

Article

Neutron Shielding by Concrete Slabs and Its Impact on the Soft-Error Rate of Electronics in Nuclear Fusion

Daniela Munteanu ^{1,*}, Jean-Luc Autran ¹, Soilihi Moindjie ¹, Matteo Cecchetto ^{2,3} and Martin Dentan ^{2,4}

¹ Univ. Rennes, CNRS, IPR (UMR 6251), 35042 Rennes, France; jean-luc.autran@univ-rennes.fr (J.-L.A.); soilihi.moindjie@univ-rennes.fr (S.M.)

² CERN, CH-1211 Geneva, Switzerland; matteo.cecchetto@cern.ch (M.C.); martin.dentan@cern.ch (M.D.)

³ Aix-Marseille Univ, CNRS, IM2NP (UMR 7334), 13397 Marseille, France

⁴ CEA, IRFM, Centre de Cadarache, 13108 Saint-Paul-lez-Durance, France

* Correspondence: daniela.munteanu@univ-rennes.fr

Abstract

The present study investigates the effects of neutron shielding by concrete slabs in the context of nuclear fusion (14 MeV neutrons). MCNP and Geant4 numerical simulations have been performed to characterize neutron transport through concrete slabs with thicknesses ranging from 1 to 160 cm. Using a monoenergetic, normally incident 14 MeV neutron source, we examine neutron-flux attenuation and spectral evolution after propagation through concrete. The results show that multiple elastic and inelastic scattering processes dominate the transport, leading to a strong spectral redistribution and a significant build-up of scattered neutrons. For intermediate thicknesses (50–100 cm), the transmitted flux is largely composed of scattered and secondary neutrons, with a pronounced epithermal slowing-down component approximately following a $1/E$ behavior, a thermal peak resulting from hydrogen moderation, and a residual high-energy tail corresponding to partially degraded primary neutrons. At larger thicknesses (≥ 100 cm), absorption and capture of thermalized neutrons become dominant, resulting in a sharp decrease in the transmitted flux. The impact of these spectral modifications on the soft-error rate (SER) of microelectronic devices is evaluated by folding the transmitted neutron spectra with energy-dependent single-event upset (SEU) cross-sections representative of advanced semiconductor technologies. The results indicate that, although total neutron flux decreases significantly with increasing concrete thickness, the spectral redistribution and the persistence of intermediate-energy neutrons can maintain a non-negligible contribution to SER in certain configurations. These findings highlight the importance of using full transport simulations, including spectral effects, when assessing radiation-induced reliability risks in fusion facilities.

Keywords: nuclear fusion; D–T neutrons; neutron shielding; concrete slabs; soft-error rate; electronics reliability

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1. Introduction

The development of future fusion power plants (FFPPs) requires integrating numerous electronic systems, including diagnostics, control electronics, monitoring devices, and safety-related instrumentation, within environments characterized by intense radiation fields [1–3]. In these environments, radiation-induced effects can significantly impact re-

liability, performance, and lifetime [3]. In deuterium–tritium (D–T) fusion reactors, 14 MeV neutrons are produced as the main carriers of fusion energy and represent one of the principal sources of radiation-induced degradation in materials and electronic systems [4–6]. Unlike charged particles, neutrons can penetrate deeply into surrounding structures and undergo multiple nuclear interactions, including elastic scattering, inelastic scattering, moderation, absorption, and capture [7–9]. As a result, the neutron field outside the plasma chamber is not only attenuated by shielding materials but also strongly modified in energy and angular distribution [10,11].

Concrete is widely used as a biological and structural shielding material in nuclear facilities because of its availability, mechanical robustness, cost-effectiveness, and favorable composition for neutron moderation and gamma attenuation [12,13]. In fusion environments, however, the shielding performance of concrete cannot be described solely by a simple exponential attenuation law because neutron transport involves scattering, moderation, absorption, and secondary radiation production [14,15]. The presence of light elements, especially hydrogen, promotes neutron slowing down, while heavier elements contribute to scattering and absorption processes [12,16]. Consequently, the transmitted neutron spectrum after propagation through concrete may contain a complex mixture of residual fast neutrons, epithermal neutrons generated by moderation, thermalized neutrons, and secondary particles [10,13,17]. This spectral redistribution is particularly important when assessing radiation effects on sensitive electronic components located behind shielding barriers [18].

Modern microelectronic devices are increasingly vulnerable to radiation-induced single-event effects (SEEs), including single-event upsets (SEUs), due to the continuous reduction in feature sizes, operating voltages, and critical charge thresholds [19–21]. As defined by the JEDEC standard JESD89B [22], an SEE designates any measurable or observable change in state or performance of a microelectronic device, component, subsystem, or system (digital or analog) resulting from a single energetic particle strike. An SEE can result in a soft (reversible) or hard (irreversible) error in device or circuit operation [22]. An SEU is a soft error caused by a state change in a latch, flop, memory cell, or other bistable element from the particle strike [22]. In neutron environments, soft errors may be induced indirectly by neutron interactions through secondary charged particles produced in semiconductor materials and device packaging [23]. Attenuating high-energy neutrons through shielding is a straightforward strategy for reducing SEUs [24,25]. Several studies have addressed neutron attenuation in concrete while explicitly considering the resulting reduction in soft-error rate (SER) [26–29]. The soft-error rate (SER), therefore, depends not only on the total neutron flux but also on the detailed neutron energy spectrum and on the energy-dependent response of the electronic technology considered [30]. In the context of fusion facilities, where electronics may be placed in shielded galleries, diagnostic areas, remote handling systems, or control zones, a reliable evaluation of neutron-induced soft errors requires an accurate description of neutron transport through shielding structures [31].

Monte Carlo particle transport codes provide a powerful approach for modeling neutron propagation in complex materials and geometries. Codes such as MCNP [32,33], Geant4 [34–36], and FLUKA [37,38] are commonly used to simulate nuclear interactions over broad energy ranges and to predict particle fluxes, energy spectra, and secondary radiation fields. By combining transport calculations with energy-dependent SEU cross-sections, it becomes possible to estimate the impact of shielding-induced spectral changes on the SER of electronic devices [39].

This work investigates the neutron-shielding behavior of concrete slabs exposed to 14 MeV neutrons, representative of those produced in a D–T fusion plasma. The term “slab” is quite generic and refers to structures that are almost one-dimensional, such as slabs or walls. Concrete thicknesses ranging from 1 to 160 cm are studied using MCNP

and Geant4 simulations in order to characterize neutron attenuation, spectral redistribution, and the relative contributions of scattered, moderated, and residual fast neutrons. The transmitted neutron spectra are then folded with energy-dependent SEU cross-sections characteristic of advanced semiconductor technologies to evaluate the corresponding SER. The objective is to determine how concrete thickness affects both neutron transport and electronic reliability, and to demonstrate the importance of considering full spectral information, rather than total flux attenuation alone, when assessing radiation-induced risks in nuclear fusion environments. This work is part of the NERITA project (“Neutron Electronics Reliability In Tokamaks and Accelerators”) [40], which aims to evaluate the risks of SEE induced by neutrons in tokamak and accelerator environments for commercial off-the-shelf (COTS) electronics.

This paper is structured as follows: Section 2 introduces the main mechanisms that govern neutron transport through a concrete slab in a nuclear fusion environment. Then, it provides a brief overview of the MCNP and Geant4 codes, used to numerically simulate neutron–concrete interactions. This section also describes the basic mechanisms of neutron interactions with semiconductor circuit materials, as well as the models used to estimate the neutron-induced SER. Section 3 details the results of the numerical simulation, beginning with a preliminary comparison of the MCNP and Geant4 results. The results are then presented in terms of the fraction of transmitted neutrons, the build-up factor, the energy distribution of transmitted neutrons, and the contributions from different energy domains. Section 4 discusses all these results, along with their implications for the neutron-induced SER of shielded integrated circuits.

2. Materials and Methods

2.1. Neutron Shielding by a Concrete Slab

Figure 1 summarizes the principal mechanisms governing neutron transport through a concrete shield in a fusion environment. A large population of incident fusion neutrons, typically dominated by high-energy D–T neutrons at approximately 14 MeV, enters the concrete slab. As they propagate through the bulk material, these neutrons may undergo scattering, absorption, energy degradation, or secondary-neutron production through interactions with concrete nuclei. Consequently, only a fraction of the incident neutrons reaches the exit surface, while many are absorbed, backscattered, or significantly moderated by successive collisions within the shielding material.

The transmitted neutron population can be separated into two contributions. The first contribution is the uncollided, or ballistic component, made of neutrons that cross the slab without interaction and therefore keep an energy close to the initial value, $E \approx 14$ MeV. This component decreases exponentially with the slab thickness and rapidly becomes very small for thick concrete shielding. The second contribution is the collided component, which includes neutrons that have undergone one or several scattering reactions, and secondary neutrons produced inside the slab. These neutrons generally emerge with degraded energies, producing a transmitted spectrum that is no longer peaked at 14 MeV but shifted towards lower energies, with possible intermediate-energy and thermalized components.

In the fusion context, this distinction is essential. Concrete shielding does not simply attenuate the neutron flux; it also modifies the neutron energy spectrum. A thick slab can strongly suppress the direct 14 MeV component while leaving a degraded scattered spectrum behind the shield. Consequently, and as we will discuss later, radiation effects on electronics located behind shielding must be evaluated using the transmitted spectrum, not only the source spectrum because the relative importance of high-energy, epithermal, and thermal neutrons can be substantially changed by neutron transport through the concrete. In addition to neutrons, other secondary particles are generated when neutrons interact with concrete. These particles include charged particles, such as protons and elec-

trons, as well as electromagnetic radiation, such as photons. These particles are generally shielded by the concrete, so the exit flux is low but still present [41].

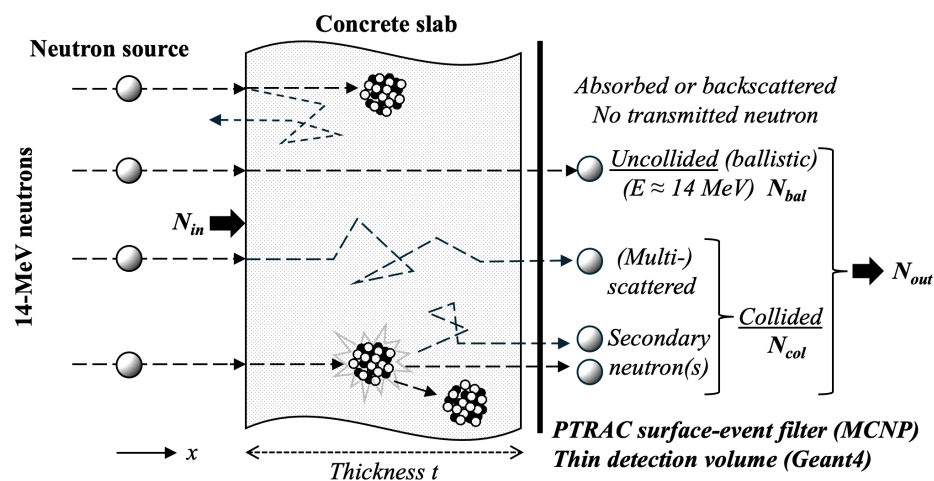


Figure 1. Schematic representation of neutron transport through a concrete shield in a fusion environment. Incident 14 MeV D–T neutrons enter the slab and undergo scattering, absorption, moderation, and secondary-neutron production. The transmitted neutron population at the exit surface consists of uncollided ballistic neutrons and collided neutrons, including multiply scattered and secondary neutrons.

If N_{in} denotes the total number of incident neutrons entering the concrete shield, while N_{out} represents the total number of neutrons emerging from the exit surface after transport, the transmitted population N_{out} can be decomposed into two contributions: the ballistic component N_B , corresponding to neutrons that cross the shield without undergoing any interaction, and the collided component N_C , which includes neutrons that have experienced one or more interactions, such as scattering, moderation, or secondary production, before reaching the detector surface. These quantities are linked by $N_{out} = N_B + N_C$. In Monte Carlo simulations, and as detailed in the next sections, this transmitted population can be estimated either by a surface-event filter in MCNP [32,33] or by a thin scoring volume placed after the slab in Geant4 [34–36].

2.2. MCNP Simulations

MCNP version 6.3 [32,33] was used to perform quasi-one-dimensional neutron transport simulations through ordinary concrete slabs. The slab thickness t was defined along the x -axis, with the frontal and rear faces located at $x = 0$ and $x = t$, respectively. The lateral dimensions were $10t \times 10t$, extending from $-5t$ to $+5t$ along both y and z . The slab was surrounded by void regions on the source and transmission sides, and the lateral boundaries were treated as a vacuum. A monoenergetic 14 MeV neutron source was placed at the center of the frontal face and emitted neutrons in the $+x$ direction with direction vector $(1, 0, 0)$. The source was modeled as a pencil beam. The concrete was modeled with a density of 2.30 g/cm^3 and a material composition representative of ordinary concrete, including the following elements in weight fractions: H (0.45%), O (51.26%), Si (36.04%), Al (3.55%), Na (1.53%), Ca (5.79%), and Fe (1.38%). The ENDF/B-VIII.0 evaluated nuclear data library was considered for these elements [32,33]. The ENDF/B-VIII.0 data were taken at room temperature, which corresponds to normal-temperature conditions of approximately 293 K. This assumption is consistent with the generic, ordinary concrete shielding configuration considered in this study.

A total of N_{in} neutron histories (varying from 10^6 to 10^9 as a function of concrete slab thickness) were simulated to obtain statistically meaningful transmission data. The char-

acteristics of the neutrons crossing the exit surface at $x = t + 1$ mm (see Figure 1) were recorded individually in a file using a PTRAC surface-event filter. The PTRAC file enables a detailed analysis of the transmitted neutron population in terms of its energy spectrum, attenuation, and the relative contribution of ballistic and collided neutrons following its passage through the shield. It also facilitates a direct comparison with Geant4, since this file is similar to the Geant4 output, which records the individual characteristics of the outgoing neutrons (Section 2.3).

2.3. Geant4 Simulations

The same quasi-one-dimensional MCNP model was reproduced in Geant4 version 11.3 [34–36] using the same geometry and concrete composition. The physics list “Shielding”, recommended for simulation of deep shielding, was considered. For neutron energies of 20 MeV and below, the high-precision (HP) neutron models and cross-sections are used to describe elastic and inelastic scattering, capture, and fission. The Geant4 production cutoff thresholds are set to 1 mm in range for photons, electrons, and positrons, while the proton cutoff is set to 0 mm. The corresponding energy thresholds for photons, electrons, and positrons are material-dependent and are converted by Geant4 into an energy value for each material, whereas the proton cutoff corresponds nominally to 0 keV. The individual characteristics of neutrons crossing a thin detection volume located at $x = t + 1$ mm (see Figure 1) were recorded in an output simulation file.

Verifying the results using Geant4 strengthens the reliability of our simulation results by providing an independent cross-check with two well-established Monte Carlo transport codes. Consistent results between both codes help consolidate the conclusions and reduce the risk of code-specific bias or modeling errors.

2.4. Neutron Interactions with Circuit Semiconductor Materials

When a neutron strikes the semiconductor material of an integrated circuit, it may undergo several types of interactions with the material, depending primarily on its incident energy. Owing to its electrical neutrality, the neutron does not directly induce ionization through Coulomb interactions with atomic electrons. Instead, the neutron interacts with the nuclei of atoms through nuclear processes, including elastic scattering, inelastic scattering, and neutron capture reactions [9].

In elastic scattering events, a fraction of the neutron kinetic energy is transferred to a target nucleus, producing a recoil nucleus. If the transferred energy exceeds the displacement threshold energy of the semiconductor lattice, the recoil nucleus can be displaced from its crystallographic site, thereby generating lattice defects and contributing to displacement damage [6]. For higher-energy neutrons, inelastic nuclear reactions and capture processes may occur, leading to the emission of secondary charged particles such as protons, alpha particles, or heavier charged fragments. The recoil nuclei and the secondary particles deposit energy along their trajectories through the semiconductor via ionization mechanisms. This process is called indirect ionization because the neutron itself does not ionize the material directly; instead, ionization is caused by the charged particles generated after the neutron interacts with nuclei [42,43].

The generated charge carriers may be transported and collected by electric fields present in sensitive regions of the circuit, including reverse-biased p-n junctions, memory nodes, or other critical volumes. If the collected charge exceeds the critical charge required to perturb the logical or electrical state of the node, the device response may be altered [44]. Such radiation-induced perturbations are generally known as single-event effects (SEEs). Depending on the device architecture, operating conditions, and amount of collected charge, SEEs may manifest as transient signals, logic upsets, functional interruptions, or memory bit flips [45]. A particularly common manifestation is the soft error, in

which the stored state of a memory element is inverted without inducing permanent structural damage to the device [46–48].

2.5. SER Estimation

The soft-error rate (SER) quantifies the frequency of such radiation-induced soft errors in a device or system under a specified radiation environment [47]. It is therefore a key reliability metric for evaluating the susceptibility of semiconductor components to neutron-induced effects. SER is commonly expressed in terms of failures in time (FIT), corresponding to the number of failures that occur in 10^9 h, or alternatively through the mean time between failures (MTBF), which represents the average time interval between successive failures. Consequently, SER provides a quantitative basis for assessing radiation sensitivity, comparing device technologies, and predicting the operational reliability of electronic systems exposed to neutron radiation.

In the field of radiation effects on electronic devices [19,20], the neutron-induced SER of a given integrated device or circuit is defined as follows [46]:

$$SER = \int \phi(E) \sigma_{SER}(E) dE. \quad (1)$$

where $\phi(E)$ is the neutron flux per unit energy and $\sigma_{SER}(E)$ is the device or circuit neutron-induced SER cross-section [46], expressed in cm^2 . The SER obtained from this equation has units of s^{-1} . To convert the SER into FIT, the calculated value must be multiplied by 3.6×10^{12} .

In the domain of SEEs in semiconductor memories, the neutron-induced cross-section is often expressed in terms of a single memory bit. In such cases, it is referred to as the cross-section per bit, which is expressed in cm^2/bit . The resulting SER (Equation (1)) is therefore obtained per bit and then converted to FIT/Mbit when appropriate. This will be the case throughout the rest of this paper. Moreover, in the context of fusion neutron energies, the cross-section per bit, which results from the different neutron–circuit material interaction mechanisms, is usually described by two analytical models depending on the neutron energy range considered, as explained in the following.

2.5.1. Thermal and Low-Energy Neutrons

In the case of thermal and low-energy neutrons, the cross-section per bit is referred to as the thermal circuit cross-section. It follows a $1/v$ dependence, where v is the neutron velocity, and is given by the following equation [30]:

$$\sigma_{Th}(E) = \sigma_{kT} \sqrt{\frac{E_{Ref}}{E}} \quad (2)$$

In Equation (2), E is the neutron energy, $E_{Ref} = 25$ meV, and σ_{kT} is the cross-section value for $E = E_{Ref}$. The dependence of the thermal cross-section on $1/\sqrt{E}$ is related to the probability of neutron absorption in circuit materials as a function of energy [30].

2.5.2. Fast Neutrons

In the case of fast neutrons, the high-energy neutron-induced cross-section per bit, σ_{FN} , is usually accurately represented by a saturating Weibull model [22]:

$$\sigma_{FN}(E) = \sigma_{sat} \left[1 - e^{-\left(\frac{E-E_{Th}}{w}\right)^s} \right] H(E - E_{Th}) \quad (3)$$

where σ_{sat} is the saturation cross-section, E_{Th} is the threshold energy below which the cross-section is zero, w is a scale parameter with the same unit and dimension as energy,

and s is a dimensionless shape parameter. In this equation, $H(E - E_{Th})$ is the Heaviside step function, equal to 0 when $E \leq E_{Th}$ and equal to 1 when $E > E_{Th}$ [49].

The integration of the energy-dependent cross-section over the neutron spectrum, as given in Equation (1), can be carried out numerically using standard numerical integration techniques. These include the rectangle method and Simpson's method, especially the adaptive Simpson method [50], which is particularly appropriate for this kind of integration.

3. Results

3.1. Preliminary Comparison Between MCNP and Geant4

Figure 2 compares the transmitted neutron energy spectra calculated using Geant4 and MCNP for a concrete slab irradiated by monoenergetic 14 MeV neutrons. Two slab thicknesses are considered: 50 cm and 100 cm. The spectra (histograms) show the number of neutrons per energy bin, normalized per neutron source, versus the neutron energy. They cover the range from thermal energies to the incident neutron energy. For both slab thicknesses, Geant4 and MCNP produce very similar spectral shapes across the entire energy spectrum. The calculations accurately reproduce the key characteristics of neutron transport through concrete, including a significantly low-energy component resulting from moderation, an intermediate-energy continuum, and a high-energy contribution associated with neutrons that experience minimal energy loss prior to transmission. As expected, and discussed later in Section 3.2, increasing the slab thickness from 50 cm to 100 cm significantly reduces the transmitted neutron intensity, demonstrating neutron attenuation and moderation in concrete.

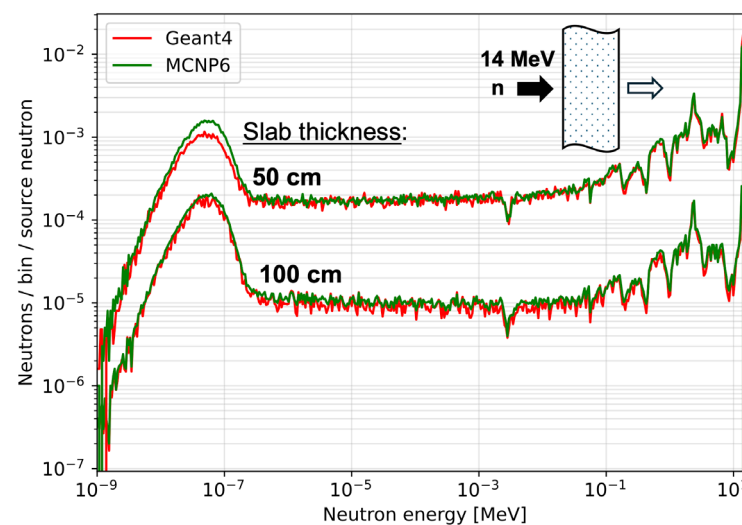


Figure 2. Transmitted neutron energy spectra after passage through 50 cm and 100 cm thick slabs, comparing results from Geant4 and MCNP simulations for an incident 14 MeV neutron beam. The spectra show the number of neutrons per energy bin, normalized per source neutron, as a function of neutron energy (500 logarithmically spaced bins from 10^{-9} to 10^2 MeV). Geant4 and MCNP raw data were obtained with $N_{in} = 10^6$ source neutrons for a 50 cm thick slab and with $N_{in} = 10^7$ source neutrons for a 100 cm thick slab.

The close agreement observed between the Geant4 and MCNP calculations supports the reliability of the simulation results. The comparison shows that the two transport codes produce very similar transmitted spectra within the investigated energy range and for the considered slab thicknesses. In the following sections, only the MCNP results are presented; however, the corresponding Geant4 simulations were systematically per-

formed for cross-checking purposes and consistently produced results that were in very good agreement.

3.2. Fraction of Transmitted Neutrons and Build-Up Factor

Figure 3 shows the evolution of the fraction of transmitted neutrons as a function of concrete slab thickness. Two distinct transmission quantities are represented: the fraction of total transmitted neutrons or total transmission, T_{tot} , expressed as

$$T_{tot} = \frac{N_{out}}{N_{in}} \quad (4)$$

and the fraction of ballistic (or uncollided) transmitted neutrons or ballistic transmission, T_{bal} , given by

$$T_{bal} = \frac{N_{bal}}{N_{in}}. \quad (5)$$

The results of Figure 3 show that as the concrete slab thickness increases, both transmission curves decrease, indicating that neutron transmission becomes progressively weaker when the concrete thickness is greater. However, the two curves exhibit very different attenuation behaviors, revealing two distinct physical regimes. The ballistic transmission follows a pure exponential decay as a function of the slab thickness, t , as follows

$$T_{bal}(t) = \exp(-\Sigma_r t) \quad (6)$$

where Σ_r is an effective attenuation coefficient expressed in cm^{-1} and t is expressed in cm. Fitting Equation (6) to the ballistic transmission curve of Figure 3 leads to $\Sigma_r = 0.113 \text{ cm}^{-1}$, corresponding to a neutron mean free path, λ , in concrete of approximately 8.86 cm, a value of the same order as expected for 14 MeV neutrons in ordinary concrete [17]. The behavior of the ballistic transmission shows that the probability for a neutron to cross the concrete slab without any collision rapidly becomes extremely small. For thin slabs, the ballistic component is still relatively large, but it drops by several orders of magnitude as the thickness increases, reaching values close to 10^{-8} for the largest slab thicknesses.

The total transmission decreases much more slowly than the ballistic transmission. For $t > 50 \text{ cm}$, the total transmission can be described by the following expression

$$T_{tot}(t) \propto \exp(-\Sigma_{eff} t) \quad (7)$$

with $\Sigma_{eff} \approx 0.054 \text{ cm}^{-1}$, revealing the increasing importance of multiply scattered neutrons.

Figure 3 shows that at small thicknesses, the total and ballistic transmissions are relatively close because many transmitted neutrons have not yet undergone collisions. As the slab becomes thicker, the two curves separate strongly. The total transmission remains several orders of magnitude above the ballistic transmission, especially for greater thicknesses. This indicates that, although the direct uncollided contribution is almost completely suppressed, a significant number of neutrons still exit the slab after undergoing one or more scattering events.

This difference between the two curves highlights the importance of collided neutrons in the transmitted flux. For thick slabs, the transmission is no longer dominated by ballistic neutrons but by scattered neutrons that have changed direction and energy during their transport through the material. Consequently, the total attenuation is less steep than a simple exponential law based only on uncollided particles. The figure therefore demonstrates that multiple scattering strongly enhances the transmitted neutron population compared with the purely ballistic prediction, particularly at large slab thicknesses.

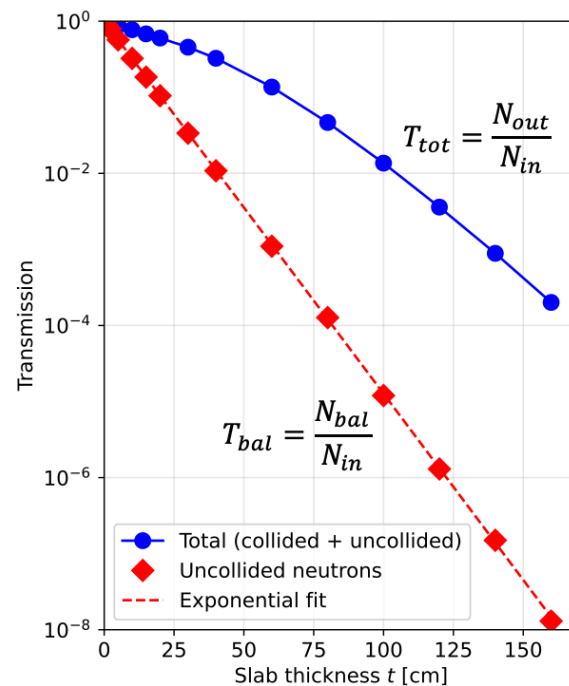


Figure 3. Total transmission, T_{tot} , and ballistic transmission, T_{bal} , as a function of slab thickness. The total transmission includes both collided and uncollided neutrons, while the ballistic transmission involves only uncollided neutrons. The collided and uncollided flux components were derived directly from the PTRAC files using post-treatment. The red dashed line gives the exponential attenuation fit of the ballistic transmission.

The build-up factor quantifies the increase in transmitted flux due to particles that have undergone collisions within the material. It can be defined as follows:

$$B = \frac{T_{tot}}{T_{bal}} \quad (8)$$

A build-up factor equal to one means that the transmission is purely ballistic, with no significant contribution from scattered neutrons. A build-up factor higher than one indicates that collided neutrons contribute to the transmitted flux. The higher the build-up factor, the greater the contribution of scattered particles relative to the uncollided component.

Figure 4 shows the variation in the logarithm of the build-up factor with the concrete slab thickness. The natural logarithm of the build-up factor increases continuously as the material thickness increases, rising from a value close to zero for very thin slabs to a value of around 10 for a thickness of approximately 160 cm. The increase is rapid at low thicknesses: the build-up factor rises sharply from the very first few centimeters, indicating that the contribution from scattered neutrons quickly becomes significant compared to the ballistic component. For $t < 50$ cm, the curve of the logarithm of the build-up factor can be fitted by the law $a_1 \times t$, with $a_1 = 0.0869 \text{ cm}^{-1}$ (coefficient of determination $R^2 \sim 0.998$). This indicates that the build-up factor increases very rapidly with thickness: each centimeter multiplies the build-up factor B by $e^{0.089} = 1.09$, i.e., an increase of 9% per centimeter.

As the slab thickness continues to increase, the curve remains upward-sloping, but the slope gradually becomes shallower. For $t > 70$ cm, the curve can be fitted by the law $a_2 \times t + b_2$, with $a_2 = 0.0457 \text{ cm}^{-1}$ and $b_2 = 2.3602$ (coefficient of determination $R^2 \sim 0.994$); this means that the build-up factor B increases by 5% per centimeter. This trend reflects a continuing increase in the role of collided neutrons, but with a slower rate of increase at greater thicknesses. Thus, the change in slope indicates the shift from an initial regime where the first collisions efficiently drive the transmitted component to a

more diffusive regime where deceleration, absorption, backscattering, and lateral leakage gradually limit the growth of the transmitted component.

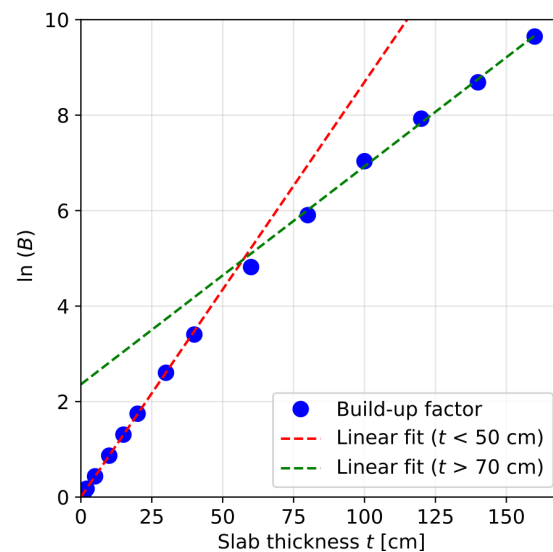


Figure 4. Natural logarithm of the build-up factor, B , as a function of concrete slab thickness. The red dashed line gives the linear fit for slab thicknesses smaller than 50 cm, and the green dashed line gives the linear fit for slab thicknesses greater than 70 cm.

Overall, Figure 4 shows that the thicker the slab, the greater the contribution of scattering phenomena to the total transmission. The build-up quantifies this difference between total transmission and purely ballistic transmission: it highlights the growing importance of scattered neutrons in the flux transmitted through the material. The results in Figures 3 and 4 are quantitatively consistent with the classical theory of fast neutron transport in concrete [51].

3.3. Energy Distributions of Transmitted Neutrons

The energy distributions of the transmitted neutrons are shown in Figures 5 and 6 for several concrete slab thicknesses. Each curve corresponds to a specific slab thickness, t , ranging from thin slabs (1–40 cm) to thicker ones (50–100 cm).

Figure 5 shows that, particularly for slabs of 1 to 10 cm, the transmitted spectrum is dominated by a very pronounced peak around 14 MeV. This peak corresponds to neutrons that pass through the slab without interacting or with very little energy loss. The transmission, therefore, strongly retains the signature of the incident source. As the thickness of the slab gradually increases, this high-energy peak gradually diminishes. This decrease reflects the reduction in the ballistic component: the thicker the slab, the lower the probability that a neutron will pass through the material without colliding. At the same time, the spectrum gradually broadens towards lower energies. This broadening is due to the successive collisions that the neutrons undergo within the material. During each interaction, some of the neutrons' energy may be transferred to the medium, producing slowed-down neutrons. As the thickness increases from 1 to 10, 15, 20, 30, and then 40 cm, a gradual redistribution of the neutron population is observed from the high-energy region towards the intermediate, epithermal, and thermal regions. The spectrum, therefore, becomes less dominated by fast neutrons close to 14 MeV and is increasingly influenced by scattered and slowed-down neutrons.

This trend becomes even more pronounced for thicker slabs, as shown in Figure 6. The curves corresponding to thicknesses of 50, 60, 80, and 100 cm show that the 14 MeV contribution is significantly reduced while the population of lower-energy neutrons be-

comes dominant. The spectrum then exhibits a broad distribution over several orders of magnitude in energy, indicating highly collisional transport. The transmitted neutrons are no longer primarily ballistic, but rather, they are neutrons that have undergone numerous scatterings before exiting the slab. A peak of thermal neutrons at very low energies is also observed in thick slabs. This peak indicates that a significant proportion of the neutrons have been slowed down by interactions within the material enough to reach the thermal range. This peak becomes more pronounced as the slab thickens because the path length and average number of collisions within the material increase. Thus, the material acts as both an attenuator of fast neutrons and a moderator that gradually transforms the initial fast neutron spectrum into one enriched with low-energy neutrons.

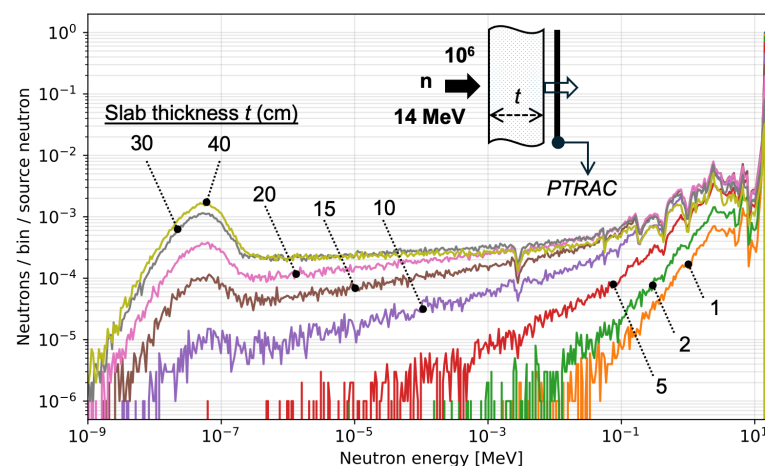


Figure 5. Energy spectra of transmitted neutrons for various thicknesses, t , of the concrete slab: $t = 1, 2, 5, 10, 15, 20, 30$, and 40 cm (500 logarithmically spaced bins from 10^{-9} to 10^2 MeV). The diagram (in inset) shows the configuration used for the calculation: incident neutrons of 14 MeV pass through the concrete slab, after which the transmitted neutrons are recorded individually in an output file using the PTRAC output command in MCNP.

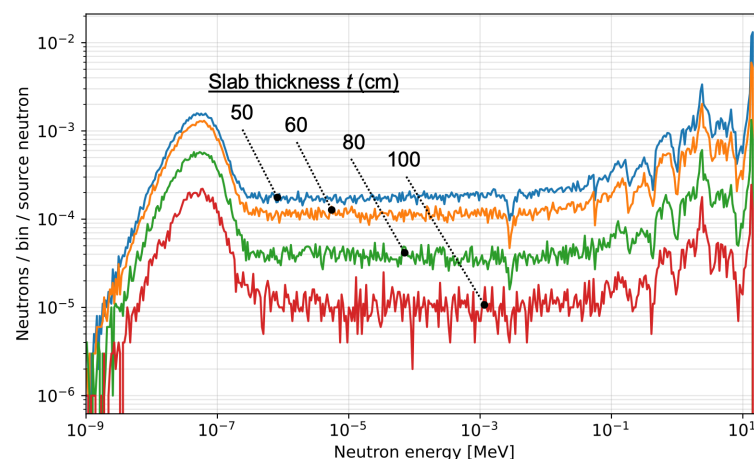


Figure 6. Energy spectra of transmitted neutrons for various thicknesses, t , of the concrete slab: $t = 50, 60, 80$, and 100 cm. The same configuration as shown in the inset of Figure 5, and the same histogram parameters were used for the calculation.

3.4. Contributions per Energy Domain

As shown in the previous section, the transmitted neutron spectrum spans a wide range of energies, especially with thick concrete slabs. For a more detailed analysis and for the upcoming SER analysis (Section 4.2), this spectrum is divided into three energy

domains. Figure 7 shows these domains according to their energy ranges: Part I covers energies below 1 eV, Part II covers energies between 1 eV and 0.1 MeV, and Part III covers energies above 0.1 MeV. The number of transmitted neutrons in each energy domain is obtained by summing the histogram bin counts over the corresponding energy interval. It is denoted N_I for Part I, N_{II} for Part II, and N_{III} for Part III. These quantities are linked by the relation $N_{out} = N_I + N_{II} + N_{III}$.

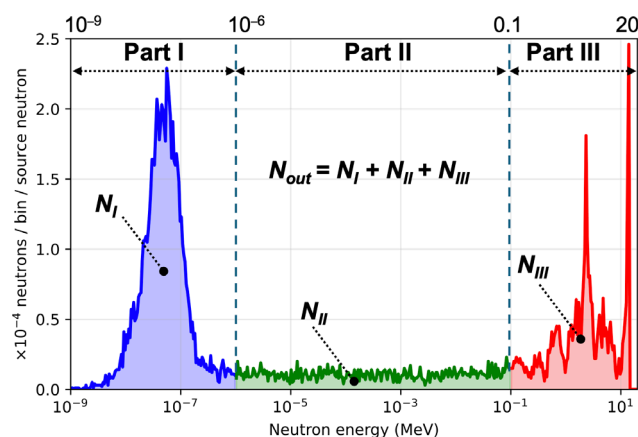


Figure 7. Energy spectrum of transmitted neutrons for a concrete slab thickness of 100 cm (500 logarithmically spaced bins from 10^{-9} to 10^2 MeV). The spectrum is divided into three parts: Part I is for energies below 1 eV, Part II covers energies between 1 eV and 0.1 MeV, and Part III is for energies above 0.1 MeV. The number of transmitted neutrons is indicated for each part of the spectrum.

Figure 8 shows the fraction of transmitted neutrons as a function of slab thickness for the three regions of the spectrum. For Part III (fast neutrons, $E > 0.1$ MeV), the curve peaks at a very small slab thickness of around 0 to 1 cm. The fraction of transmitted fast neutrons is then close to 1, which means that most incident neutrons pass through the slab while retaining a high energy. As the thickness increases, this fast component decreases continuously, reflecting the gradual attenuation due to interactions within the material. Fast neutrons undergo collisions, lose energy, and are gradually transferred to lower energy regions. At greater thicknesses, the fast component becomes negligible because very few neutrons retain an energy higher than 0.1 MeV after passing through a large amount of material.

The curve for Part II (intermediate-energy neutrons, $1 \text{ eV} < E < 0.1 \text{ MeV}$) shows different behavior. It initially increases rapidly with slab thickness, reaching a maximum around 30 cm before decreasing gradually. This trend results from a balance between two opposing effects. For thin slabs, few neutrons have undergone enough collisions to be slowed down into the intermediate energy range, which explains the low initial value of this component. As the slab thickens, fast neutrons are increasingly slowed by scattering, thereby increasing the population of intermediate-energy neutrons. The curve therefore rises to a maximum, reached for a slab thickness of approximately 30 cm. Beyond this slab thickness, the intermediate neutrons continue to undergo collisions: some are further slowed down towards the thermal range, while others are absorbed or unable to escape the slab. The transmitted population in this energy range then decreases.

As with the curve of Part II, the transmission in Part I (low-energy neutrons, $E < 1$ eV) shows an initial increase followed by a decrease. It reaches its maximum at a thickness of around 40 cm. For very thin layers, this component is nearly nonexistent because the 14 MeV incident neutrons have not had enough time to undergo collisions and reach thermal or sub-thermal energies. As the thickness increases, the number of collisions increases, which slows down the neutrons to the $E < 1$ eV range. Therefore, the curve rises sharply and reaches its maximum at a greater thickness than the curve in Part II. This shift

is consistent with the fact that more collisions—and thus greater material thickness—are required to produce highly slowed neutrons than intermediate-energy neutrons. Beyond approximately 40 cm, however, the transmitted thermal component decreases because low-energy neutrons are more likely to be absorbed or trapped by multiple scattering before reaching the slab's exit.

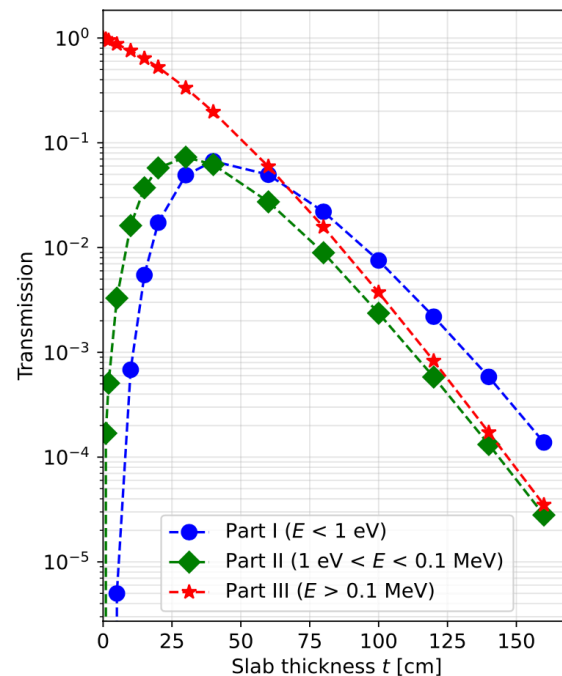


Figure 8. Fraction of transmitted neutrons as a function of slab thickness for the three energy domains of the transmitted neutron spectrum.

4. Discussion

4.1. Neutron Shielding by Concrete Slabs

First, the total transmission shown in Figure 3 remains below 1, meaning that the number of neutrons transmitted through an ordinary concrete slab remains lower than the number of incident neutrons. This result can be understood from the balance between neutron loss mechanisms and neutron multiplication reactions occurring within the material. As indicated in Section 2.2, the ordinary concrete considered in this work is mainly composed of H, O, Si, Na, Ca, Al, and Fe atoms. When 14 MeV neutrons originating from a D–T fusion source enter the concrete, they undergo numerous elastic and inelastic interactions with these nuclei. Elastic scattering, particularly on H, efficiently slows down the neutrons and redistributes their directions [7,52]. Inelastic scattering on O, Si, Na, and Fe further degrades the neutron energy and contributes to the generation of a broad slowing-down spectrum. As a result, a significant fraction of the incident neutron population is either backscattered toward the source, lost through lateral leakage, or eventually absorbed after moderation to lower energies. This behavior is consistent with the classical description of neutron transport and slowing-down in shielding material [13,53,54].

In principle, neutron multiplication reactions can occur in concrete. At 14 MeV, some nuclei present in concrete exhibit threshold reactions of the type $(n, 2n)$, $(n, 3n)$, or more generally (n, xn) , producing secondary neutrons. Examples include reactions on O, Si, and Fe nuclei. However, these reactions have relatively high thresholds and modest cross-sections at fusion-neutron energies. Consequently, only a limited fraction of the incident neutron population undergoes such multiplication processes. In our simulations, the only neutron-multiplication channels observed were $(n, 2n)$ reactions, which occurred only

rarely. These reactions represent 0.38% of n-Si interactions, 0.12% of n-Fe interactions, and 0.04% of n-O interactions. Moreover, many of the secondary neutrons are emitted at lower energies and remain subject to further scattering, moderation, and absorption before reaching the exit surface [17,54]. This behavior contrasts with dedicated neutron-multiplying materials such as beryllium or fissile materials. For instance, beryllium is commonly used as a neutron multiplier because the ${}^9\text{Be}(n, 2n)$ reaction is efficient at fusion-neutron energies. Ordinary concrete does not possess such multiplying properties. Its role is instead dominated by moderation, scattering, leakage, and eventual capture, which explains its widespread use as a neutron shielding material [13,17]. Therefore, although secondary-neutron production contributes to the transmitted population and to the build-up effect, the losses due to backscattering, moderation followed by capture, and lateral leakage largely exceed the neutron gain associated with (n, xn) reactions.

The neutron-transport results through a concrete slab shown in Figures 3–8 indicate a progressive redistribution of the transmitted neutron flux as the slab thickness increases, along with a strong spectral redistribution and a significant build-up of scattered neutrons. For thin slabs, the transmitted flux is mainly dominated by fast neutrons close to the incident energy of 14 MeV. As the slab becomes thicker, elastic and inelastic scattering processes become increasingly important, reducing the 14 MeV peak and broadening the spectrum toward lower energies. At intermediate thicknesses, multiple collisions generate a significant population of slowed-down neutrons, producing an epithermal component approximately following a $1/E$ behavior, a thermal peak associated with hydrogen moderation, and a residual high-energy tail from partially degraded primary neutrons. Figure 8 shows that the transmission maxima of the different energy parts occur at different thicknesses, around 0–1 cm for fast neutrons, 30 cm for intermediate-energy neutrons, and 40 cm for low-energy neutrons. For larger thicknesses, absorption and capture of thermalized neutrons become dominant, leading to a sharp decrease in the transmitted flux despite the continued production of slowed-down neutrons within the material.

It should be noted that biological shields in real fusion facilities are generally made of reinforced concrete and other high-density materials rather than purely homogeneous ordinary concrete. In the present study, the steel reinforcement was not explicitly modeled, and the concrete was treated as a homogeneous material. This assumption may affect the calculated neutron transmission and spectral redistribution [55]. Steel rebars increase the local iron content, which can modify the probabilities of fast-neutron scattering and inelastic interactions, as well as affect the intermediate-energy spectrum through resonance absorption in iron [56]. Depending on the reinforcement fraction, bar spacing, and position relative to the neutron path, the transmitted spectrum may therefore differ from that obtained for homogeneous ordinary concrete. Consequently, the present results should be interpreted as a reference case for homogeneous ordinary concrete, while reinforced-concrete biological shields require explicit modeling of the steel distribution for quantitative design calculations.

Finally, it is important to note that in a real tokamak environment, the neutron source exhibits spectral broadening, and the neutron field reaching the biological shield may have a broad angular distribution due to previous scattering in surrounding structures [57,58]. The source model in the present work assumes monoenergetic 14 MeV neutrons normally incident on the concrete slab. This configuration was chosen as a reference case to isolate the effect of concrete thickness on neutron attenuation, spectral redistribution, and SER. For an ideal homogeneous slab, the first-order effect of oblique incidence is an increase in the effective path length from t to $t/(\cos \theta)$, where θ is the angle of incidence with respect to the slab's normal. Thus, incidence angles of 30°, 45°, and 60° correspond to effective thickness increases of approximately 15%, 41%, and 100%, respectively. In the ballistic approximation, this increased thickness should be considered in Equation (6).

Oblique incidence is therefore expected to enhance the suppression of the direct 14 MeV component and to shift the transmitted spectrum toward lower energies. Since the SER is obtained by folding the transmitted neutron spectrum with the device-specific SEU cross-section, any change in the transmitted spectrum induced by angle may also modify the calculated SER. However, realistic angular distributions cannot be reduced to a single effective path length, especially when multiple scattering and room-return effects are present. The conclusions of this study should therefore be regarded as reference results for a normal-incidence slab configuration, while quantitative predictions for real fusion facilities require angular-dependent, three-dimensional transport calculations [15,17,59].

4.2. Implications for the Neutron-Induced SER of Shielded Integrated Circuits

We investigated the impact of these spectral changes on the soft-error rate (SER) of two types of complementary metal-oxide-semiconductor (CMOS) static random-access memory (SRAM) circuits. The first circuit is a 65 nm bulk CMOS SRAM test vehicle fabricated by STMicroelectronics. The memory circuit contains 8.5 Mbits of single-port SRAM (no deep N-well) with a bit cell area of $0.525 \mu\text{m}^2$, operating at a nominal core voltage of 1.2 V [60]. The second circuit is a commercial 32-Mbit SRAM fabricated in 40 nm bulk CMOS by Integrated Silicon Solution Inc. (ISSI) and operating at a core voltage of 1.1 V (obtained as an extrapolated value based on the technology node) [60]. These two technologies have been characterized in terms of neutron-induced SEUs, and the parameters of the models that give the neutron bit-flip cross-section (Equations (2) and (3)) as a function of the neutron energy are precisely known. These parameters are summarized in Table 1 [61–64]. Figure 9 shows the variation in the neutron bit-flip cross-section as a function of the neutron energy for the two technologies.

Table 1. Cross-section model parameters for the 65 nm ST and 40 nm ISSI CMOS bulk SRAM technologies [61–64].

SRAM	σ_{KT} (cm^2/bit)	σ_{sat} (cm^2/bit)	E_{Th} (MeV)	w (MeV)	s
65 nm ST SRAM [61,62]	1.90×10^{-16}	3.17×10^{-15}	0.148	9.115	0.856
40 nm ISSI SRAM [63,64]	3.16×10^{-15}	1.40×10^{-14}	0.01	14.05	0.82

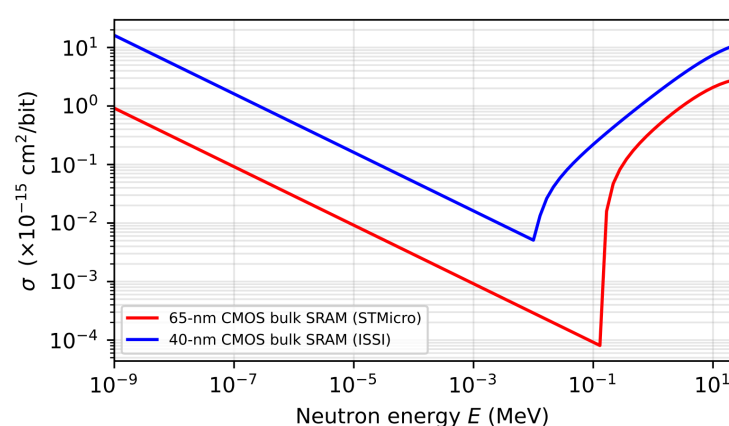


Figure 9. Neutron-induced bit-flip cross-section for the 65 nm STMicroelectronics and 40 nm ISSI CMOS bulk SRAM technologies.

The SER has been evaluated by folding the simulated neutron energy distributions with energy-dependent bit-flip cross-sections, as explained in Section 2.5 (Equation (1)). These energy distributions were normalized per source neutron and then scaled to the assumed incident flux before being used in the SER calculation. Figures 10 and 11 show

the calculated SER as a function of slab thickness for 65 nm and 40 nm CMOS SRAM technologies, respectively. In these figures, the SER is decomposed into the three energy domains defined in Section 3.4.

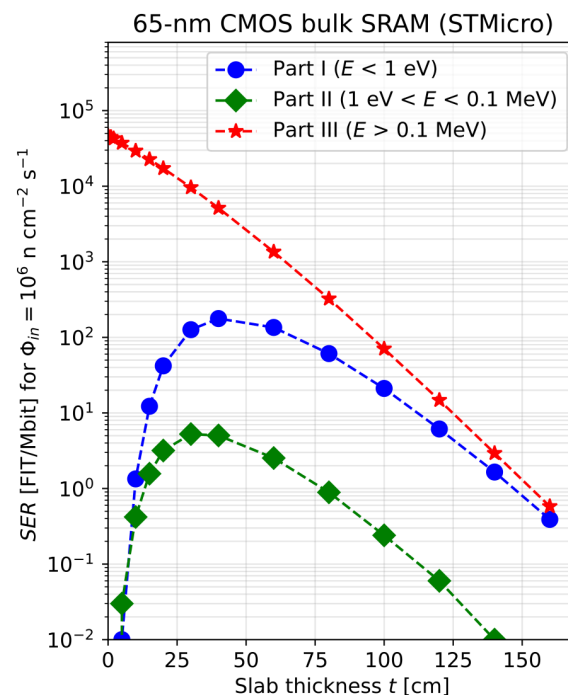


Figure 10. SER as a function of concrete slab thickness for the 65 nm STMicroelectronics CMOS bulk SRAM technology.

The SER results for the 65 nm CMOS SRAM technology (Figure 10) show that the fast-neutron contribution (Part III) is dominant over the whole thickness range. At a small concrete thickness, this contribution is very large because the transmitted spectrum still contains a significant fraction of high-energy neutrons. As the slab thickness increases, the fast component decreases continuously and almost exponentially. This is due to the attenuation and moderation of fast neutrons in concrete: elastic and inelastic scattering progressively reduce their energy, while absorption and leakage reduce their number. The thermal-neutron contribution (Part I) behaves differently. It first increases with thickness, reaches a maximum around 40 cm, and then decreases. This maximum is a typical consequence of neutron moderation. For thin slabs, only a small fraction of the incident fast neutrons has been slowed down to thermal energies, so the thermal contribution is weak. As the concrete thickness increases, more neutrons undergo multiple scattering events and populate the thermal energy range. This increases the thermal flux and therefore the thermal SER contribution. Beyond the maximum, however, the total transmitted neutron population becomes strongly attenuated, and thermal neutrons are also absorbed efficiently by the concrete constituents. The decrease in neutron intensity then dominates over the production of new thermal neutrons, leading to a reduction in the SER associated with Part I. The intermediate-energy contribution (Part II) also shows a maximum, but it remains much smaller than the two other contributions. Its peak occurs around 30 cm. This contribution corresponds to neutrons that have been partially moderated but have not yet reached the thermal range. For small thicknesses, the number of such neutrons is limited because the spectrum is still dominated by fast neutrons. For intermediate thicknesses, scattering redistributes part of the fast-neutron population into the epithermal and intermediate-energy range, which increases the SER associated with Part II. For larger

thicknesses, attenuation and further moderation toward thermal energies reduce this intermediate component.

Figure 11 shows the SER results for the 40 nm CMOS SRAM technology. These results show the same physical mechanism as for the 65 nm CMOS SRAM technology: concrete progressively transforms the incident fast neutron spectrum into a degraded spectrum containing thermal and intermediate-energy neutrons, while simultaneously attenuating the total transmitted flux. Like Figure 10, this figure illustrates the competition between neutron moderation and neutron attenuation in concrete. Increasing the slab thickness first transfers part of the fast-neutron population toward lower energies, producing maxima in the thermal and intermediate-energy SER contributions. For larger thicknesses, the transmitted flux becomes strongly reduced in all energy ranges, and all SER contributions decrease.

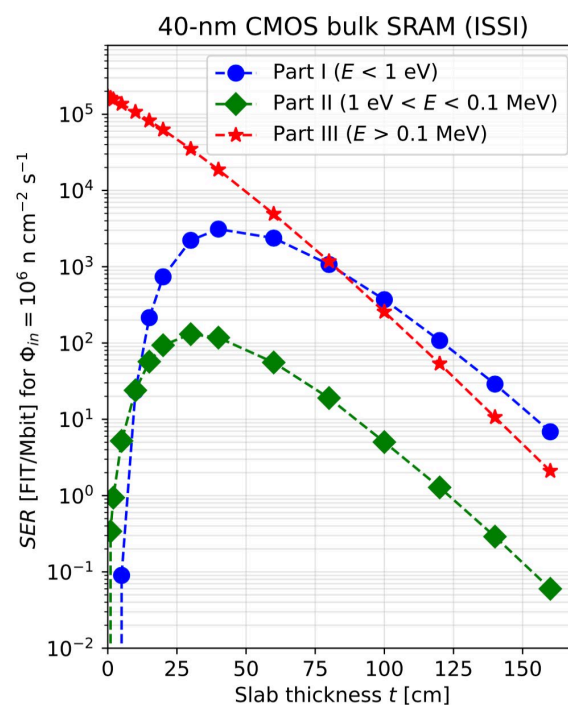


Figure 11. SER as a function of concrete slab thickness for the 40 nm ISSI CMOS bulk SRAM technology.

However, the main difference with respect to the 65 nm technology is the much larger sensitivity of the 40 nm SRAM, especially to the low-energy neutron components. The fast-neutron contribution is higher for the 40 nm device, but the increase is even more pronounced for the thermal and intermediate contributions. In the 65 nm case, the thermal contribution reaches a maximum of only about 10^2 FIT/Mbit, whereas in the 40 nm case it reaches several 10^3 FIT/Mbit. Similarly, the intermediate-energy contribution is also significantly higher in the 40 nm SRAM. Another important difference is the relative importance of the thermal contribution at large concrete thickness. In the 65 nm case, the fast-neutron contribution remains generally dominant or comparable over most of the thickness range. In the 40 nm case, the thermal contribution becomes comparable to the fast contribution around $t = 80$ cm and becomes larger for thicker slabs. This means that, after sufficient moderation in concrete, the SER of the 40 nm SRAM is no longer primarily controlled by the residual fast-neutron spectrum, but rather by the moderated thermal-neutron component. The 40 nm SRAM is then much more sensitive to the low- and intermediate-energy domains of the spectrum than the 65 nm SRAM. Consequently, for thick concrete slabs, the thermal-neutron contribution becomes a major, and eventually dominant, component of the SER in the 40 nm technology.

Figure 12 shows the total simulated SER, obtained as the sum of contributions from parts I, II, and III of the transmitted neutron spectra, versus slab thickness for the 65 nm STMicroelectronics and 40 nm ISSI CMOS bulk SRAMs. As expected from the individual contributions of parts I, II, and III discussed previously, the total simulated SER of the 40 nm SRAM is systematically higher than that of the 65 nm SRAM over the whole thickness range. The two SER curves decrease almost exponentially with increasing slab thickness and remain roughly parallel on the logarithmic scale, indicating that the SER ratio between the two technologies is nearly constant, with the 40 nm device being approximately 4–5 times more sensitive than the 65 nm device.

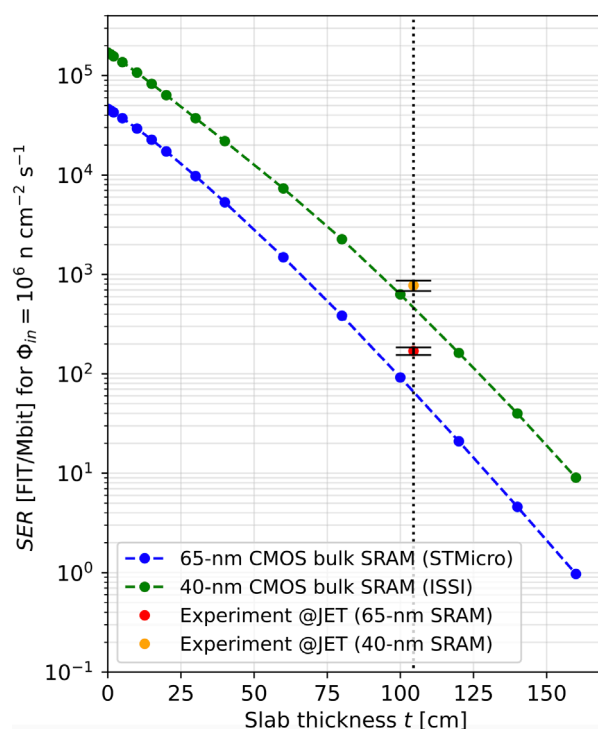


Figure 12. Total simulated SER (the sum of the SERs for parts I, II, and III) as a function of the thickness of the concrete slab for both the 65 nm STMicroelectronics and 40 nm ISSI CMOS bulk SRAMs. Experimental SER measurements obtained at the JET tokamak during its final D-T operation are also shown with experimental horizontal error bars. The vertical dotted line indicates the 104.5 cm thickness of the concrete slab behind which the two experiments were placed at JET.

From a shielding-design perspective, the curves of Figure 12 can be used to estimate the minimum concrete thickness required to reduce the SER below a specified allowable threshold. For the reference incident neutron flux considered here, $\phi_{in} = 10^6 \text{ n cm}^{-2} \text{ s}^{-1}$, approximate values obtained from the simulated curves are summarized in Table 2. These values should be understood as design-oriented estimates for the specific one-dimensional homogeneous concrete configuration studied here.

Table 2. Minimum concrete thickness required to reduce the SER below a specified allowable threshold.

Allowable SER Threshold	Minimum Thickness for 65 nm SRAM	Minimum Thickness for 40 nm SRAM
10^3 FIT/Mbit	~65–70 cm	~95–100 cm
10^2 FIT/Mbit	~100–105 cm	~125–130 cm
10 FIT/Mbit	~135–140 cm	~155–160 cm
1 FIT/Mbit	~160 cm	>160 cm

These values are clearly not universal shielding criteria. They scale with the incident neutron flux and depend on the SEU cross-section specific to the device. For a different incident flux ϕ_{in} , the calculated SER values will scale approximately linearly with the flux, provided the same neutron spectrum and device response are assumed. Therefore, the required concrete thickness must be recalculated for each radiation environment, device technology, and allowable SER requirement.

While the present study focuses on ordinary concrete, other concretes may be used in fusion shielding applications, including borated concrete and heavy concrete. Borated concrete is expected to enhance the absorption of thermal and epithermal neutrons through boron capture reactions, given the large thermal capture cross-section of ^{10}B [65,66]. This could reduce the low-energy part of the transmitted spectrum, which is particularly important for electronic technologies whose SER is sensitive to thermal neutrons [48]. Heavy concretes, which are based on high-density aggregates or iron-rich constituents, modify the fast-neutron attenuation, scattering, inelastic reaction balance, and resonance absorption structure [67]. Consequently, the transmitted neutron spectrum and the resulting SER could differ from those obtained for ordinary concrete. Although the conclusion that shielding-induced spectral redistribution must be included in SER estimates remains valid, quantitative SER values and the required thickness of shielding must be recalculated for each specific material.

Finally, it should be noted that the quantitative SER results presented in this section are limited to the two bulk-silicon CMOS SRAM technologies considered here. Other device substrates and architectures, such as FD-SOI, silicon carbide electronics, wide-bandgap devices, or radiation-hardened memory architectures, may exhibit different neutron-induced SER responses [68–70]. These differences may be due to changes in the geometry of sensitive volume, charge-collection efficiency, critical charge, substrate composition, nuclear reaction channels, layout-level hardening, and error-correction schemes [48,68,71,72]. Then, while the shielding-induced spectral modifications reported in this work are generally relevant for neutron transport, the corresponding SER values must be recalculated using technology-specific neutron-induced SEU cross-sections. The conclusions of the SER analysis should therefore be understood as applying to bulk-silicon CMOS SRAMs only.

4.3. Comparison with Previous Experiment at JET

In the context of radiation effects on electronics for fusion facilities, the 65 nm and 40 nm bulk CMOS SRAMs described in Section 4.2 were tested in real conditions at the Joint European Torus (JET) [73–75] during its final D–T plasma campaign (see [60] for details). Since D–T plasmas generate 14 MeV neutrons, JET provided a realistic environment to study neutron-induced soft errors in electronic memories representative of systems that may be used in future tokamak buildings.

Two test benches with the 65 nm and 40 nm SRAM circuits were installed in the JET basement (in position B6), below a 1045 mm reinforced concrete slab supporting the tokamak chamber, where the neutron field was partially shielded but still significant [60]. A neutron spectrometer was placed near the memories to measure the local neutron spectrum and fluence during each plasma pulse, allowing the observed single-event upsets to be directly correlated with the machine-induced neutron environment [60].

The results reported in [60] showed clear radiation-induced degradation of SRAM reliability: the 65 nm SRAMs exhibited a bit-flip rate of $493 \text{ h}^{-1} \text{ Gbit}^{-1}$ under an average residual neutron flux (at circuit level) of about $3.22 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$ in position B6, while the 40 nm SRAMs showed a higher rate of $2342 \text{ h}^{-1} \text{ Gbit}^{-1}$ under an average residual neutron flux of about $3.07 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$ at the same B6 position. These measurements clearly

demonstrated that electronics located in partially shielded areas of future fusion reactors may still experience significant neutron-induced soft errors.

To enable comparison with the slab simulations, the experimental SER values were rescaled to the transmitted neutron flux predicted by MCNP for a 104.5 cm-thick concrete slab irradiated by an incident neutron flux of $10^6 \text{ n cm}^{-2} \text{ s}^{-1}$. The resulting normalized SER values are 170 FIT/Mbit for the 65 nm SRAM and 776 FIT/Mbit for the 40 nm SRAM. These values are also reported in Figure 12. Since MCNP simulations are based on highly simplified assumptions compared to the actual JET environment (for example, a homogeneous concrete slab of fixed thickness rather than a detailed model of the building with numerous openings for cables or conduits, and a monoenergetic 14 MeV neutron source rather than the actual tokamak source), any agreement between the simulations and experimental data should be considered an order-of-magnitude estimate rather than a validation of the detailed neutron field. The ratio between the experimental SER values is approximately 4.6, in good agreement with the simulated ratio. Moreover, the absolute positions of the experimental points are reasonably close to the corresponding simulated curves, within about a factor of two. This approximately factor-of-two difference between the JET experimental points and the simulated slab curves can be explained by the idealized assumptions adopted in the present model. The simulation considers a homogeneous ordinary-concrete planar slab, a monoenergetic 14 MeV pencil-beam source, normal incidence, vacuum lateral boundaries, and the absence of cavities, penetrations, ducts, access doors, cable paths, multilayer shielding structures, or room-return scattering. In contrast, the real JET environment involves a realistic D–T neutron source with energy-angle distributions shaped by transport through the tokamak and surrounding structures, as well as a complex and highly heterogeneous three-dimensional geometry. These features may significantly alter the neutron field behind the shield [57–59,76,77]. Penetrations and ducts can create paths for neutrons to travel along, which can increase the transmitted flux compared to predictions for a homogeneous slab. Conversely, additional shielding layers or structural materials may further attenuate or reshape the neutron spectrum. Room-return scattering from surrounding walls and cavities may also contribute to the local neutron fluence at electronics locations. Additional uncertainties related to neutron-flux normalization, experimental positioning, board configuration, and Weibull SEU cross-section model (which is a simplified representation of the response function of a device) may also contribute. Because these effects are coupled, the present comparison should not be interpreted as a detailed validation of the JET neutron field. Rather, the fact that the experimental points are within about a factor of two of the simplified simulation confirms that our simulation approach appears suitable for providing a first-order estimate of the SER behavior of a given SRAM technology behind concrete shielding in the context of nuclear fusion. Such an approach could provide a rapid order-of-magnitude estimate of the SER value of circuits in a given radiation environment representative of nuclear fusion facilities.

5. Conclusions

This work investigated the transport of 14 MeV fusion neutrons through ordinary concrete slabs and their impact on neutron-induced soft-error rates in advanced CMOS SRAM technologies. The study was motivated by the fact that future fusion facilities will require a large number of electronic systems for diagnostics, monitoring, control, and safety functions, some of which may be located in shielded but still neutron-exposed areas. In such environments, 14 MeV D–T neutrons can penetrate deeply into structural and shielding materials and may induce single-event effects in electronic devices through secondary charged particles generated by neutron interactions in semiconductor materials and device packaging.

Monte Carlo simulations performed with MCNP and cross-checked with Geant4 showed that concrete shielding does not simply reduce the neutron flux by exponential attenuation. Instead, neutron transport through concrete produces a strong redistribution of the neutron energy spectrum. As the slab thickness increases, the uncollided ballistic component close to 14 MeV decreases rapidly, whereas multiply scattered neutrons form a build-up contribution. This leads to the emergence of intermediate-energy and thermal neutron populations in addition to the remaining high-energy tail. For thin slabs, the transmitted spectrum remains dominated by fast neutrons close to the source energy, whereas for thicker slabs the spectrum becomes increasingly shaped by moderation, scattering, absorption, capture, backscattering, and leakage.

The analysis demonstrated that these spectral modifications are essential for assessing the reliability of electronics behind concrete shielding since the SER depends on the convolution of the transmitted neutron spectrum with the energy-dependent SEU cross-section of the considered device. Consequently, two given devices exposed to the same shielded neutron field may exhibit different SER trends depending on their sensitivity to fast, intermediate-energy, or thermal neutrons. In the present work, the 65 nm bulk CMOS SRAM was mainly controlled by the fast-neutron contribution, whereas the 40 nm bulk CMOS SRAM showed a stronger contribution from moderated low-energy neutrons. This result illustrates that shielding can reduce the total neutron flux while simultaneously producing spectral components that remain relevant for soft-error production. For the incident neutron flux of $10^6 \text{ n cm}^{-2} \text{ s}^{-1}$ considered here, the simulated SER curves have been used to derive indicative minimum shielding thicknesses of concrete. For example, reducing the SER below 10^3 FIT/Mbit requires a thickness of approximately 65–70 cm for the 65 nm SRAM and 95–100 cm for the 40 nm SRAM. Reaching 10 FIT/Mbit requires a thickness of about 135–140 cm and 155–160 cm, respectively. However, these values should not be used as universal shielding design criteria since they depend on the incident neutron flux and the SEU cross-section of the device in question. Rather, they demonstrate how the proposed methodology can be used to determine the required shielding thickness for a given radiation environment, device technology, and allowable SER threshold.

The comparison with SRAM measurements performed during the JET D–T campaign further supports the relevance of this approach. Although the simplified slab model cannot reproduce the full complexity of the JET building, source distribution, angular neutron field, and material heterogeneity, the simulated SER values were found to be consistent with the experimental results at the order-of-magnitude level. This indicates that coupling Monte Carlo neutron-transport calculations with device-specific SEU cross-sections can provide useful first-order estimates of neutron-induced SER in shielded fusion environments.

The quantitative conclusions of this study are limited to the idealized configuration considered here: a quasi-one-dimensional homogeneous ordinary-concrete slab irradiated by normally incident 14 MeV neutrons. The results are therefore directly relevant to first-order estimates for slab-like walls or shielding barriers, but they should not be directly extrapolated to complex fusion-plant buildings without additional transport calculations. In realistic buildings, penetrations, ducts, cavities, air gaps, non-planar geometries, and multi-layer shielding systems may significantly modify both the neutron fluence and the transmitted spectrum. The main contribution of this work is thus the proposed methodology: coupling Monte Carlo neutron-transport simulations with device-specific SEU cross-sections to assess shielding-induced SER changes. For practical fusion-plant shielding design, this methodology must be applied to facility-specific three-dimensional models, including the actual source, geometry, materials, penetrations, and electronics locations.

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