JEITA

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JEITA SER Testing Guideline

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JEITA SER Testing Guideline

1. Scope

This document shows the guideline of estimation and testing method of soft error caused by cosmic ray and radiation from semiconductor materials. This guideline is applied for semiconductor memory devices such as SRAM and DRAM. The purpose is described below.

(1) Propose important testing methods of soft error.
(2) Recommend estimation methods for SER in accelerated tests and simulations.
(3) Recommend basic numerical values to estimate SER in accelerated tests and simulations.
(4) List up irradiation facilities in JAPAN.

2. Terms and Definitions

(1) Alpha source flux

The number of alpha particles crossing the alpha source surface in any direction per unit area per unit time. (typical units: particles/cm^2/hr)

(2) ASER (Accelerated Soft error Rate)

Soft error rate at accelerated test.

(3) Alpha source activity

The number of alpha particle decays in the alpha source per unit time.
(typical units: Becquerel (Bq) and Curie (Ci)) (JESD89)

(4) Critical charge (Q_c)

The minimum amount of charge that when collected at any sensitive node (array or support circuit) will cause the node to change state. (JESD89)

(5) DUT (Device under test)

Device Under Test.

(6) ECC

Error Correction Code, sometimes called Error Detection and Correction (EDAC). (JESD89)

(7) FIT (Failure In Time)

One FIT is one failure in 1E9 device-hours. (JESD89)

(8) Fluence

The particle flux integrated over the time required for the entire run, expressed as particles/cm^2. (JESD89)

(9) Flux

The number of particles passing through a one square centimeter area per unit time (particles/cm^2/s). (JESD89)

(10) Hard error

A permanent circuit or device failure. The error is “hard” because the data is lost and the circuit/device no longer functions properly, even after power reset and re-initialization.

(11) MCU (Multi-Cell Upset)

Multiple bit soft errors at one event.

(12) MBU (Multi-Bit Upset)

Multiple bit soft errors in a same word at one event.

(13) Mono-energy neutron

Neutron beam with a sharp flux peak without any noisy component.

(14) Nucleon

Proton and neutron.

(15) Process

The manufacturing steps and methodologies used to fabricate an integrated circuit. (JESD89)

(16) Product

A complete integrated circuit sold to satisfy a particular customer. (JESD89)

(17) Quasi-mono energy neutron

Neutron beam with a sharp flux peak at a certain energy with lower flux ‘tail’ in the lower energy range.

(18) Sensitive volume

A region, or multiple regions, of a device from which deposited charge can be collected by device nodes, in such a manner as to produce SEU/SER. (JESD89)

(19) Single-event upset (SEU)

An event that induces a data error or upset in which the state of a latch or memory cell is reversed (one to zero, or vice versa). (JESD89)

(20) Single-event Transient (SET)

An event to be recovered during operation continuation among events that induce a data error or upset in which the state of a latch or memory cell is reversed.

(21) Soft error

An SEU in a latch or memory cell that can be correctly rewritten. The error is “soft” because the circuit itself is not permanently damaged and behaves normally after the data state has been restored. (JESD89)

(22) Soft error rate (SER)

The rate that soft errors are occurring. (JESD89)

(23) SSER (System Soft error Rate)

Soft error rate at the ground. no radiation source present other than what is there naturally.

(24) Static Soft error

An error which is sustained during repeated reading alone, but is corrected by re-writing without the removal of power. (JESD89)

(25) White neutron

Neutron beam with broad energy range of typically more than tens MeV.

3. Test Method

3.1 Field test

3.1.1 General

Various field test methods are summarized in **Table 3-1**. In a field test, SER is obtained by measuring number of failures in devices operated in the actual use condition. A large number of devices and special test equipment are necessary. Generally, field tests are continued for an extended period of more than several months. System-SER (SSER) is obtained using the following equation.

$$\mathrm{SSER} = \frac{\text{\# of fail events}}{\text{\# of devices} \times \text{time [h]}} \times 10^9\ \text{[FIT]}$$

Table 3-1 Summary of field test methods

Test Item	Method	Radiation		
		Thermal neutron	High energy neutron	Alpha particle
Standard test	Real use condition	SER_t	SER_h	SER_α
Thermal neutron shield test	Covered with shield sheet		SER_h	SER_α
Cosmic ray shield test	Underground			SER_α

SER_t : SER induced by thermal neutron

SER_h: SER induced by high energy neutron

SER_α: SER induced by alpha particle

3.1.2 Standard Test

A large number of devices, typically from hundreds to thousands, are tested for several months in the actual use condition. The SSER is valid only at the location and period measured since it depends largely on the altitude, geomagnetic latitude, shielding conditions (typically buildings nearby), and solar activity. Corrections are necessary to estimate SSER at different places or periods based upon the measured data (See **5.2.4** Altitude correction and **5.2.5** Geographic correction).

3.1.3 Thermal Neutron Shield Test

SER other than the thermal neutron-induced SER is obtained by using thermal neutron shield. Materials containing ^{3}He, ^{6}Li, ^{10}B, ^{113}Cd, ^{157}Gd nuclei are useful to shield thermal neutron because these nuclei have large absorption cross section for thermal neutrons. Boron-nitride containing silicon rubber sheet is available on the market which absorbs more than 99% of thermal neutrons with thickness of 2mm.

3.1.4 Underground Test

The underground test shielded from cosmic rays is useful to obtain only alpha particle-induced SER. The depth of the test site should be reported. It is desirable to measure neutron flux at the test site.

3.2 Accelerated test

3.2.1 General

The field test requires a large number of DUTs and test periods of months or years so that its availability is very limited and accelerated tests are strongly recommended to obtain basic SEU data in a short period of time. Mono energy proton, (quasi-) mono energy neutron and white neutron are used for the accelerated tests to simulate nuclear spallation reaction by which a nucleus in the DUT is broken to some secondary light particles and a residual nucleus.

Various accelerated test methods are summarized in **Table 3-2**. In an accelerated test, devices are irradiated with a specific high intensity radiation using radioisotopes, particle accelerators or nuclear reactors. It requires only a few devices and a short period of time. Accelerated-SER (ASER) is calculated from the following equation. Fluxes of radiation both in the accelerated tests and in the actual use conditions should be known.

$$\text{ASER} = \frac{\text{\# of fail events}}{\text{\# of devices} \times \text{time [h]} \times \text{acceleration factor}} \times 10^9 \text{ [FIT]}$$

Table 3-2 Summary of accelerated test methods

Test Item	Method	Radiation		
		Thermal neutron	High energy neutron	Alpha particle
Thermal neutron	Nuclear reactor	SER_t		
	^{252}Cf			
High energy neutron	White neutron		SER_h	
	Mono-energy neutron			
Alpha particle	^{238}U, ^{232}Th, ^{210}Po, ^{241}Am			SER_α

SER_t : SER induced by thermal neutron

SER_h: SER induced by high energy neutron /proton

SER_α: SER induced by alpha particle

3.2.2 Accelerated Test for Alpha Particle

3.2.2.1 Device

The mold compound of the DUT should be etched off to expose the surface of the chip. Test should be performed at the typical operating voltage (V_{dd}) and at the typical frequency of the device. At least two devices from different lots should be tested to evaluate the SER variation among lots.

3.2.2.2 Alpha source

In order to estimate SER induced by alpha particles from mold compound, ^{238}U or ^{232}Th source are preferable. However, since the use of these sources is restricted in Japan, ^{241}Am source can be used as a substitute. ^{210}Po or ^{241}Am are preferable to simulate alpha particles from Pb-solder bumps.

3.2.2.3 Distance between alpha particle source and DUT

Distance between the source of alpha particle and DUT is desirable to be less than 1mm in order to reduce energy loss of alpha particle in air, and to simulate actual angular distribution. If it is difficult to make the distance less than 1mm due to geometrical reason, it is allowed to estimate SER by extrapolation in data of the distance dependence.

3.2.2.4 Emission rate of alpha particle

Alpha particle sources available on the market are usually indicated only their activities [μCi](1), and the emission rates of alpha particle [α/cm^2/hour] are seldom indicated. The emission rate can not be determined simply from the activities because of the effects of absorption of alpha particle in the source itself and the housing. For example, the activity of 1μCi is 3.7e4 decays/sec, however, the alpha emission rate from the source would be less than 3.7e4 α/sec. Therefore, it is desirable to measure the alpha emission rate of the source used in the SER test.

3.2.2.5 Note on using ^{241}Am

Results from the ^{241}Am test should be used only for the relative comparison such as operation voltage dependence, and should not be used to predict absolute value of SER. It is considerably difficult to predict absolute value of SER from accelerated test using ^{241}Am because the energy spectrum of alpha particle from ^{241}Am is different from that of ^{238}U or ^{232}Th. Characteristic energies of alpha particles emitted from ^{241}Am and ^{238}U decay series are summarized in **Table 5-4-1** to **Table 5-4-5**. Furthermore, each ^{241}Am source has different energy spectra of alpha particle due to difference of shape of housing, thickness of window, etc. It is desirable to measure the energy spectrum of alpha particle for each source.

3.2.3 Accelerated Test for Thermal Neutron

3.2.3.1 Thermal neutron-induced soft error

The main cause of the thermal neutron-induced soft error is the thermal neutron capture reaction by ^{10}B nuclei and subsequent nuclear fission, $n + {}^{10}B \rightarrow {}^{7}Li + \alpha + \gamma$. A 1.47MeV alpha particle and a 0.84MeV Li nucleus are emitted in this reaction, and their ranges in Si are 5.1μm and 2.5μm, respectively. These particles could induce soft errors by producing electron-hole pairs in the sensitive volume of the device. BPSG dielectric layer is the main source of ^{10}B, and the thermal neutron-induced soft error can be reduced to one of several hundreds by eliminating the BPSG layer.

3.2.3.2 Device

Test should be performed at the typical operating voltage (V_{dd}) and at the typical frequency of the device. At least two devices from different lots should be tested to evaluate the SER variation among lots. The mold compound of the DUT does not needed to be etched off because the range of thermal neutron in the device is long enough.

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(1) 1 Ci = 3.7×10^{10} Bq

3.2.3.3 Thermal neutron source

(1) Nuclear reactor

Extremely intense thermal neutron can be obtained by using a nuclear reactor. The acceleration factor of greater than 1 × 10^{10} can be easily obtained. However, facilities are limited, and the test becomes a large-scale project. It is necessary to confirm that the gamma ray contamination in the thermal neutron is negligible small for the SER measurement by monitoring the gamma ray flux.

(2) ^{252}Cf source

The test setup is simple in case of using ^{252}Cf source, however, the thermal neutron flux is relatively low compared to that at nuclear reactors. It is necessary to retard neutron energy from ^{252}Cf using a moderator such as paraffin.

3.2.3.4 Thermal neutron flux measurement

Thermal neutron flux should be measured or calculated in any methods using a nuclear reactor or a ^{252}Cf source. Radioactive analysis and measurements using a proportional counter are the common methods to measure thermal neutron flux. The method of measurement or calculation of thermal neutron flux should be in the final report.

3.2.3.5 Thermal neutron shield test

It is recommended to measure the SER of a device covered with a thermal neutron shield sheet as described above. It is useful to know the contribution of SER induced by other radiations than thermal neutrons, e.g. gamma rays and fast neutrons.

3.2.4 (Quasi-) mono energy test

3.2.4.1 Apparatus

Mono energy proton is obtained directly from a high energy accelerator, typically cyclotron. DUTs can be irradiated in the atmospheric environment by proton beam which comes out through a foil at the end of the vacuum beam line. Care must be paid the attenuation of the energy and broadening of the beam line by scattering in the DUT itself. Normally, energy more than 20MeV is required to penetrate deep enough to the sensitive volume in the DUTs. Mono-energy proton beam is beneficial for its high flux but handling is rather difficult compared to neutron beam.

Mono-energy neutron which has a sharp flux peak at a certain energy of neutron energy is obtained by utilizing a specific nuclear reaction channel.

(Quasi-) mono energy neutron is produced typically by prompt (p,n) intra-nuclear reaction in which a neutron directly knocked-on by a bombarded proton is released from target nucleus. The neutron released in forward direction has almost the same energy as bombarded. The most popular target is ^{7}Li-plate of a few mm thick. Quasi-mono energy neutron is obtained by ^{7}Li(p,n)^{7}Be nuclear reaction.

Typical flux is in the order of 10^4 to 10^5n/cm^2/s, which is much higher than in the environment by a factor of 10^6 to 10^7.

3.2.4.2 Measurement

The neutron spectrum has to be measured at the very close timing (if possible in-situ) of the irradiation test. The differential neutron fluence (neutron/cm^2/MeV) at the DUTs has to be measured or estimated accurately as a function of neutron energy. The recommended energy range to be measured is from 1 or a few MeV to maximum neutron energy applied. Care should be taken for the uniformity of the neutron flux on the DUT boards. Attenuation of neutron flux by the boards themselves is also to be evaluated. Typical neutron spectra are shown in **Fig. 3-1** for FNL [3-1], CYRIC [3-2] at Tohoku University, TSL of Uppsala University [3-3] and RCNP of Osaka University [3-4]. The peak neutron energies are taken as the tested energies. It is recommended to make numerical simulations to estimate necessary test duration beforehand if such a numerical simulator is available. As for quasi-mono energy neutron spectrum, there are spectrum tails in the lower range of the energy and their contribution to total errors must be eliminated or corrected. Such corrections can be carried out by an iterative method based on experimental data at several different energies [3-4] or numerical simulation [3-5] if available.

The SEU cross section σ (E_n) can be calculated from the number of errors N_{err} and total fluence Ψ for the tested energy E_n.

$$\sigma(E_n) = \frac{N_{err}(E_n)}{\Psi(E_n)} \quad \cdots\cdots\cdots \quad (3\text{-}1)$$

Total fluence may be calculated from flux ϕ and test duration T as

$$\Psi(E_n) = \phi(E_n) \times T \quad \cdots\cdots\cdots \quad (3\text{-}2)$$

only when the flux is very stable, which is not the case in many facilities, so that integrated dosimetry for fluence is recommended.

The shapes of σ (E_n) for memory devices are quite similar to each other with different threshold energy E_{th} and saturation level σ_∞ [3-6, 3-7].

Neutron energies below 20MeV is recommended for test energy to identify or estimate the threshold energy E_{th} where σ (E_n) shows sharp increase. Some energy points between 20 to 70MeV are recommended as test energies to identify the shape of the curvature approaching the saturated cross section at higher energies. Energies from 70MeV to over 100MeV are recommended as test energy to identify or estimate the saturation level.

3.2.4.3 Estimation

Soft error rates for any given spectrum are recommended to be estimated from the measured SEU cross sections in the following manner:

First, make an SEU approximation function σ_{appx} (E_n) as a function of energy by fitting test data. The following Weibull Fit is often used as σ_{appx} (E_n) (for other methods, see **APPENDIX A.3**) [3-8].

$$\sigma_{appx}(E_n) = \sigma_\infty \left[1 - \exp\left\{ - \left(\frac{E - E_{th}}{W} \right)^S \right\} \right] \quad \cdots\cdots\cdots \quad (3\text{-}3)$$

where σ_∞ is saturated SEU cross section for higher energy (usually beyond 70-100MeV), *W* is width factor, and *s* is shape factor. Then, the SER for any given neutron spectrum can be obtained by

$$SER = \int_{E_{th}}^{E_{\max}} \frac{\partial \phi(E)}{\partial E} \sigma_{appx}(E)dE \quad \text{..........} \quad (3\text{-}4)$$

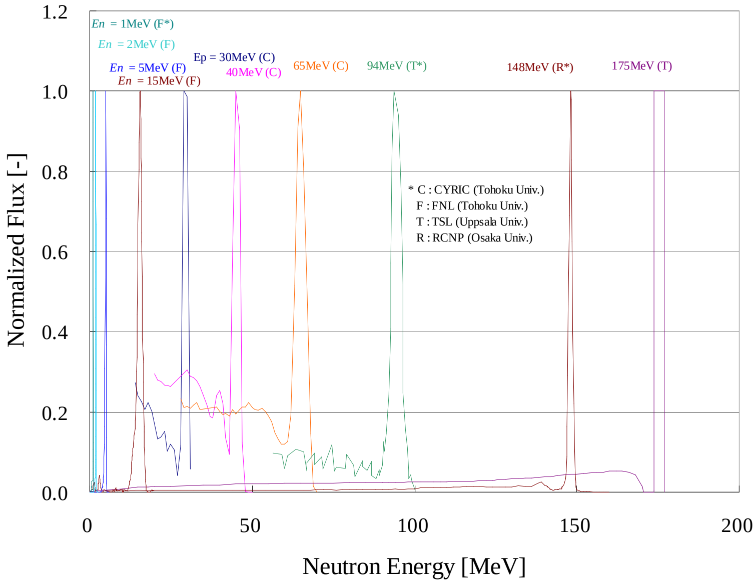


Fig. 3-1 Energy Spectra of (Quasi-) Mono Energy Neutron

3.2.5 White neutron test

3.2.5.1 Apparatus

White neutron spectrum can be obtained by bombarding high energy protons at relatively thick target of typically tungsten or lead, which may simulate terrestrial neutron spectrum at the ground. The beam line 4FP30L at Los Alamos Neutron Science Center (LANSCE) is widely known and used as such a neutron source [3-9]. As shown in **Fig. 3-2**, the neutron spectrum in the beam line is well defined over 1MeV by the combination of a fission chamber and a TOF (Time Of Flight) system [3-10]. The neutron flux is in the range of as high as 10^6n/cm^2/s. The white neutron beam line at Research Center for Nuclear Physics (RCNP) has been in operation since 2004. A neutron beam with flux of 6 × 10^5n/cm^2/s is available using a 400MeV proton beam. The neutron energy spectrum is shown in **Fig. 3-3**, which was measured by a TOF method using liquid scintillators.

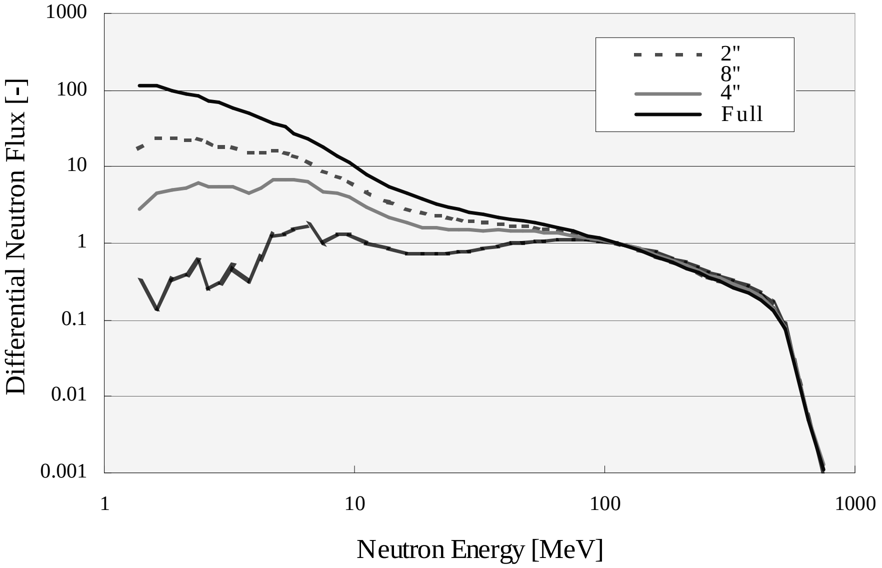
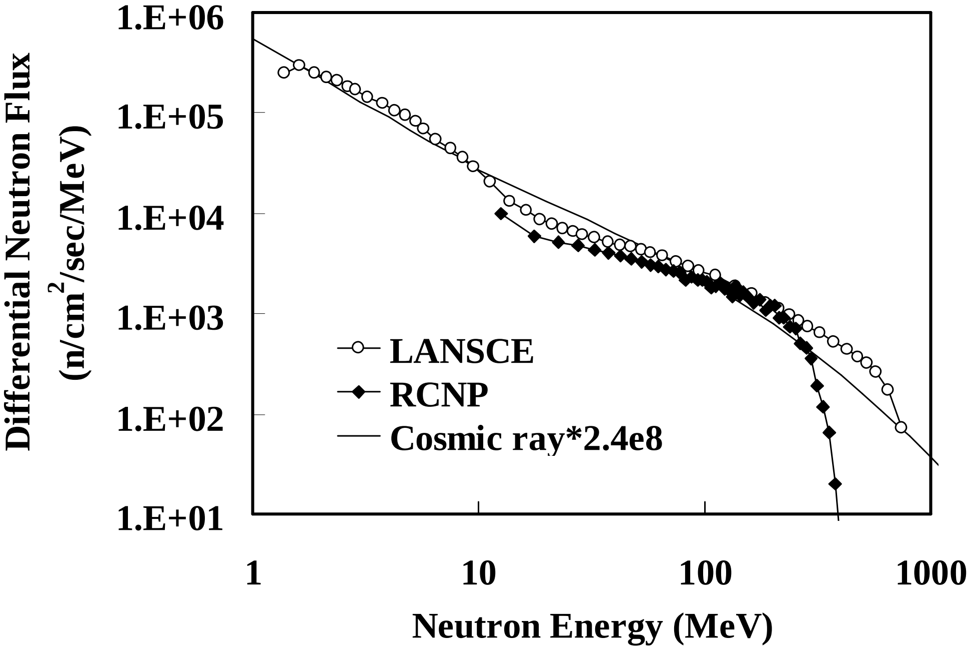


Fig. 3-2　Typical White Neutron Spectra with Different Shield (polyethylene) Thickness



Remarks: Cosmic ray spectrum is quoted from JESD89.

Fig. 3-3　Typical neutron flux at RCNP

3.2.5.2 Measurement and estimation

The set-up of DUTs and measuring system are the same as the other accelerated tests.

The effective SEU cross section σ_{eff} over the specific range of energy can be defined as follows:

$$\sigma_{eff} = \frac{N_{err}}{\Phi(E_{\min}, E_{\max})} \quad \cdots\cdots \quad (3\text{-}5)$$

where, N_{err} is total number of errors counted per device, and Φ (E_{min}, E_{max}) is total fluence in the energy range from E_{min} to E_{max}. On the condition that the shape of white neutron spectrum is close enough to the field spectrum, SSER can be estimated by

$$SSER = \sigma_{eff}\phi_{field}(E_{\min}, E_{\max}) \quad \cdots\cdots \quad (3\text{-}6)$$

where ϕ_{field} (E_{min}, E_{max}) is the neutron flux in the field (n/cm^2/s).

3.2.5.3 Facilities

LANSCE (USA), CERN-EU High-Energy Reference Field (CERF; CERN, Switzerland) [3-11] and RCNP (Japan) [3-11] and TRIUMF are facilities currently known as white neutron source which simulates terrestrial neutron spectrum.

3.2.6 Report

Items below are to be included in SER report.

(a) Test circumstance (shielding material, board angular orientation, location of board)
(b) Test condition (Core voltage, I/O voltage, cycle time, temperature)
(c) Operation mode (Dynamic mode, Battery back up mode, stand by mode)
(d) Data pattern (All 0, All 1, Checkerboard etc.)
(e) Test sequence (Write-Read-Write-(repeat)…, Write-Read-Read-(repeat))
(f) Redundancy status (ECC, without ECC, refresh mode)
(g) Error information (SEU, MCU, MBU, fail address, I/O, fail date and time, board location, cumulative duration etc.)

References for Sec. 3

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[3-11] http://tis-div-rp-cerf.web.cern.ch/tis-div-rp-cerf/

4. SER Estimation Method

4.1 Simple estimation method of high-energy-neutron-induced SER

Soft error rate (SER) estimation method is indispensable to predict SER at the circuit design stage. In this section, simple estimation method for high-energy-neutron-induced SER (called *BGR* model) is introduced. SER simulation method for high-energy-neutrons, thermal neutrons, and alpha-particles are described in **APPENDIX**.

Several types of *BGR* (Burst Generation Rate) model for simple estimation of high-E neutron-induced SER were proposed [4-1] [4-2] [4-3] [4-4]. Most convenient form of *BGR* model equation is given by [4-4]

$$SER = V \cdot N \cdot BGR(d; Qc) \quad \cdots\cdots \quad (4\text{-}1)$$

BGR : Burst generation rate ($\mathrm{cm}^2/\mu\mathrm{m}^3$)

Q_c : Critical charge (fC)

d : Sensitive depth (μm)

V : Sensitive volume ($\mu\mathrm{m}^3$)

N : Neutron flux ($\mathrm{n/cm}^2$/hour, E > 10MeV)

The burst generation rate *BGR* (Q) indicates the rate of neutron-nuclear reactions induced by an incident neutron with charge deposited of greater than Q in a unit volume.

The simple way to determine the parameter *V* is to choose a rectangular parallelepiped as the sensitive volume with dimensions that were determined by the junction area plus the depletion area for the lateral direction (only the junction area for the technology using STI (Shallow Trench Isolation)) and the funneling length for the sensitive depth d. The funneling length is given by [4-5].

$$d = W\left(1+\beta \frac{N_0}{N_0 + N_A}\right) \quad \text{..} \quad (4\text{-}2)$$

where W is the depth of the junction plus the depletion width, and values of constants of β and N_0 are 1.95 and 8.27 × 10^{17}(cm^{-3}) for the n^+ diffusion layer and 0.68 and 1.70 × 10^{18}(cm^{-3}) for the p^+ diffusion layer. Estimation of Q_c is given in Sec. **4.2**.

Neutron-induced SERs can be easily estimated using Eq. (4-1) together with **Table 4-1**. As an example, we consider a 0.5μm × 0.5μm junction, which is an nMOSFET drain area in an arbitrary circuit. We assume a dopant concentration of 1.0 × $10^{20}$$cm^{-3}$ for the n^+-layer and of 3.0 × $10^{17}$$cm^{-3}$ for the p-substrate, and the depth of n^+-layer as 0.15μm. We also assume a supply voltage of 2.5V and a node capacitance of 5fF. The critical charge is then estimated as 12.5fC. We obtain a depletion width of 0.12μm by using the depletion approximation for an abrupt junction and obtain a funneling length of 0.66μm by employing Eq. (4-2). We then obtain a sensitive depth of 0.66μm and a sensitive volume of 0.17μm^3. Using a sea level neutron number of 14n/cm^2/hour (which is the value for New York), the neutron-induced SER according to Eq. (4-1) and **Table 4-1** is

$$\text{SER} = 0.17\mu m^3 \times 14\ n/cm^2/hour \times 1.0 \times 10^{-13}\ cm^2/\mu m^3$$

$$= 2.4 \times 10^{-13}\ error/hour.$$

Table 4-1 Numerical values for *BGR* (*d* ; Q_c) [4-6]

Qc	Burst generation rate (cm²/μm³)								
(fC)	d = 0.25μm	0.35 μm	0.5μm	0.7 μm	1.0 μm	1.4 μm	2.0 μm	2.8 μm	5.6 μm
0.2	1.21E-12	1.01E-12	7.79E-13	5.89E-13	4.36E-13	3.29E-13	2.50E-13	1.95E-13	1.26E-13
0.4	8.49E-13	7.33E-13	6.29E-13	5.28E-13	4.14E-13	3.19E-13	2.42E-13	1.89E-13	1.22E-13
0.6	6.92E-13	6.00E-13	5.15E-13	4.50E-13	3.77E-13	3.05E-13	2.35E-13	1.85E-13	1.19E-13
0.8	5.94E-13	5.20E-13	4.48E-13	3.90E-13	3.37E-13	2.85E-13	2.28E-13	1.81E-13	1.16E-13
1.0	5.39E-13	4.61E-13	4.04E-13	3.50E-13	3.05E-13	2.64E-13	2.19E-13	1.77E-13	1.14E-13
1.5	4.45E-13	3.84E-13	3.27E-13	2.90E-13	2.51E-13	2.21E-13	1.92E-13	1.64E-13	1.09E-13
2.0	3.83E-13	3.36E-13	2.88E-13	2.50E-13	2.21E-13	1.94E-13	1.70E-13	1.50E-13	1.05E-13
2.5	3.42E-13	3.00E-13	2.61E-13	2.27E-13	1.97E-13	1.76E-13	1.54E-13	1.37E-13	1.01E-13
3.0	3.14E-13	2.72E-13	2.39E-13	2.09E-13	1.80E-13	1.61E-13	1.42E-13	1.27E-13	9.69E-14
3.5	2.94E-13	2.52E-13	2.20E-13	1.95E-13	1.69E-13	1.50E-13	1.33E-13	1.18E-13	9.29E-14
4.0	2.77E-13	2.36E-13	2.05E-13	1.83E-13	1.59E-13	1.40E-13	1.26E-13	1.12E-13	8.89E-14
4.5	2.63E-13	2.24E-13	1.93E-13	1.73E-13	1.51E-13	1.33E-13	1.19E-13	1.07E-13	8.54E-14
5.0	2.51E-13	2.14E-13	1.83E-13	1.63E-13	1.44E-13	1.27E-13	1.13E-13	1.02E-13	8.23E-14
6.0	2.31E-13	1.96E-13	1.67E-13	1.48E-13	1.32E-13	1.18E-13	1.04E-13	9.49E-14	7.69E-14
7.0	2.08E-13	1.82E-13	1.56E-13	1.37E-13	1.22E-13	1.10E-13	9.74E-14	8.85E-14	7.25E-14
8.0	1.86E-13	1.70E-13	1.45E-13	1.28E-13	1.13E-13	1.03E-13	9.22E-14	8.33E-14	6.93E-14
9.0	1.67E-13	1.59E-13	1.37E-13	1.20E-13	1.06E-13	9.70E-14	8.77E-14	7.94E-14	6.66E-14
10.0	1.50E-13	1.47E-13	1.29E-13	1.14E-13	1.00E-13	9.16E-14	8.36E-14	7.64E-14	6.44E-14
12.5	1.20E-13	1.19E-13	1.13E-13	1.00E-13	8.85E-14	8.07E-14	7.49E-14	6.96E-14	5.97E-14
15.0	9.70E-14	9.93E-14	9.75E-14	8.91E-14	7.94E-14	7.23E-14	6.76E-14	6.40E-14	5.57E-14
17.5	7.85E-14	8.41E-14	8.39E-14	7.99E-14	7.14E-14	6.55E-14	6.14E-14	5.91E-14	5.24E-14
20.0	6.39E-14	7.19E-14	7.29E-14	7.16E-14	6.47E-14	5.99E-14	5.65E-14	5.48E-14	5.00E-14
22.5	5.19E-14	6.15E-14	6.40E-14	6.40E-14	5.90E-14	5.49E-14	5.22E-14	5.11E-14	4.77E-14
25.0	4.15E-14	5.26E-14	5.66E-14	5.72E-14	5.41E-14	5.05E-14	4.84E-14	4.77E-14	4.56E-14
27.5	3.26E-14	4.52E-14	5.02E-14	5.13E-14	4.96E-14	4.65E-14	4.51E-14	4.47E-14	4.36E-14
30.0	2.54E-14	3.87E-14	4.47E-14	4.63E-14	4.55E-14	4.29E-14	4.20E-14	4.20E-14	4.17E-14
35.0	1.54E-14	2.80E-14	3.54E-14	3.82E-14	3.84E-14	3.69E-14	3.65E-14	3.72E-14	3.81E-14
40.0	1.03E-14	1.96E-14	2.83E-14	3.19E-14	3.27E-14	3.22E-14	3.22E-14	3.34E-14	3.51E-14
45.0	7.58E-15	1.36E-14	2.25E-14	2.68E-14	2.81E-14	2.83E-14	2.85E-14	3.01E-14	3.23E-14
50.0	5.83E-15	9.54E-15	1.77E-14	2.26E-14	2.44E-14	2.50E-14	2.55E-14	2.72E-14	2.99E-14

4.2 Estimation of critical charge

4.2.1 Critical charge for DRAMs

The critical charge Q_c for DRAMs is given by [4-7].

(1) Memory cell Mode

$$Q_c = C_{cell} \cdot V_{dd} / 2 - (C_{cell} + C_{bit}) \cdot \Delta V \quad \text{(4-3a)}$$

(2) Bit line Mode

$$Q_c = C_{cell} \cdot V_{dd} / 2 - (C_{cell} + C_{bit} + C_{SA}) \cdot \Delta V \quad \text{(4-3b)}$$

C_{cell} : Memory cell capacitance
C_{bit} : Bit line capacitance
C_{SA} : Sense amplifier capacitance
V_{dd} : Supplied voltage
ΔV : Minimum voltage difference required by the sense amplifier

In most cases, Q_c is approximated by $C_{cell} \times V_{dd}/2$.

4.2.2 Critical charge for SRAMs

The critical charge Q_c for SRAMs is given by [4-8] (see **Fig. 4-1 (b)**).

$$Q_c = V_{dd}\left(1 + \frac{C_3}{C_2}\right)\left(C_1 + \frac{C_2 \cdot C_3}{C_2 + C_3}\right) \quad \text{(4-4a)}$$

Assuming $C_1 = C_2$,

$$Q_c = V_{dd}(C_1 + 2C_3) \quad \text{(4-4b)}$$

C_1 and C_3 are estimated by using circuit simulations. For estimating high-E neutron-induced SERs, Q_c is approximated as $C_{node} \times V_{dd}$ ($C_{node} \sim C_1 + C_2 . C_3/(C_2 + C_3)$), because the variation of SERs with the change of collected charges is much smaller than for alpha-induced SERs.

More exactly, Q_c for SRAMs is estimated by using circuit simulations (**Fig. 4-1 (a)**). The wave form of a charged particle-induced noise current is, for example, given by eq. (A-2) in **Appendix**. If the nodal voltages changes (V_{high} to V_{low}), the Q_c is determined.

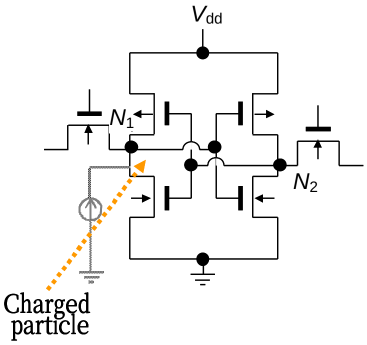

Fig. 4-1 (a) Circuit simulation of an SRAM with an alpha-particle-induced noise current

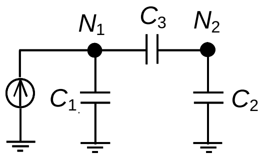

Fig. 4-1 (b) Capacitance model for the SRAM

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5. Numerical Values of radiation

5.1 Basic numerical values of radiation source

The basic numerical values of radiation sources such as high energy neutron, thermal neutron and alpha particle, which are incident on semiconductor devices under using condition are summarized in **Table 5-1**.

Table 5-1 Basic numerical values of radiation source

Source			Flux	Note
High Energy Neutron			< 14/hour.cm^2(*)	10MeV-10,000MeV (JESD89)
Thermal Neutron			< 10/hour.cm^2(*)	[5-8]
Alpha Particle	Mold Resin		< 0.1/hour.cm^2	General
			< 0.001/hour.cm^2	Low Alpha
	Solder Bump	Pb-Sn	>1/hour.cm^2	General
			<1/hour.cm^2	Low Alpha
		Sn-Ag	< 0.02/hour.cm^2	Low Alpha
			< 0.001/hour.cm^2	Ultra Low Alpha
	Inter Layer (Al, Cu)		< 0.002/hour.cm^2	

(*) typical New York City sea-level neutron flux

5.2 High Energy Neutron

5.2.1 Neutron Spectra Measured and Calculated at the Ground level

Terrestrial neutron flux from **JEDEC** Standard is most general to use for SER estimation. However, it has been reported that the SER obtained by using the neutron flux of **JEDEC** standard becomes larger than that of the actual field test results [5-1]. Recent works by Tohoku University show that terrestrial neutron flux from **JEDEC** Standard may be larger than actual measured neutron flux as shown in **Fig. 5-1** [5-2]. Therefore, it is considered that the accuracy of terrestrial neutron flux is a problem. SER estimation from accelerated test should be considered carefully. It is considered to survey terrestrial neutron flux again.

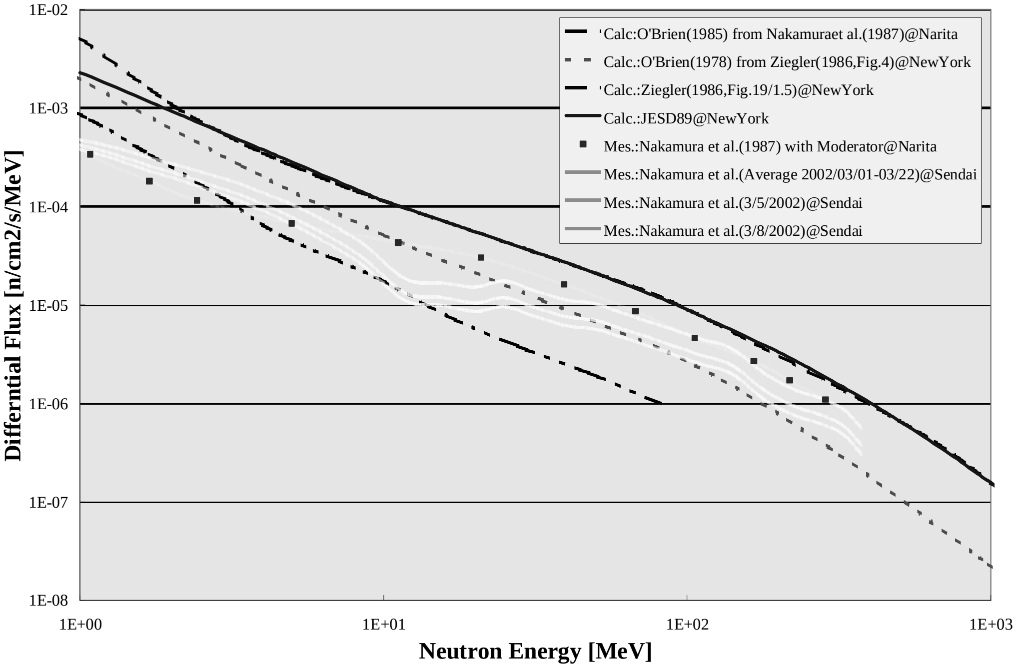
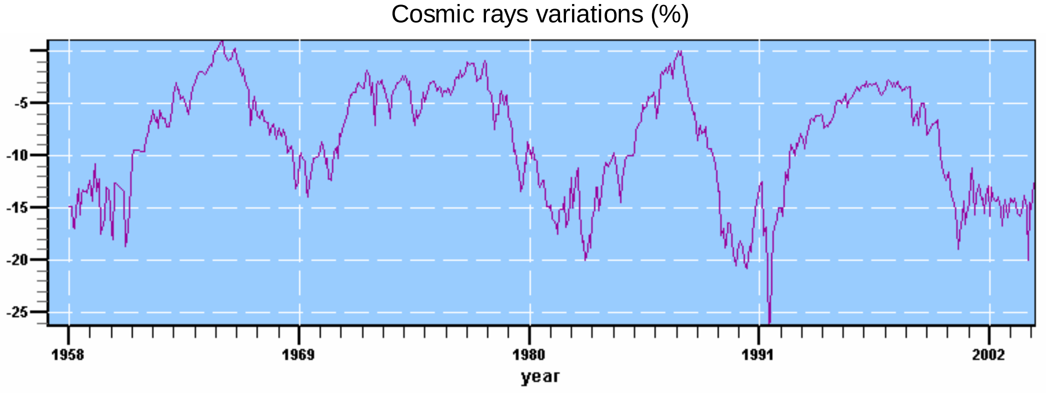


Fig. 5-1 Differential Flux as a function of neutron energy

5.2.2 Variation of Neutron Flux with time

Solar activity has roughly 11 years cyclic changes in time. The long-term and short-term trends in solar activity can be obtained from thermal neutron monitors in the world [5-3, 4, 5]. **Fig. 5-2** shows such typical long-term trend observed in Moscow [5-3]. If field test is carried out for a certain long period of time without any neutron monitor, the total fluence can be corrected based upon the reference flux measured at different time.

The particles from the Sun do not have high energies so that the direct contribution of those particles can be neglected as the origin of SEUs. When energetic solar flare takes place, however, it may affect the field test to create abnormal accumulation of errors. Such occurrence can be monitored in the Space Environment Center [5-6]. If this happened, the data during such period may well be eliminated.



http://cr0.izmiran.rssi.ru/mosc/main.htm

Fig. 5-2 Long-term Trend in Neutron Flux in Moscow

5.2.3 Altitude correction

Since air acts as a shield against high energy neutron, the neutron flux depend on altitude; the higher altitude is, the higher neutron flux is. The altitude correction factor γ is calculated with the following equation.

$$\gamma = \frac{\Phi_n}{\Phi_0} = \exp\left[-\frac{A-A_0}{L}\right] \qquad \text{(5-1)}$$

or if reference altitude is sea level,

$$\gamma = \frac{\Phi_n}{\Phi_0} = \exp\left[-\frac{A-1033}{L}\right] \qquad \text{(5-2)}$$

where Φ_n and Φ_0 are neutron flux at the altitude of interest and reference altitude, respectively. A and A_0 are air pressures at relevant altitudes (g/cm^2). L is flux attenuation factor (L = 148g/cm^2 is recommended for neutron [5-7]).

The calculated value for the air pressure A differs according to the formula used. There are two formulae proposed:

$$A = 1033 \times \exp\left[-0.03813 \times (a/300) - 0.00014 \times (a/300)^2 + 6.4 \times 10^{-7} \times (a/300)^3\right] \qquad \text{(5-3)}$$

(NASA-Langley formulation [JESD89])

where a is altitude in meters from the sea level. It is noted that Eq. (5-3) is are valid only for average condition. The value changes depending on daily atmospheric pressure.

5.2.4 Geographic correction

Since environmental neutrons are produced from nuclear spallation reactions between mostly energetic cosmic-ray proton and nuclei (nitrogen and oxygen) in the mesosphere and stratosphere and the protons generally twine around magnetic force lines [5-7], their intensities substantially depend on the geomagnetic locations on the earth. In other words, geomagnetic and heliomagnetic fields act as shields against energetic protons. The strength of shielding is expressed in terms of geomagnetic cut-off rigidity (R_c), which is kinetic energy sufficient to reach the stratosphere. RXY can be calculated based on the **Table 5-2** given by NASA [JESD89]. The rigidity, R_c, for city C is obtained by interpolation with these four rigidity values.

R_c = (1 - p) × (1 - q) × R00 + p(1 - q) × R10 + q(1 - p) × R01 + pq × R11
p = (Z - Lon0) / (Lon1 - Lon0)
q = (Y - Lat0) / (Lat1 - Lat0).

R_c : The rigidity value at city C
Lat0 and Lat1 : The bounding latitudes (Lat0 < The latitude at city C < Lat1) (**Table 5-2**)
Lon0 and Lon1: The bounding longitudes (Lon0 < The longitude at city C < Lon1) (**Table 5-2**)
R00 : The rigidity value at location (Lon0 - Lat0)
R01 : The rigidity value at location (Lon0 - Lat1)
R10 : The rigidity value at location (Lon1 - Lat0)
R11 : The rigidity value at location (Lon1 - Lat1)

The correction factor δ (normalized 1 for R_c = 0) to calculate neutron flux can be estimated from the following equation based on the data in **References for Sec. 5** [5-7].

$$\delta = \begin{cases} -0.0009R_c^{\ 2} - 0.0012R_c + 1.0026 & (R_c < 1.76) \\ -0.0068R_c^{\ 2} + 0.0092R_c + 1.0007 & (1.76 \leqq R_c < 3.37) \\ 0.0006R_c^{\ 2} - 0.0486R_c + 1.1134 & (R_c \geqq 3.37) \end{cases} \quad \cdots\cdots\cdots\cdots \quad (5\text{-}4)$$

Calculated corrections factors are summarized in **Table 5-3** for most important cities in the world [5-12].

Table 5-2 Vertical Rigidity Cutoffs in GV at 20km Altitude, 0-360° Longitude East

Latitude	Logitude East																								
	0	15	30	45	60	75	90	105	120	135	150	165	180	195	210	225	240	255	270	285	300	315	330	345	360
90	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
85	0.03	0.04	0.05	0.06	0.06	0.07	0.07	0.07	0.07	0.07	0.06	0.05	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03
80	0.02	0.04	0.06	0.09	0.09	0.10	0.10	0.11	0.11	0.11	0.08	0.06	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
75	0.10	0.14	0.18	0.20	0.23	0.25	0.25	0.26	0.27	0.28	0.26	0.24	0.20	0.14	0.09	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.07	0.10
70	0.26	0.34	0.41	0.47	0.49	0.51	0.52	0.55	0.59	0.60	0.62	0.56	0.47	0.36	0.23	0.13	0.06	0.00	0.00	0.00	0.00	0.05	0.11	0.18	0.26
65	0.58	0.72	0.80	0.89	0.93	0.97	1.01	1.03	1.12	1.19	1.20	1.13	0.95	0.74	0.53	0.32	0.17	0.09	0.05	0.04	0.08	0.16	0.28	0.42	0.58
60	1.14	1.34	1.46	1.57	1.61	1.67	1.73	1.82	1.95	2.05	2.05	1.99	1.75	1.40	1.00	0.65	0.40	0.22	0.16	0.14	0.21	0.38	0.59	0.86	1.14
55	1.94	2.28	2.47	2.61	2.68	2.78	2.85	2.92	3.12	3.31	3.35	3.15	2.88	2.22	1.75	1.23	0.78	0.50	0.36	0.36	0.46	0.75	1.13	1.59	1.94
50	3.21	3.54	3.81	3.97	4.14	4.27	4.36	4.37	4.68	4.93	4.92	4.67	4.27	3.38	2.81	2.03	1.41	0.95	0.73	0.69	0.89	1.34	1.98	2.65	3.21
45	4.77	5.12	5.36	5.51	5.73	5.90	6.11	6.29	6.57	6.86	6.86	6.33	5.59	4.85	4.08	3.16	2.37	1.74	1.32	1.22	1.49	2.21	3.16	4.20	4.77
40	6.75	7.27	7.48	7.70	8.19	8.73	9.14	9.29	9.49	9.89	9.74	8.95	7.86	6.46	5.41	4.55	3.61	2.76	2.07	1.93	2.42	3.41	4.82	5.92	6.75
35	9.54	9.89	10.10	10.53	11.15	11.44	11.52	11.71	11.93	12.04	11.55	10.60	9.49	8.97	7.65	6.12	5.21	4.25	3.19	2.89	3.58	4.98	6.80	8.70	9.54
30	11.30	11.71	12.13	12.67	13.34	14.07	14.37	14.40	14.26	13.95	13.44	12.72	11.65	10.48	9.63	8.78	7.00	5.60	4.44	4.07	4.87	6.98	9.67	10.60	11.30
25	13.10	13.64	14.10	14.53	15.06	15.58	15.85	15.79	15.49	15.03	14.44	13.76	13.07	12.43	11.81	10.98	9.74	7.89	6.08	5.44	6.56	9.65	11.47	12.46	13.10
20	14.11	14.62	15.09	15.57	16.12	16.63	16.87	16.75	16.37	15.83	15.20	14.55	13.93	13.40	12.91	12.33	11.47	9.69	7.82	6.84	8.65	11.45	12.76	13.54	14.11
15	14.61	15.14	15.65	16.17	16.74	17.25	17.47	17.34	16.93	16.37	15.76	15.17	14.63	14.16	13.76	13.30	12.62	11.27	9.49	8.46	10.71	12.52	13.43	14.07	14.61
10	14.73	15.26	15.80	16.34	16.94	17.44	17.67	17.56	17.18	16.65	16.10	15.61	15.16	14.75	14.39	14.00	13.44	12.55	11.50	11.07	12.16	13.09	13.76	14.25	14.73
5	14.50	14.99	15.52	16.10	16.71	17.22	17.47	17.42	17.11	16.66	16.21	15.83	15.49	15.15	14.82	14.47	14.03	13.41	12.67	12.40	12.78	13.36	13.80	14.11	14.50
0	13.94	14.37	14.87	15.46	16.10	16.62	16.90	16.94	16.73	16.38	16.05	15.81	15.59	15.32	15.03	14.71	14.33	13.06	13.32	12.95	13.05	13.38	13.58	13.69	13.94
-5	13.13	13.45	13.91	14.50	15.14	15.65	15.97	16.10	16.00	15.77	15.58	15.50	15.42	15.25	15.02	14.74	14.41	14.01	13.53	13.14	13.08	13.19	13.15	13.04	13.13
-10	12.11	12.31	12.71	13.29	13.89	14.35	14.68	14.90	14.91	14.80	14.74	14.84	14.94	14.90	14.76	14.55	14.29	13.94	13.51	13.10	12.92	12.82	12.55	12.20	12.11
-15	10.75	10.91	11.23	11.69	12.18	12.70	13.00	13.25	13.25	13.32	13.48	13.78	14.09	14.24	14.24	14.15	13.97	13.69	13.30	12.89	12.59	12.31	11.76	11.15	10.75
-20	9.21	9.06	9.29	9.70	10.21	10.25	10.41	10.65	10.84	10.62	10.74	11.93	12.78	13.19	13.44	13.51	13.46	13.28	12.94	12.53	12.14	11.65	10.73	9.78	9.21
-25	7.55	7.50	7.72	7.88	7.86	7.37	7.08	7.24	7.43	7.71	8.47	9.55	10.22	11.22	12.01	12.63	12.76	12.72	12.46	12.04	11.53	10.74	9.63	8.36	7.55
-30	6.36	6.02	5.86	5.79	5.42	5.23	5.10	5.16	5.19	5.39	5.89	6.58	7.99	9.45	9.43	10.64	11.85	12.00	11.88	11.43	10.75	9.83	8.39	7.09	6.36
-35	5.24	4.59	4.45	4.31	4.07	3.72	3.35	3.32	3.37	3.65	4.10	4.90	5.65	6.54	7.88	9.11	9.58	11.12	11.16	10.67	9.90	8.72	7.16	6.18	5.24
-40	4.29	3.74	3.40	3.21	2.83	2.43	2.08	2.00	2.01	2.21	2.65	3.24	4.11	4.76	5.56	6.65	8.20	9.75	10.18	9.77	8.98	7.61	6.42	5.31	4.29
-45	3.46	2.96	2.53	2.30	1.93	1.53	1.28	1.12	1.11	1.25	1.51	2.04	2.72	3.33	4.24	4.93	5.91	7.83	9.00	8.76	7.84	6.91	5.63	4.32	3.46
-50	2.87	2.37	1.95	1.60	1.27	0.94	0.66	0.54	0.53	0.60	0.84	1.15	1.63	2.24	2.94	3.76	4.48	5.57	7.02	7.57	6.98	5.68	4.51	3.50	2.87
-55	2.23	1.79	1.42	1.12	0.87	0.53	0.34	0.23	0.21	0.26	0.38	0.59	0.90	1.38	1.88	2.64	3.38	4.20	4.96	5.19	5.02	4.45	3.67	2.93	2.23
-60	1.78	1.32	1.03	0.75	0.49	0.30	0.15	0.08	0.06	0.08	0.14	0.27	0.48	0.79	1.18	1.62	2.23	3.00	3.77	3.95	3.97	3.52	2.88	2.27	1.78
-65	1.30	0.98	0.72	0.50	0.30	0.15	0.06	0.00	0.00	0.00	0.03	0.11	0.23	0.43	0.71	1.06	1.51	1.98	2.53	2.71	2.72	2.50	2.10	1.61	1.30
-70	0.89	0.64	0.47	0.31	0.18	0.08	0.00	0.00	0.00	0.00	0.00	0.03	0.10	0.22	0.41	0.64	0.96	1.24	1.58	1.75	1.80	1.67	1.39	1.14	0.89
-75	0.59	0.43	0.30	0.19	0.10	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.12	0.23	0.36	0.54	0.72	0.91	1.02	1.03	1.05	0.88	0.76	0.59
-80	0.37	0.28	0.19	0.13	0.07	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.08	0.13	0.21	0.30	0.40	0.48	0.55	0.56	0.54	0.49	0.42	0.37
-85	0.29	0.24	0.20	0.17	0.14	0.12	0.10	0.10	0.10	0.10	0.10	0.10	0.12	0.14	0.17	0.21	0.25	0.30	0.34	0.38	0.38	0.37	0.35	0.31	0.29
-90	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21

Table 5-3 Calculated Correction Factors in Cities of the World

City Name	Latitude (north +, south -)	Longitude (east + only)	Altitude (m)	Rc (GV)	Altitude correction (NASA-Langley)	Geomagnetic correction (-)
Tokyo	35.70	139.80	0.00	11.60	1.00	0.63
Sendai	38.30	140.90	61.00	10.52	1.06	0.67
San, Jose	37.41	238.07	2.00	4.56	1.00	0.90
New York	40.70	286.00	1.00	1.86	1.00	0.99
Uppsala	59.90	17.60	6.00	1.38	1.01	1.00
Paris	48.50	2.20	34.00	3.73	1.03	0.94
London	51.50	0.00	16.00	2.83	1.01	0.97
Roma	41.90	12.50	15.00	6.38	1.01	0.83
Honolulu	21.30	202.10	5.00	12.90	1.00	0.59
Stuttgart	48.77	9.18	414.00	3.80	1.43	0.94
Singapore	1.00	103.00	1.00	17.03	1.00	0.46

5.2.5 Shielding Effect of Concrete

Shielding effect of the building where the system is located should be considered. But usually attenuation length of concrete depend on component of materials. For our convenience, 216g/cm^2 as attenuation length of concrete is reasonable to use [5-7].

NF/NF0 = exp (-D/L)

NF : Neutron Flux inside building
NF0: Neutron Flux outside building
D : Thickness of concrete
L : Attenuation length of concrete 216g/cm^2

5.3 Thermal Neutron

5.3.1 Thermal Neutron at the Ground

Thermal neutron flux drastically increases by the interaction of cosmic ray with materials such as building or ground as shown in **Fig. 5-3-1** [5-10]. Hence, it is difficult to estimate the actual thermal neutron flux. However, a standard value of thermal neutron flux should be defined to estimate SER as follows. Thermal neutron flux in New York City is defined as 10n/hour/cm^2 [5-8, 9].

5.3.2 Altitude and Geographic correction

It is defined approximately that the altitude and geographic correction of thermal neutron flux are the same as these of high energy neutron flux. **Fig. 5-3-2** shows a summary of the SERs from various field tests [5-9]. All data were corrected taking account of altitude and location. High altitude and sea level data are well consistent, which means that these corrections are appropriate.

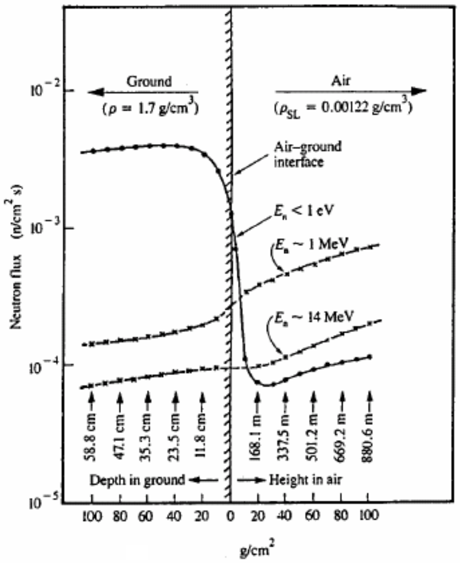


Fig. 5-3-1 Interaction of cosmic ray with materials

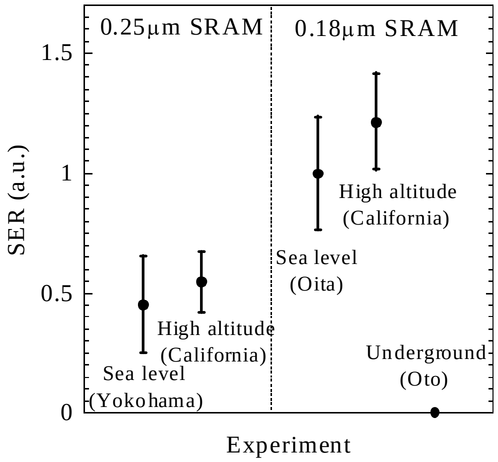


Fig. 5-3-2 SERs from various field tests

5.4 Alpha Particle from alpha source

5.4.1 Alpha Particle spectra

Characteristic energies of alpha particles emitted from Americium and Uranium, Thorium, Actinium series and Neptunium series are summarized in **Table 5-4-1**, **Table 5-4-2**, **Table 5-4-3**, **Table 5-4-4** and **Table 5-4-5** respectively.

Table 5-4-1 Alpha particles from ^{241}Am

Alpha energy (MeV)	Decay ratio
5.486	85.2%
5.443	13.1%
5.388	1.33%

Table 5-4-2
Alpha particles from Uranium series

Nucleus	Half life	Alpha energy (MeV)
^{238}U	4.47 x 109 y	4.197 (77%)
^{234}Th	24.1 d	β
^{234}Pa	6.75 h	β
^{234}U	2.45 x 105 y	4.775 (73%)
^{230}Th	7.7 x 104 y	4.688 (76%)
^{226}Ra	1600 y	4.784 (95%)
^{222}Rn	3.82 d	5.490 (100%)
^{218}Po	3.05 m	6.002 (100%)
^{214}Pb	26.8 m	β
^{214}Bi	19.8 m	β
^{214}Po	164 us	7.687 (100%)
^{210}Pb	22.3 y	β
^{210}Bi	5.01 d	β
^{210}Po	138 d	5.304 (100%)
^{206}Pb	stable	

Table 5-4-3
Alpha particles from Thorium series

Nucleus	Half life	Alpha energy (MeV)
^{232}Th	1.41 x 1010 y	4.013 (77%)
^{228}Ra	5.77 y	β
^{228}Ac	6.13 h	β
^{228}Th	1.91 y	5.423 (73%)
^{224}Ra	3.66 d	5.685 (95%)
^{220}Rn	55.6 s	6.288 (100%)
^{216}Po	0.15 s	6.778 (100%)
^{212}Pb	10.6 h	β
^{212}Bi	60.6 m	β
^{212}Po	0.296 us	8.784 (100%)
^{208}Pb	stable	

Table 5-4-4
Alpha particles from Actinium series

Nucleus	Half life	Alpha energy (MeV)
^{235}U	7.04 x 108 y	4.400 (57%)
^{231}Th	25.5 h	β
^{231}Pa	3.28 x 104 y	5.014 (25%)
^{227}Ac	21.8 y	β
^{227}Th	18.7 d	6.038 (25%)
^{223}Ra	11.4 d	5.716 (53%)
^{219}Rn	3.96 s	6.819 (81%)
^{215}Po	1.78 us	7.386 (100%)
^{211}Pb	36.1 m	β
^{211}Bi	2.13 m	6.623 (84%)
^{207}Tl	4.77 m	β
^{207}Pb	stable	

Table 5-4-5
Alpha particles from Neptunium series

Nucleus	Half life	Alpha energy (MeV)
^{237}Np	2.14 x 106 y	4.788 (47%)
^{233}Pa	27.0 d	β
^{233}U	1.59 x 105 y	4.824 (84%)
^{229}Th	7340 y	4.845 (56%)
^{225}Ra	14.8 d	β
^{225}Ac	10.0 d	5.830 (51%)
^{221}Fr	4.8 m	6.341 (83%)
^{217}At	32.3 us	7.069 (100%)
^{213}Bi	45.59 m	β
^{213}Po	4.2 us	8.376 (100%)
^{209}Pb	3.25 h	β
^{209}Bi	stable	

5.4.2 Range of Alpha Particles in Semiconductor Materials

Ranges of alpha particle in typical semiconductor materials are shown in **Fig. 5-5**. SRIM [5-11] is used for this calculation.

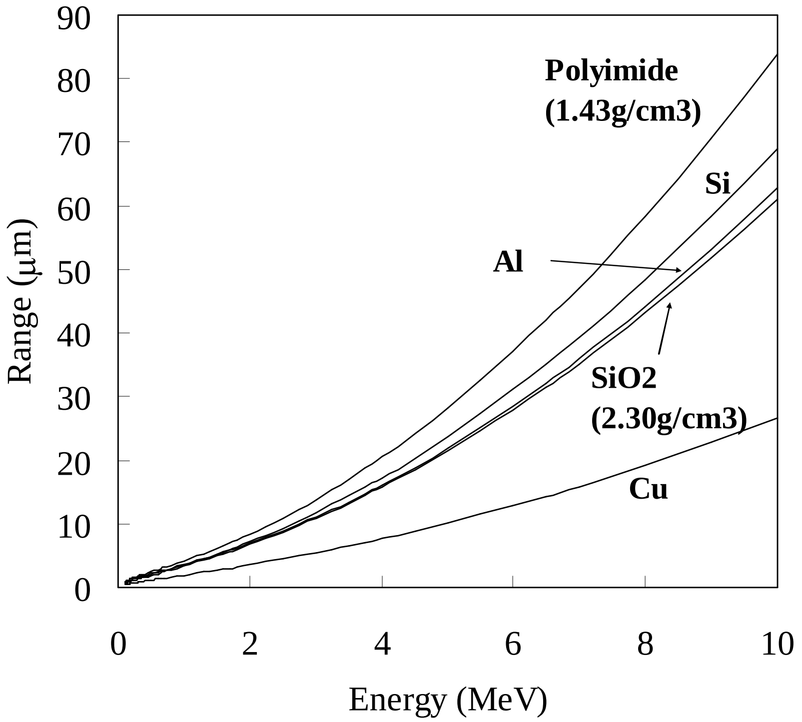


Fig. 5-5 Ranges of alpha particle in typical semiconductor materials

References for Sec. 5

[5-1] H. Kobayashi et al., “Comparison between Neutron-Induced System-SER and Accelerated-SER in SRAMs”, 2004 International Reliability Physics Symposium Proceedings, pp.288-293, 2004.

[5-2] Y. Yahagi et al., “Versatility of SEU Function and Its Derivation from the Irradiation Tests with Well-defined White Neutron Beams”, *in Abstract Book of RADECS 2004*, pp.103-106, CIEMAT, Madrid, Spain, Sept., 22-24, (2004).

[5-3] http://cr0.izmiran.rssi.ru/mosc/main.htm

[5-4] http://www.bartol.udel.edu/~NeutroNM

[5-5] http://kspc4.unibe.ch/nm/links.html

[5-6] http://www.sec.noaa.gov/alerts/SPE.html

[5-7] J. F. Ziegler, “Terrestrial cosmic rays”, *IBM J. Res. Develop*., Vol.40, No.1, pp.19-39 (1996).

[5-8] R. C. Baumann et al. “Neutron-induced Boron fission as a major source of soft errors in Deep Submicron SRAM Devices”, 2000 International Reliability Physics Symposium Proceedings, pp.152-157, 2000.

[5-9] H. Kobayashi et al., “Soft errors in SRAM Devices Induced by High Energy Neutrons, Thermal Neutrons and Alpha Particles”, Digest of the 2002 IEDM, pp.337-340, 2002.

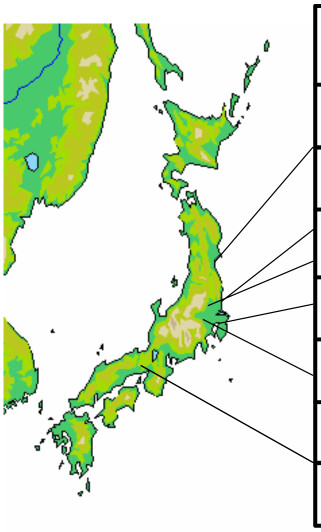
[5-10] R. Baumann, “A Tutorial on Radiation Induced Soft errors”, 2001 International Reliability Physics Symposium Tutorial.

[5-11] J. F. Ziegler, http://www.srim.org/

[5-12] E. Ibe, *et al*. “Single Event Effects of Semiconductor Devices at the Ground”, *Ionizing Radiation*, Vol.30, No.7, pp.263-281 (2004).

6. Irradiation Facilities in Japan

Facilities where (quasi-) mono energy neutron/proton test may be carried out are summarized in **Fig.6-1**.



Facility	Quasi-mono Neutron	White Neutron	Proton etc.
CYRIC	30-85MeV	N.A.	30-90MeV
FNL	0.25-15MeV	N.A.	N.A.
TIARA/JAERI	30-70MeV	N.A.	30-90MeV
HIMAC	N.A.	N.A.	800MeV/n,p
RARF	210MeV	N.A.	270MeV/n,p
RCNP	14-400MeV	<400MeV	17-400MeV
OKTAVIAN	14MeV	N.A.	N.A.

Fig. 6-1 Japanese Facilities Suitable for SEU Research

7. Deliberating member

Deliberating of this standard has been made by “Soft Error PG” of the Technical Standardization Committee on Semiconductor Device/Semiconductor Devices Reliability Group.

The members of deliberation of standard are below.

<Technical Standardization Committee on Semiconductor Devices>

Chair	Hisao Kasuga	NEC Electronics Corp.

<Group on Semiconductor Device Reliability>

Chief	Kazutoshi Miyamoto	Renesas Technology Corp.

<Soft Error Project Group>

Chair	Nobuyuki Wakai	Toshiba Corp.
Vice Chair	Shigehisa Yamamoto	Renesas Technology Corp.
Member	Hiroshi Furuta	NEC Electronics Corp.
	Hajime Kobayashi	SONY Corp.
	Masanori Fukui	Toshiba Corp.
	Eishi Ibe	Hitachi, Ltd.
	Yasuo Yahagi	Hitachi, Ltd.
	Yohiharu Tosaka	Fujitsu Ltd.
	Hideya Matsuyama	Fujitsu Ltd.
	Hideaki Kameyama	Renesas Technology Corp. (until May/2003)

APPENDIX

A.1 Estimation method of alpha-particle-induced SER

Origin of alpha-particles in VLSI is the radioactive impurity in device materials (solder bump, mold compound, Al or Cu wiring, and etc.). When an alpha-particle from radioactive impurity hits the drain diffusion layer, the generated charges are collected by the drift, funneling, and diffusion mechanisms (**Fig. A-1**). Alpha-particle-induced noise current is expressed as

$$I_{noise} = I_{drift} + I_{diff} + I_{funnel} \quad \text{(A-1)}$$

where I_{drift}, I_{diff}, and I_{funnel} are the drift, funneling, and diffusion current. In the recent technology, I_{diff} decreases as the junction area decreases and the I_{noies} is approximated as $I_{\mathrm{noise}} \sim I_{\mathrm{funnel}}$.

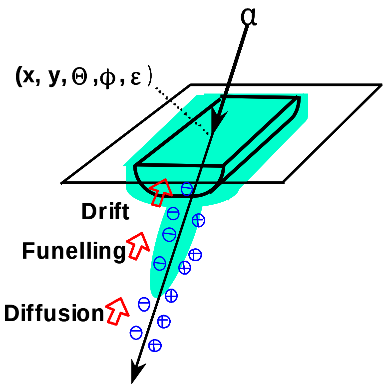


Fig. A-1 Mechanism of charge collection induced by an alpha-particle.

The wave form of I_{funnel} is given by [A1-1] [A1-2].

$$I_{funnel}(t) = \frac{Q_0}{\tau_2 - \tau_1}\left\{\exp\left(-\frac{t}{\tau_2}\right) - \exp\left(-\frac{t}{\tau_1}\right)\right\} \quad \text{(A-2)}$$

$$\tau_1 = W / V_{sat}, \quad \tau_2 = CR$$

Q_0 : Generated charge in the funneling region
W : Width of the diffusion and depletion layers
V_{sat} : Saturation velocity
C : Drain-substrate capacitance
R : Drain-well contact parasitic resistance

where time constants τ_1 and τ_2 are determined by W, V_{sat}, C and R, but we also be able to get them by fitting to the simulated wave form.

The soft error rate, SER, is given by

$$SER = \int f(x, y, \theta, \phi, \varepsilon)\, u(x, y, \theta, \phi, \varepsilon)\, dx dy d\theta d\phi d\varepsilon \quad \text{(A-3)}$$

where (x, y), (θ, ϕ), and ε are the alpha-particle-incident position, angle, and energy. f is the alpha-particle-incident probability. u is an SE occurrence function; where $u = 1$ if a SE occurs, otherwise $u = 0$. In the case of SRAMs, we carry out circuit simulations adding the alpha-particle-induced noise current as a current source and we decide $u = 1$ or 0 if the nodal voltages changes (V_{high} to V_{low}) or not.

We can define the critical charge Q_c, where $u = 1$ for $Q_0 > Q_c$ or $u = 0$ for $Q_0 < Q_c$. Therefore, if Q_c is obtained in advance, the 5-fold integration in Eq. (A-3) can easily be calculated.

References for A.1

[A1-1] G.R. Srinivasan, P. C. Murley, ad H. K. Tang, IEEE Proc. 1994 IRPS, p.12.

[A1-2] S. Satoh, R. Sudo, H. Tashiro, N. Higaki, and N. Nakayama, IEEE Proc. 1994 IRPS, p.339.

A.2 Estimation method of thermal-neutron-induced SER

Thermal neutron-induced soft errors are occurred due to thermal neutron capture reactions of ^{10}B (**Fig. A-2**) in devices with BPSG as follows:

$$\mathrm{n} + {}^{10}\mathrm{B} \rightarrow \alpha + {}^{7}\mathrm{Li} + \gamma \quad (94\%) \quad \text{(a)}$$

$$\rightarrow \alpha + {}^{7}\mathrm{Li} \quad (\ 6\%) \quad \text{(b)}$$

(a): $E(\alpha) = 1.47\mathrm{MeV}$, $E(\mathrm{Li}) = 0.84\mathrm{MeV}$

(b): $E(\alpha) = 1.77\mathrm{MeV}$, $E(\mathrm{Li}) = 1.01\mathrm{MeV}$

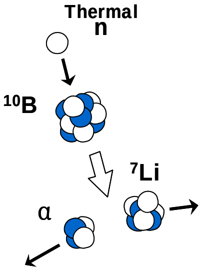


Fig. A-2 Thermal neutron capture reaction of ^{10}B

The alpha-particle (or ^{7}Li) flux Φ_α is estimated by [A2-1].

$$\Phi_\alpha = \frac{1}{2} \cdot \Phi_n \cdot N_{10B} \cdot W_{BPSG} \cdot \sigma_n \quad \cdots\cdots\cdots \quad \text{(A-4)}$$

σ_{n} : Thermal neutron capture reaction cross section (cm^2)

Φ_α : Thermal neutron flux (n/cm^2/hour)

N_{10B} : Number of ^{10}B in the BPSG layer (cm^{-3})

W_{BPSG} : Width of BPSG layer (cm)

The thermal neutron capture reaction cross section σ_n for $^{10}B(n, \alpha)^7Li$ is 3838 × $10^{-24}cm^2$ and the typical thermal neutron flux is 10n/cm^2/hour. The typical BPSG film contains the boron concentration of 5% and boron is composed of two isotopes; ^{10}B (20%) and ^{11}B (80%). Charge collection models and SER simulation method are similar to the alpha-SER estimations.

References for A.2

[A2-1] R. Baumann, T. Hossain, S. Murata, and H. Kitagawa, IEEE Proc. 1995 IRPS, p.297.

A.3 Numerical estimation method of high-energy-neutron-induced SER

High-E-neutron-induced soft errors occurred through neutron-nucleus collisions (**Fig.A-3**). We can apply three types of models for neutron-nucleus collisions as follows:

- **(a)** Cascade + Statistical decay model [A3-1] [A3-2]
- **(b)** QMD + Statistical decay model [A3-3]
- **(c)** AMD+ Statistical decay model [A3-4]

(a) The cascade model is based on classical dynamics (and the statistical evaporation model), **(b)** QMD (Quantum Molecular Dynamics) is based on semi-classical approach for the wave packet, and **(c)** AMD (Antisymmetrized Molecular Dynamics) is a quantum mechanical approach which satisfies Fermi-Dirac statistics.

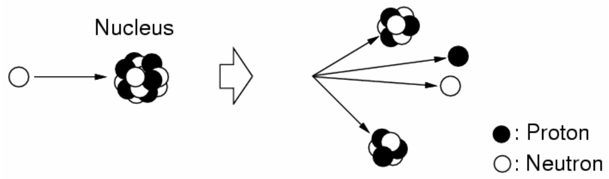


Fig. A-3 Neutron-nucleus collision

For electron-hole pair generation (or stopping power) induced by various reaction products, the Ziegler's model or TRIM (SRIM) code [A3-5] can be used for estimations. Charge collection models and SER simulation method are similar to the alpha-SER estimations.

References for A.3

[A3-1] G. R. Srinivasan, P. C. Murley, ad H. K. Tang, IEEE Proc. 1994 IRPS, p.12.

[A3-2] E. Ibe, Y. Yahagi, F. Kataoka, Y. Saito, A. Eto, M. Sato, and H. Kameyama, 2002 ICITA, Bathurst, No.273-1.

[A3-3] M. Hane et al., 2003 SISPAD, p.239.

[A3-4] Y. Tosaka, H. Kanata, T. Itakura, and S. Satoh, IEEE Trans. Nucl. Sci., vol.46, p.774, 1998.

[A3-5] J. F. Ziegler, http://www.research.ibm.com/ionbeams/SRIM/SRIMLEGL.HTM

A.4 Other approximation functions for SEU cross section

Historically, the following functions are used in the field of SER estimation for space application.

$$\sigma_{appx}(E) = \left(\frac{24}{E_{th}}\right)^{14} \left\{1 - \exp\left(-0.18\sqrt{Y}\right)\right\}^{4}$$ (Bendel's one parameter expression [A-1])

…………………………………………………………………………………… (A-5)

where,

$$Y = \sqrt{\frac{18}{E_{th}}}(E - E_{th})$$ …………………………………………………………………… (A-6)

$$\sigma(E) = \left(\frac{B}{E_{th}}\right)^{14} \left\{1 - \exp\left(-0.18\sqrt{Y}\right)\right\}^{4}$$ (Bendel's two parameter expression [A4-2])

…………………………………………………………………………………… (A-7)

where B is a fitting parameter.

References for A.4

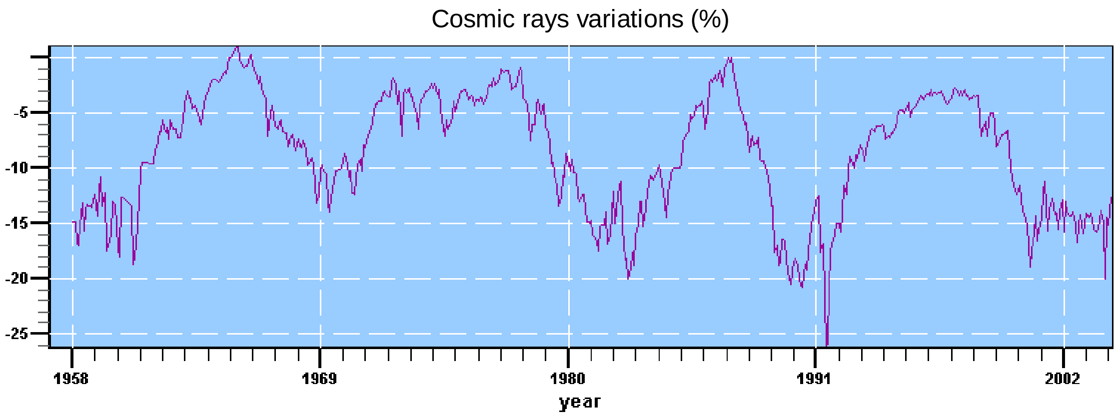
[A4-1] P. Calvel, *et al*., "An Empirical Model for Predicting Proton Induced Upset", *IEEE Trans. Nuc. Sci*., Vol.43, No.6, pp.2827-2832 (1996).

[A4-2] W. J. Stapor, J. P. Meyers, J. B. Langworthy, and E. L. Petersen, "Two Parameter BENDEL Model Calculations for Predicting Proton Induced Upsets", *IEEE Trans. Nuc. Sci*., Vol.37, No.6, pp.1966-1973 (1990).

A.5 Variation of Neutron Flux with time

Solar activity has roughly 11 year cyclic changes in time. The long-term and short term trends in solar activity can be obtained from neutron monitors in the world [A5-1, A5-2, A5-3]. **Fig. A-4** shows such typical long-term trend observed in Moscow [A5-1]. If field test is carried out for a certain long period of time without any neutron monitor, the total fluence can be corrected based upon the reference flux measured at different time.

The particles from the Sun do not have high energies so that the direct contribution of those particle can be neglected as the origin of SEUs. When energetic solar flare takes place, however, it may affect the field test to create abnormal accumulation of errors. Such occurrence can be monitored in the Space Environment Center [A5-4]. If this happened, the data during such period may well be eliminated.



http://cr0.izmiran.rssi.ru/mosc/main.htm

Fig. A-4　Variation in Neutron Flux with Time in Moscow

References for A.5

[A5-1]　http://cr0.izmiran.rssi.ru/mosc/main.htm

[A5-2]　http://www.bartol.udel.edu/~NeutroNM

[A5-3]　http://kspc4.unibe.ch/nm/links.html

[A5-4]　http://www.sec.noaa.gov/alerts/SPE.html

A.6　Altitude correction

There are two formula proposed:

$$A = 1033 \times \exp\left[-0.03813 \times (a/300) - 0.00014 \times (a/300)^2 + 6.4 \times 10^{-7} \times (a/300)^3\right]$$

.... (A-8)

(NASA-Langley formulation [JESD89])

and

$$A = 1033 - (0.03648 \times a/0.3) + \left[4.26 \times 10^{-7} \times (a/0.3)^2\right] \quad \text{..................................} \quad \text{(A-9)}$$

(Ziegler's recommendation[A6-1]), where a is altitude in meters from the sea level.

The calculated correction factors are not so different but become substantial at high altitude as shown in **Fig. A-5** (For example, γ = 193 with Eq. (A-8) while γ = 151 with Eq. (A-9) at a = 10,000m) [A6-2].

This guideline recommend NASA-Langley formulations well as JESD89.

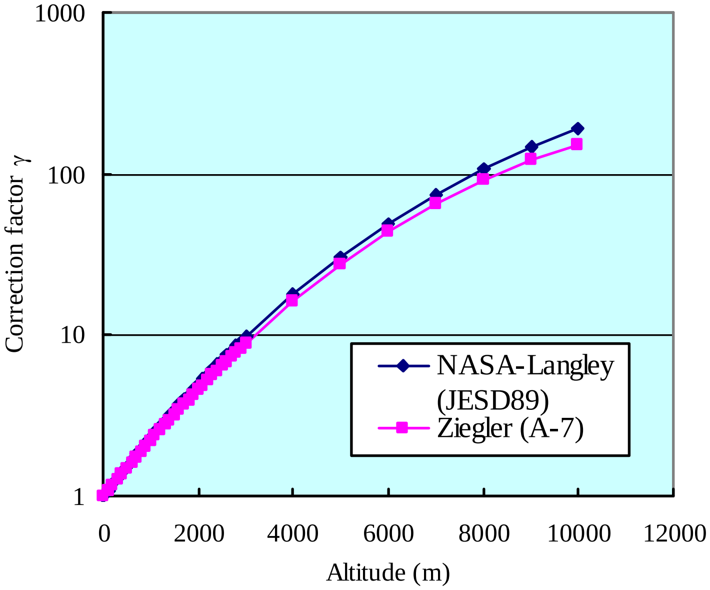


Fig. A-5 Altitude Correction Factors

References for A.6

[A6-1] J. F. Ziegler, “Terrestrial cosmic rays”, *IBM J. Res. Develop.*, Vol.40, No.1, pp.19-39 (1996).

[A6-2] E. Ibe, *et al*. “Single Event Effects of Semiconductor Devices at the Ground”, *Ionizing Radiation*, Vol.30, No.7, pp.263-281 (2004).

A.7 Analysis of alpha particles from device materials

In order to estimate the acceleration factor in the acceleration test for alpha particles, it is necessary to know the emission rate of alpha particles from materials in devices, such as mold resin, solder and Al/Cu metal. Typical methods to measure such a low-level alpha emission are described in this section.

A.7.1 Gas flow proportional counter

The gas flow proportional counter is widely used to measure low-level alpha emission, which has the following features.

- No energy loss of alpha particles because of the window-less structure.
- Large area detector is available (4,000cm^2 is available on the market).

When a low-alpha type mold resin with an emission rate of 1 × 10^{-3}α/cm^2/h are measured using the detector with detection area of 4,000cm^2, the counting rate of alpha particles will be approximately 100α/day. In such a low-level measurement, background should be reduced carefully. Major backgrounds are alpha decay of radon and cosmic rays. The radon background can be reduced to leave the radon gas cylinder as it is for a month before use so as to finish most alpha decays. The cosmic ray background can be reduced using anti-coincidence method.

A.7.2 Materials analysis

The detection limit of the direct measurement of alpha particle is approximately 5 × $10^{-4}\alpha/\text{cm}^2$/hour. Moreover, it takes several days and requires large area samples. As an alternative method, the high sensitive material analysis is useful to estimate the alpha emission rate from the concentration of alpha emitting nuclei, such as ^{238}U or ^{232}Th. **Table A-8** summarizes the methods and the features of the major high sensitive materials analysis.

Table A-8 High-sensitive materials analysis

Analysis method	Sensitivity for Uranium (ppb)	Sensitivity for alpha (α/cm^2/hour)	Advantages	Disadvantages
ICP-MS	0.01	2×10^{-5}	Quick measurement High sensitivity	
Fluorescence Spectrophotometry	0.01 ~ 0.1	2×10^{-5} ~ 2×10^{-4}	Quick measurement Low cost	Contamination in pretreatment Background of organic material
SIMS	0.1	2×10^{-4}	Quick measurement No pretreatment	Poor accuracy
Activation Analysis	0.01	2×10^{-5}	High sensitivity No pretreatment	Large scale measurement Complicated data analysis

A.8 SSER statistics

System-SER (SSER) is sometimes expressed as an upper limit using the following equation with a confidence level defined by χ^2 statistics.

$$\text{SSER} < \frac{\chi^2_{2(k+1)}}{2 \times \# \text{ of devices} \times \text{time [h]}} \times 10^9 \quad \text{[FIT]}$$

where k is the number of fail events and 2(k+1) is the degrees of freedom. The relationship between the number of fail events and χ^2 with typical confidence levels are shown in **Table A-9**.

Table A-9 χ^2 for SSER calculation

# of fail events = k	degree of freedom = 2(k+1)	Confidence Level		
		60%	90%	95%
0	2	1.833	4.605	5.991
1	4	4.045	7.779	9.488
2	6	6.211	10.645	12.592
3	8	8.351	13.362	15.507
4	10	10.473	15.987	18.307
5	12	12.584	18.549	21.026
6	14	14.685	21.064	23.685
7	16	16.780	23.542	26.296
8	18	18.868	25.989	28.869
9	20	20.951	28.412	31.410
10	22	23.031	30.813	33.924
11	24	25.106	33.196	36.415
12	26	27.179	35.563	38.885
13	28	29.249	37.916	41.337
14	30	31.316	40.256	43.773
15	32	33.381	42.585	46.194
16	34	35.444	44.903	48.602
17	36	37.505	47.212	50.998
18	38	39.564	49.513	53.384
19	40	41.622	51.805	55.758
20	42	43.679	54.090	58.124

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