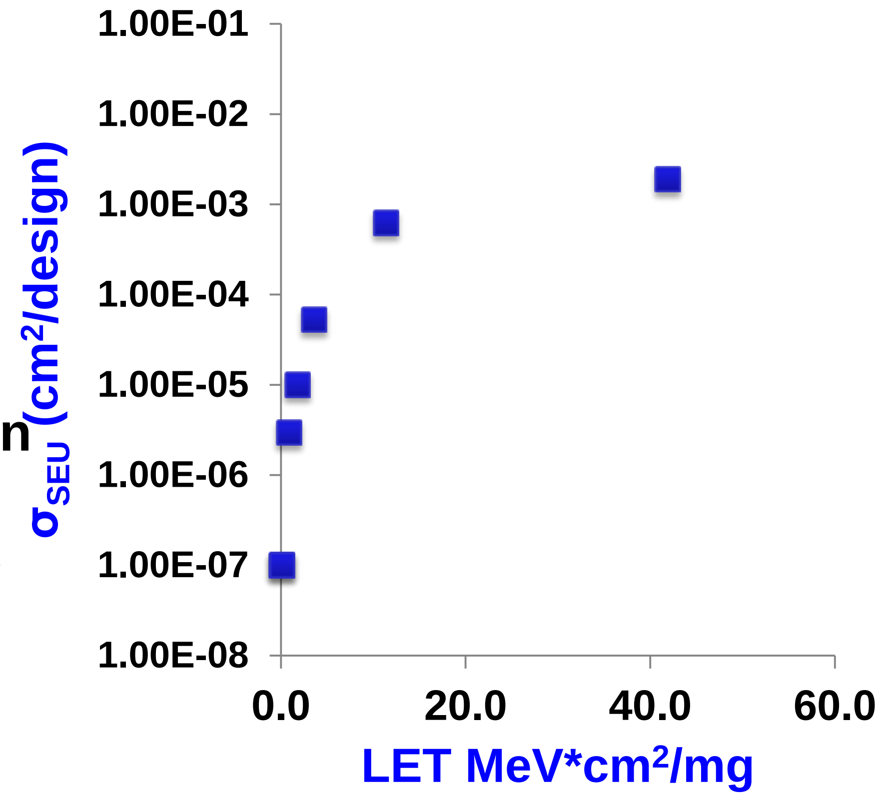
- **Bottom-Up approach** (transistor level):
  - Given σ_{SEU} (per bit) use an error rate calculator (such as CRÈME96) to obtain an error rate per bit (λ_{bit}).
  - Multiply λ_{bit} by the number of used memory bits (#*UsedBits*) in the target design to attain a system error rate (λ_{system}). Configuration and DFFs.
- **Top-Down approach** (system level):
  - Given σ_{SEU} (per system) use an error rate calculator (such as CRÈME96) to obtain an error rate per bit (λ_{system}).





Technical Problems with Current Methods of Error Rate Calculation

- **For submission to CRÈME96, σ_{SEU} data (in Log-linear form) are fitted to a Weibull curve.**
  - **During the curve fitting process, a large amount of error can be introduced.**
  - **Consequently, it is possible for resultant error rates (for the same design) to vary by decades.**
- **Because of the error rate calculation process, σ_{SEU} data are blended together and it is nearly impossible to hone in on the problem spots. This can become important for mitigation insertion.**



Technical Problems with Bottom-Up Analysis Method

- Multiplying each bit within a design by λ_{bit} is not an efficient method of system error rate prediction.
  - Works well with memory structures… but…complex systems do not operate or respond like memories.
  - If an SEU affects a bit, and the bit is either inactive, disabled, or masked, a system malfunction might not occur.
    - Using the same multiplication factor across DFFs will produce extreme over-estimates.

$$\lambda_{system} < \lambda_{bit} \times \#UsedBits$$

Let's Not Reinvent The Wheel… A Proven Solution Can Be Found in Classical Reliability System-Level Analysis

Mapping Classical Reliability Models from The Time Domain To The Fluence Domain

- The exponential model that relates reliability to MTTF assumes that during useful-lifetime:
  - Failures are independent.
  - Error rate is constant.
  - MTTF = $1/\lambda$.

$R(t)=e^{-t/MTTF}$ or $R(t)=e^{-\lambda t}$

Weibull slope = 1… exponential.

Parallel between time and fluence.

- For a given LET (across fluence):
  - SEUs are independent.
  - σ_{SEU} is constant.
  - MFTF = $1/\sigma_{SEU}$.

σ_{SEU} = #errors/fluence

λ_{system} = #errors/time

- Hence, mapping from the time domain to the fluence domain (per LET) is straight forward:
  - $t \Leftrightarrow \Phi$
  - MTTF $\Leftrightarrow$ MFTF
  - $\lambda \Leftrightarrow \sigma_{SEU}$

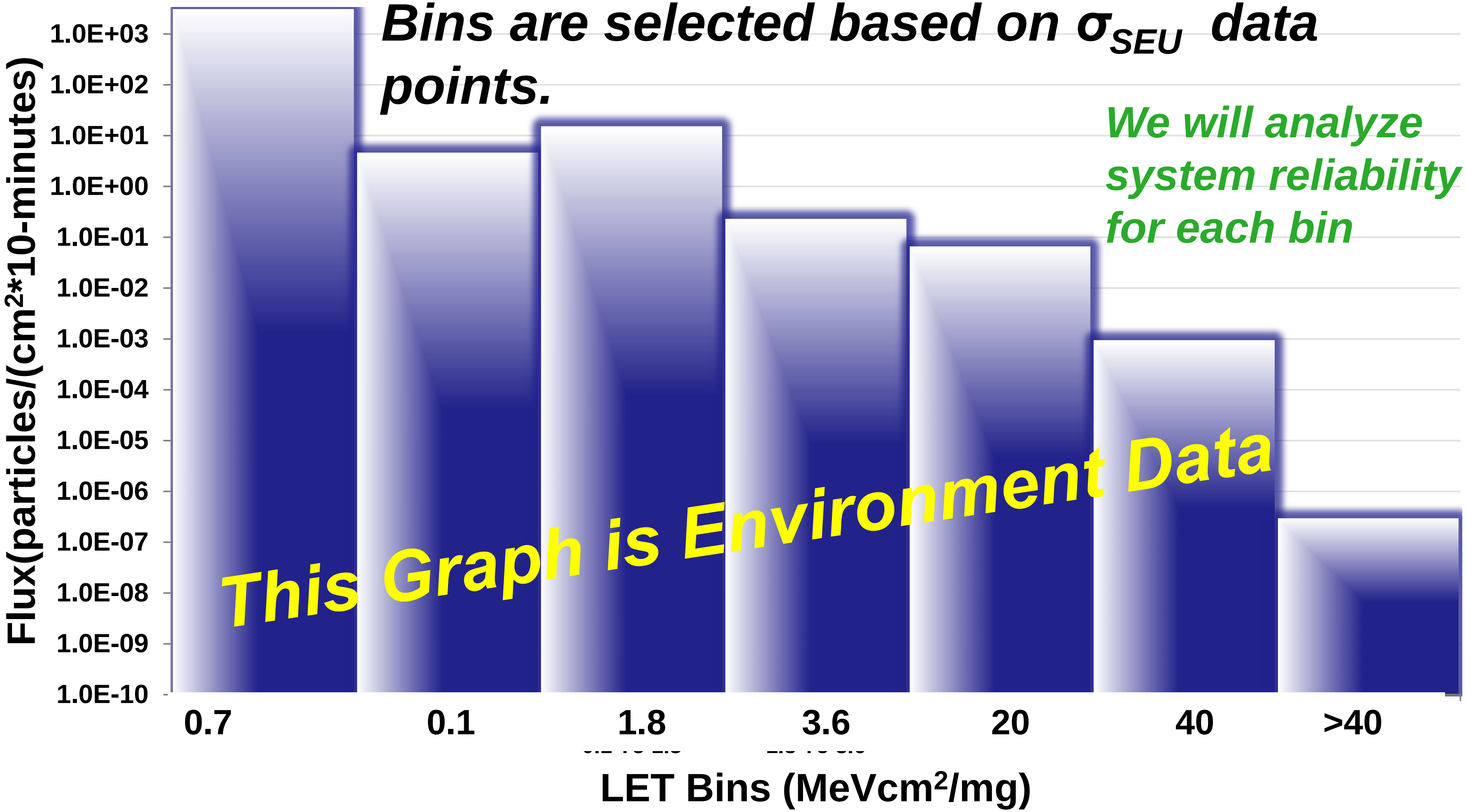
$$R(t)=e^{-t/MTTF} \Leftrightarrow R(\Phi)=e^{-\Phi/MFTF}$$

Example of Proposed Methodology Application

- **Mission requirements:**
  - Selection shall be made between a Xilinx V5QV (relatively expensive device) or a Xilinx V5 with embedded PowerPC (relatively cheap device).
  - FPGA operation shall have reliability of 3-nines (99.9%) within a 10 minute window at Geosynchronous Equatorial Orbit (GEO).
- **Proposed methodology:**
  - Create a histogram of particle flux versus LET for a 10-minute window of time for your target environment.
  - Calculate MFTF per LET (obtain SEU data).
  - Graph $R(\Phi)$ for a variety of LET values and their associated MFTFs. $R(\Phi)=e^{-\Phi/MFTF}$
  - For selected ranges of LETs, use an upper bound of particle flux (number of particles/cm^2•10-minutes), to determine if the system will meet the mission's reliability requirements.

Environment Data: Flux versus LET Histogram for A 10-minute Window

Geosynchronous Equatorial Orbit (GEO) 100-mils shielding



Bins are selected based on σ_{SEU} data points.

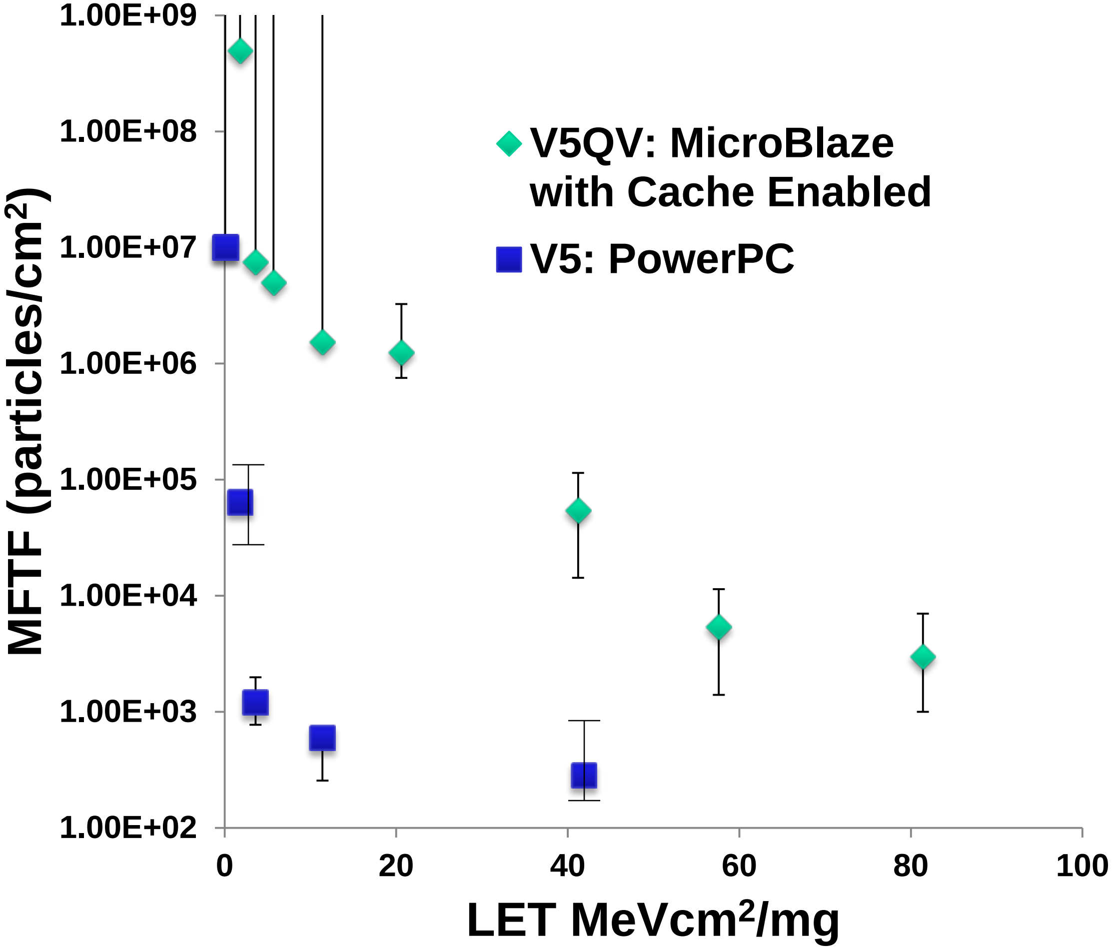
We will analyze system reliability for each bin

This Graph is Environment Data

MFTF versus LET for the Xilinx V5 Embedded PowerPC Core and the Xilinx V5QV MicroBlaze Soft Processor Core

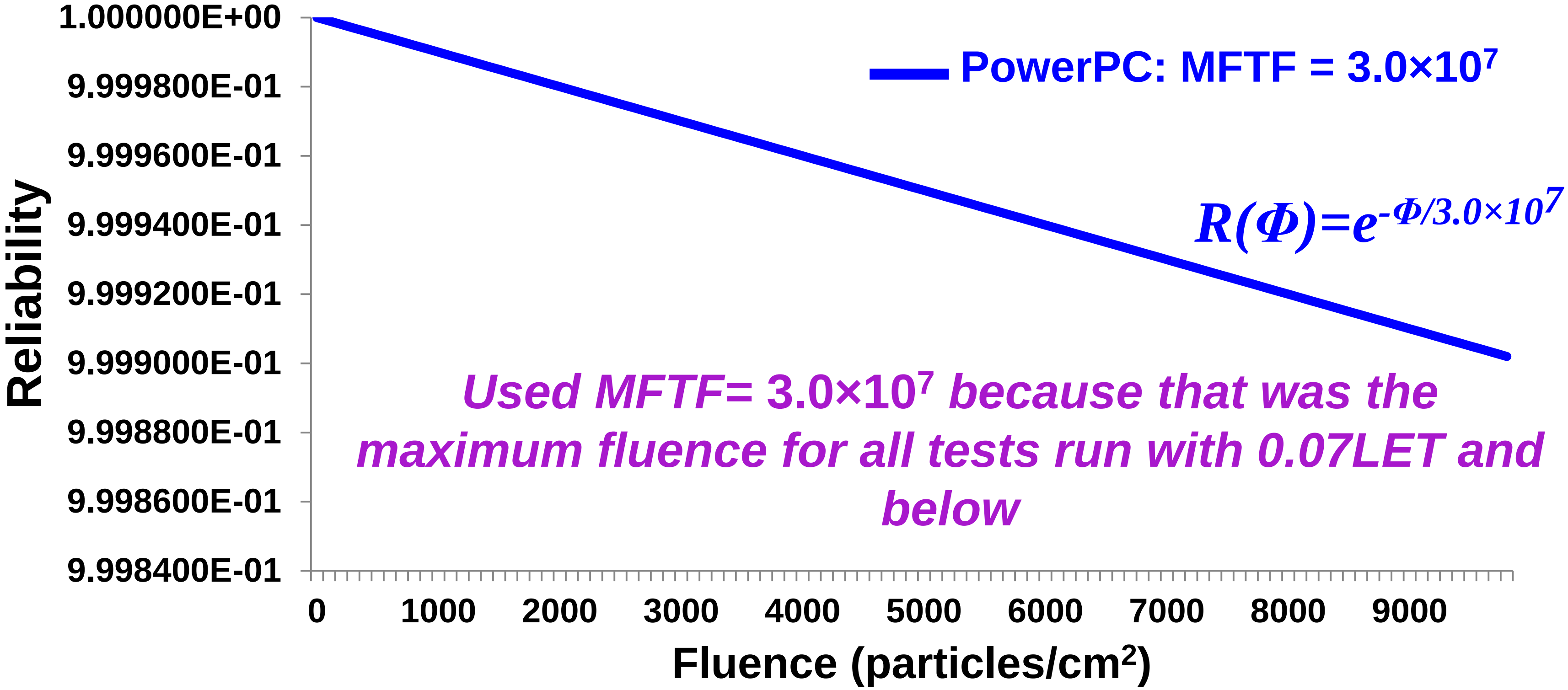
- **V5QV:** **no system errors were observed below LET=1.8 MeV•cm²/mg. Total fluence > 5.0×10⁸ particles/cm².**
- **PowerPC:**
  - **No system errors were observed below LET=0.07MeV•cm²/mg with total fluence = 3.×10⁷ particles/cm².**
  - **Hence, at 0.07, we will assume an upper-bound MFTF = 3.0×10⁷ particles/cm².**
  - **More tests would increase the MFTF for this bin.**

MFTF = $1/\sigma_{SEU}$



Reliability across Fluence up to LET=0.07MeV•cm^2/mg

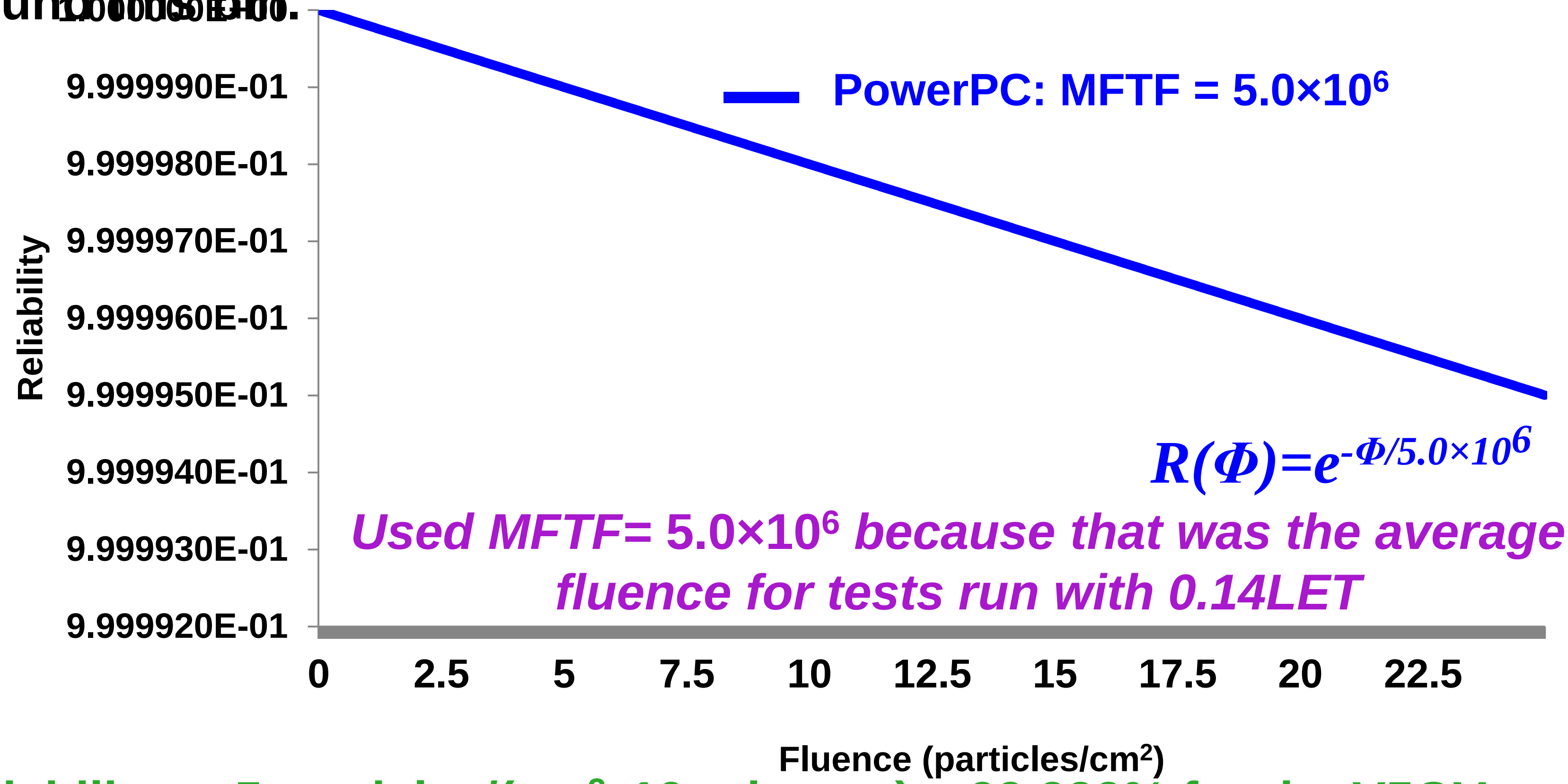
Binned GEO Environment data show approximately 3000 particles/(cm^2•10-minutes), in the range of 0.0MeV•cm^2/mg to 0.07MeV•cm^2/mg. We are using MFTF for 0.07MeV•cm^2/mg to upper bound this bin.



Reliability at 3000 particles/(cm^2•10-minutes) > 99.99% for the PowerPC design implementation. "9's" could be increased with more tests.

Reliability across Fluence up to LET=0.14MeV•cm^2/mg

Binned GEO Environment data show approximately 11 particles/(cm^2•10-minutes), in the range of 0.07MeV•cm^2/mg to 0.14MeV•cm^2/mg. We are using MFTF for 0.14MeV•cm^2/mg to upper bound this bin.



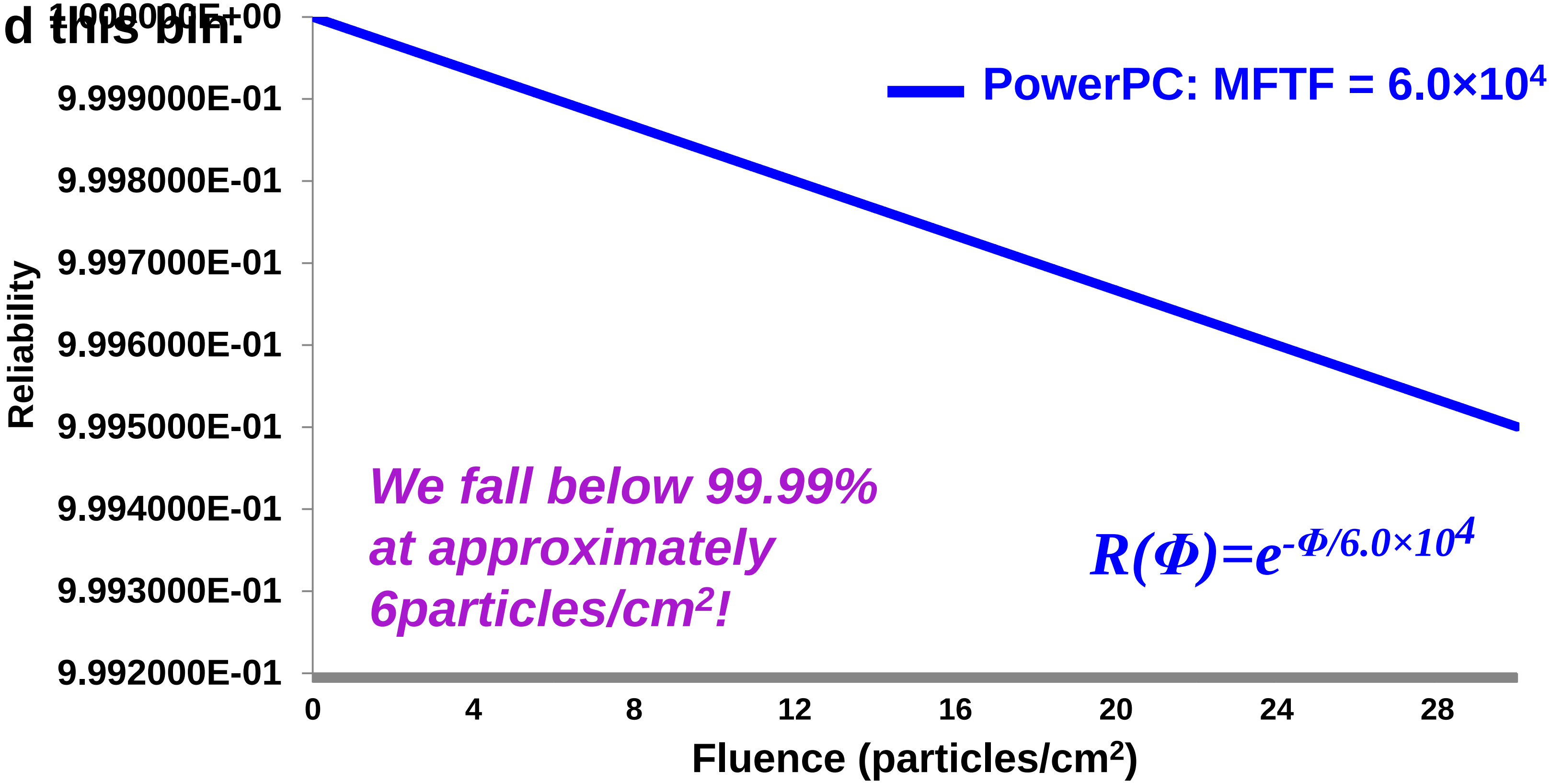
$$R(\Phi)=e^{-\Phi/5.0\times10^6}$$

Used MFTF= 5.0×10^6 because that was the average fluence for tests run with 0.14LET

Reliability at 5 particles/(cm^2•10-minutes) > 99.999% for the V5QV PowerPC design implementation.

Reliability across Fluence up to LET=1.8 MeV•cm^2/mg

Binned GEO Environment data show approximately 9 particles/(cm^2•10-minutes), in the range of 0.14MeV•cm^2/mg to 1.8MeV•cm^2/mg. We are using MFTF for 1.8MeV•cm^2/mg to upper bound this bin.



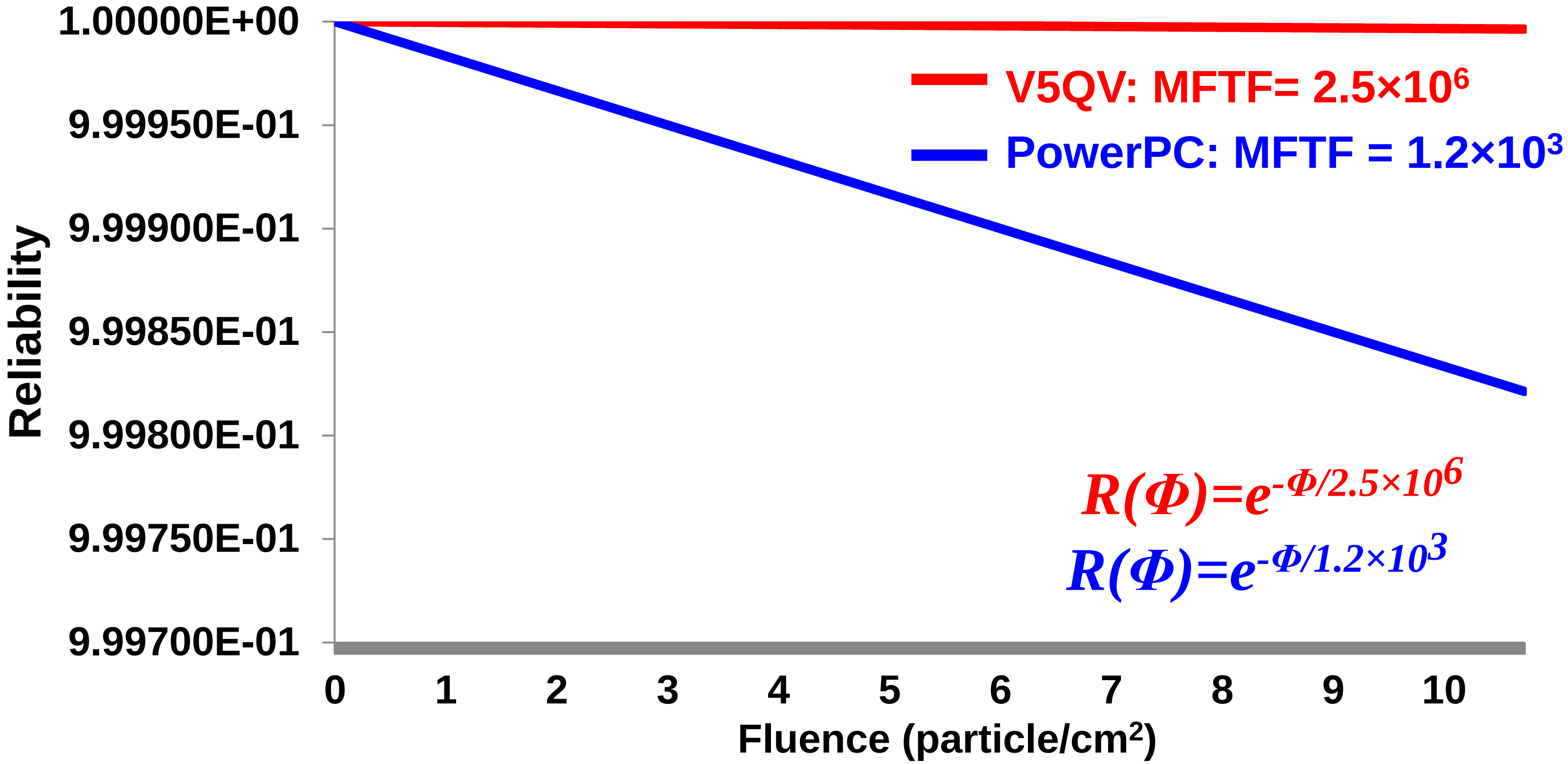
We fall below 99.99% at approximately 6particles/cm^2!

$$R(\Phi)=e^{-\Phi/6.0\times10^4}$$

Reliability at 9 particles/(cm^2•10-minutes) > 99.9% for the PowerPC design implementation. This is the most susceptible bin for the system.

Reliability across Fluence up to LET=3.6MeV•cm^2/mg

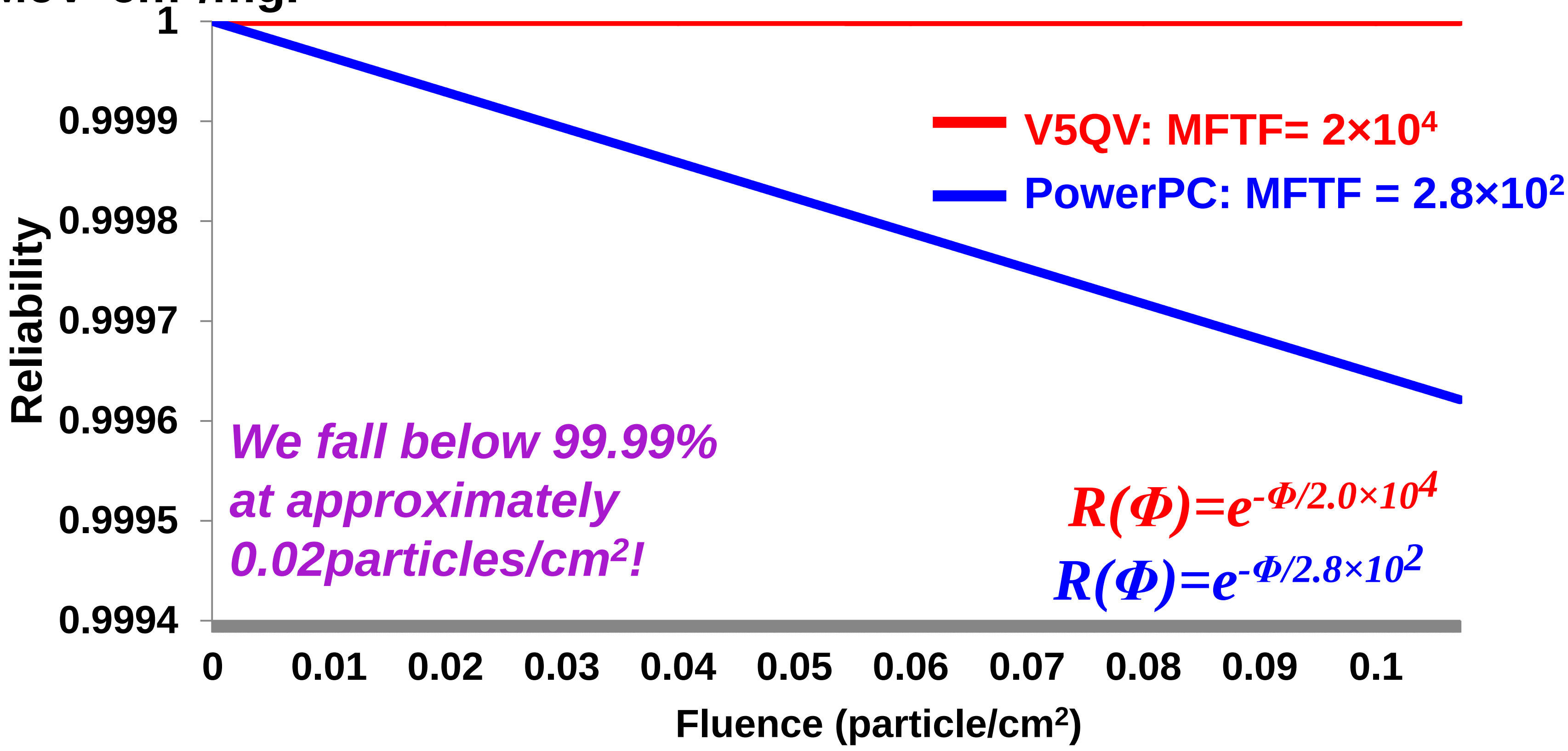
Binned GEO Environment data show approximately 0.23 particles/(cm^2•10-minutes), in the range of 1.8MeV•cm^2/mg to 3.6MeV•cm^2/mg.



Within this LET range, reliability at 0.23 particles/(cm^2•10-minutes) > 99.999% for both design implementations.

Reliability across Fluence at LET=40MeVcm²/mg

Binned GEO environment data show approximately 0.07 particles/(cm²•10-minutes), in the range of 3.6MeV•cm²/mg to 40.0MeV•cm²/mg.



We fall below 99.99% at approximately 0.02particles/cm²!

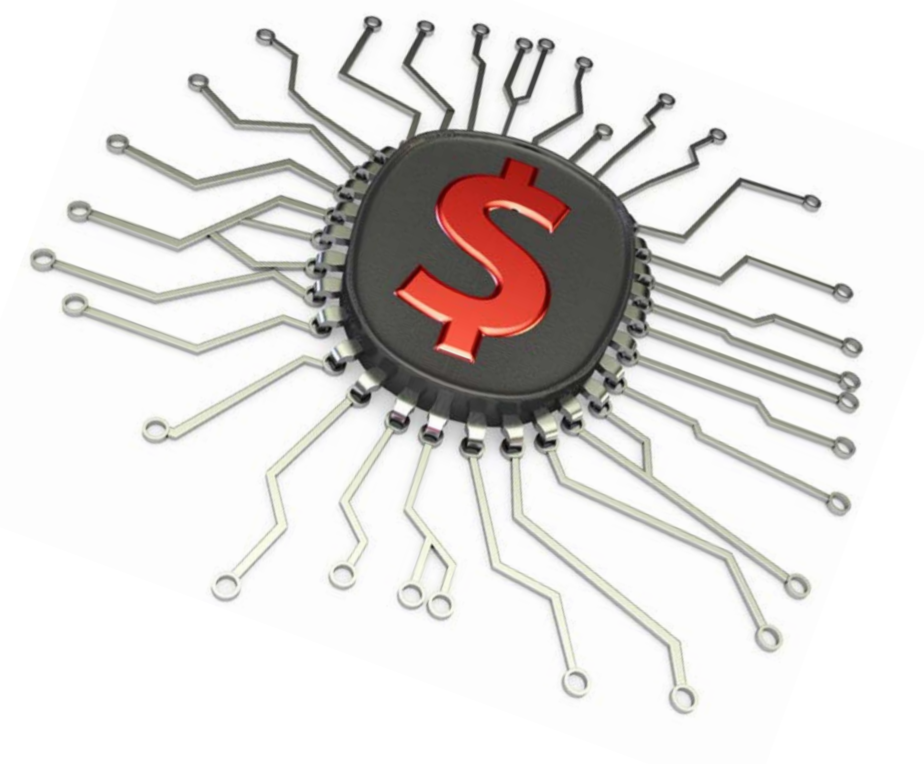
$R(\Phi)=e^{-\Phi/2.0\times 10^4}$

$R(\Phi)=e^{-\Phi/2.8\times 10^2}$

Within this LET range, reliability at 0.07 particles/(cm²•10-minutes) > 99.9% for both design implementations. We can refine by analyzing smaller bins.

Example Conclusion

- **Using the proposed methodology, the commercial Xilinx V5 device will meet project requirements.**
- **In this case, the project is able to save money by selecting the significantly cheaper FPGA device and gain performance because of the embedded PowerPC.**



Conclusions

- This study transforms proven classical reliability models into the SEU particle fluence domain. The intent is to better characterize SEU responses for complex systems.
- The method for reliability-model application is as follows:
  - SEU data are obtained as MFTF.
  - Reliability curves (in the fluence domain) are calculated using MFTF; and are analyzed with a piecemeal approach.
  - Environment data are then used to determine particle flux exposure within required windows of mission operation.
- The proposed method does not rely on data-fitting and hence removes a significant source of error.
- The proposed method provides information for highly SEU-susceptible scenarios; hence enables a better choice of mitigation strategy.
- This is preliminary work. There is more to come regarding environment data transformation.

This methodology expresses SEU behavior and response in terms that missions understand via classical reliability metrics.

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