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Quality estimation methods and application guidelines for mitigation measures based on particle radiation tests

Recommendation ITU-T K.138

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Quality estimation methods and application guidelines for mitigation measures based on particle radiation tests

Summary

Recommendation ITU-T K.138 describes the reliability estimation methods based on the results of a neutron irradiation test taking into account the severity of the effect caused by soft errors. The soft error rate in the natural environment has to be calculated from the number of soft errors that occur during a neutron irradiation test. The severity of the impact of a soft error on telecommunications systems, such as the impact on the client signal and control system is analysed from the error logs created during the test.

Additional mitigation measures should be applied if the equipment is less reliable than the target level. This Recommendation also provides guidelines for applying these mitigation measures in light of the results of soft error tests.

History

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Irradiation test, neutron, soft error.

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Introduction

Highly integrated and miniaturized semiconductor devices are indispensable for the telecommunication equipment that makes up carrier telecommunications networks which have large capacity, high functionality, and high reliability. However, preventing the occurrence of soft errors in these semiconductor devices is not possible at an acceptable cost. Accordingly, it is necessary to implement soft error measures that reduce the impact of soft errors on the operation of the equipment at the time when devices and equipment are designed. This Recommendation provides the methods to determine whether equipment satisfies each type of reliability requirement described in [ITU-T K.139] based on the results of a neutron irradiation test described in [ITU-T K.130].

Recommendation ITU-T K.138

Quality estimation methods and application guidelines for mitigation measures based on particle radiation tests

1 Scope

This Recommendation provides the methods which are applied to the results of a neutron irradiation test described in [ITU-T K.130] to evaluate whether equipment satisfies each type of reliability requirement described in in [ITU-T K.139].

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T K.124] Recommendation ITU-T K.124 (2022), *Overview of particle radiation effects on telecommunication systems*.

[ITU-T K.130] Recommendation ITU-T K.130 (2022), *Neutron irradiation test methods for telecommunication equipment*.

[ITU-T K.131] Recommendation ITU-T K.131 (2022), *Design methodologies for telecommunication systems applying soft error measures*.

[ITU-T K.139] Recommendation ITU-T K.139 (2022), *Reliability requirements for telecommunication systems affected by particle radiation*.

3 Definitions

3.1 Terms defined elsewhere

None.

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

3.2.1 alert function reliability (AR): Reliability of equipment operation.

3.2.2 AR failure: Alert function failure relating to alert function reliability (AR).

3.2.3 carrier: Infrastructure provider that owns the physical network resources and provides a network as a service over these resources to its customers. A virtual network provider is a customer of the carrier.

NOTE – Definition adapted from [b-ITU-T Y.3014].

3.2.4 circuit pack: A circuit board that is inserted into a unit and can be easily changed by maintenance personnel.

3.2.5 failure in time (FIT): The unit that indicates the number of failures that can be expected in one billion (10^9) hours of operation.

3.2.6 maintenance reliability (MR): Reliability of equipment maintenance.

3.2.7 MR failure: Maintenance reliability failure relating to maintenance reliability (MR).

3.2.8 physical fault failure: Hardware failures caused by physical fault.

3.2.9 service reliability (SR): Reliability of service provision.

3.2.10 silent failure: A failure where no alert is issued to network operation equipment or maintenance personnel even though there is an effect on the client signal.

3.2.11 soft error: A phenomenon in which one or more bits within the data on the device have their values reversed. A soft error does not constitute damage to the actual device.

3.2.12 soft error failure: Failure in equipment caused by a soft error in devices.

3.2.13 soft error failure rate (SEFR): Occurrence frequency of failures in equipment caused by a soft error.

3.2.14 SR failure: Service reliability failure relating to service reliability (SR).

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

1RU	one Rack Unit
AR	Alert function Reliability
ASER	Accelerated Soft Error Rate
CL	Confidence Level
EUT	Equipment Under Test
FIT	Failure in Time
LSI	Large Scale Integration
MR	Maintenance Reliability
SEFR	Soft Error Failure Rate
SER	Soft Error Rate
SEU	Single-Event Upset
SR	Service Reliability
SR(M)	Service Reliability in relation to momentary interruption
SR(P)	Service Reliability in relation to prolonged interruption
TSER	Terrestrial Soft Error Rate

5 Conventions

None.

6 Overview of the reliability estimation methods for soft errors

This Recommendation provides the methods to evaluate whether equipment satisfies each type of reliability requirement in [ITU-T K.139] based on the results of a neutron irradiation test in [ITU-T K.130].

The three types of reliability requirements as defined in clause 7 of [ITU-T K.139] are listed here as follows:

1) the alert function reliability (AR) requirement stipulated from the viewpoint of equipment operation,
2) the service reliability (SR) requirement stipulated from the viewpoint of service provision, and
3) the maintenance reliability (MR) requirement stipulated from the viewpoint of equipment maintenance.

Conformity to reliability requirements for the relevant type and class as defined in clause 8 of [ITU-T K.139] is evaluated based on the irradiation time and the number of soft error failures corresponding to each type of reliability requirement which is obtained through the neutron irradiation test. Outlines of the evaluation methods for each type of reliability requirement are described in clauses 6.1 to 6.3.

The purpose and methods for reliability estimation of telecommunication equipment described in this Recommendation are different from the failure in time (FIT) estimation of reliability of large-scale integrations (LSIs) provided by vendors.

6.1 Outline of the estimation methods for the alert function reliability (AR) requirement

As defined in clause 9.1 in [ITU-T K.139], the alert function reliability (AR) requirement specifies the period during which no silent failure caused by a soft error is observed during the neutron irradiation test. As defined in clause 9.7 in [ITU-T K.131], a silent failure is a failure that cannot be reported to the carrier network operation system or maintenance personnel even though the failure causes a non-negligible impact on the client signal. If a silent failure does not occur during the period defined in Table 9-1 in [ITU-T K.139], the equipment under test (EUT) is evaluated as satisfying the requirement of the applied class of AR. Details of the evaluation method are provided in clause 8.3.1.

6.2 Outline of service reliability (SR) requirement evaluation

As described in clause 9.2 in [ITU-T K.139], the service reliability (SR) requirement is defined by the occurrence frequency and duration of client signal interruption in the entire network caused by soft errors in the target equipment. The level of reliability indicated by the soft error failure rate (SEFR) in the terrestrial environment is calculated from the number of failures corresponding to SR during a neutron irradiation test. Furthermore, the applicable SR class is classified according to Table 9-2 in [ITU-T K.139] based on the SEFR with statistical error taken into account. Details of the evaluation method are provided in clause 8.3.2.

6.3 Outline of maintenance reliability (MR) requirement evaluation

As described in clause 9.3 in [ITU-T K.139], the maintenance reliability (MR) requirement is defined by the frequency at which maintenance personnel have to carry out work in order to restore equipment from a soft error failure. The SEFR in the natural environment is calculated from the number of failures corresponding to MR during a neutron irradiation test. Then, the conformity to the requirement of the applied class of MR specified in the Table 9-3 in [ITU-T K.139] should be checked by comparing the SEFR in the natural environment to the SEFR evaluated from the test data with statistical error taken into account. Details of the evaluation method are provided in clause 8.3.3.

7 General conditions for evaluation of conformity to the reliability requirements

7.1 Standard implementation configuration of EUT

As described in clause 9 in [ITU-T K.139], each type of reliability requirement is specified for equipment having the standard implementation configuration when it is installed in a carrier network. Therefore, the standard implementation configuration should be determined as follows.

Usually, the EUT is configured in a unit. In the EUT, all of the different kinds of circuit packs commonly used in the equipment, e.g., a circuit pack for control, should be implemented in the EUT. If the number of circuit packs in the equipment depends on the function condition or traffic, then 50% or more of circuit packs should be implemented in mountable slots of the EUT.

Furthermore, in the case where the equipment is composed of one rack units (1RUs), the EUT should be composed of at least the minimum number of units necessary to configure a redundant system.

7.2 Acceleration factor of neutron irradiation test

In order to convert the soft error rate (SER) in a neutron irradiation test into the soft error rate caused by neutrons in the natural environment, an acceleration factor $\boldsymbol{F_A}$, which is a factor indicating the ratio of the SER in the irradiation test facility to that in the natural environment, is used. The equation of the acceleration factor $\boldsymbol{F_A}$ is given as Eq. 7-1 using the terrestrial soft error rate (TSER) in the natural environment and the accelerated soft error rate (ASER) in the neutron irradiation test.

$$F_A = \frac{ASER}{TSER} \tag{7-1}$$

The acceleration factor for each accelerator facility is different and can be adjusted for the purpose of irradiation tests. Annex A provides information on the accelerator facilities including the maximum acceleration factors. The acceleration factor is calculated for the test condition, current (***I***) of accelerated particles caught by the target and distance (***D***) from the target to the EUT.

7.3 Relationship between duration in the neutron irradiation test and carrier natural environment

Total irradiation time ($\boldsymbol{T_i}$) in the neutron irradiation test is obtained by supressing the non-irradiated time necessary for recovery of equipment from the cumulative test time. The actual operation time ($\boldsymbol{T_R}$) is obtained by multiplying the total irradiation time ($\boldsymbol{T_i}$) by the acceleration factor ($\boldsymbol{F_A}$). Figure 7-1 shows the relationship between the irradiation time ($\boldsymbol{T_i}$) and the actual operation time ($\boldsymbol{T_R}$).

Actual-operation time $\boldsymbol{T_R}$:	Operating time in natural environment
Total irradiation time $\boldsymbol{T_i}$:	Total time of neutron irradiation
Non-irradiation time:	Time during which neutrons are not irradiated to allow the EUT to perform the processes necessary to recover from a soft error failure
Cumulative test time:	Time that is the cumulative sum of the irradiation time and non-irradiation time. This time should be reserved for the neutron irradiation test.

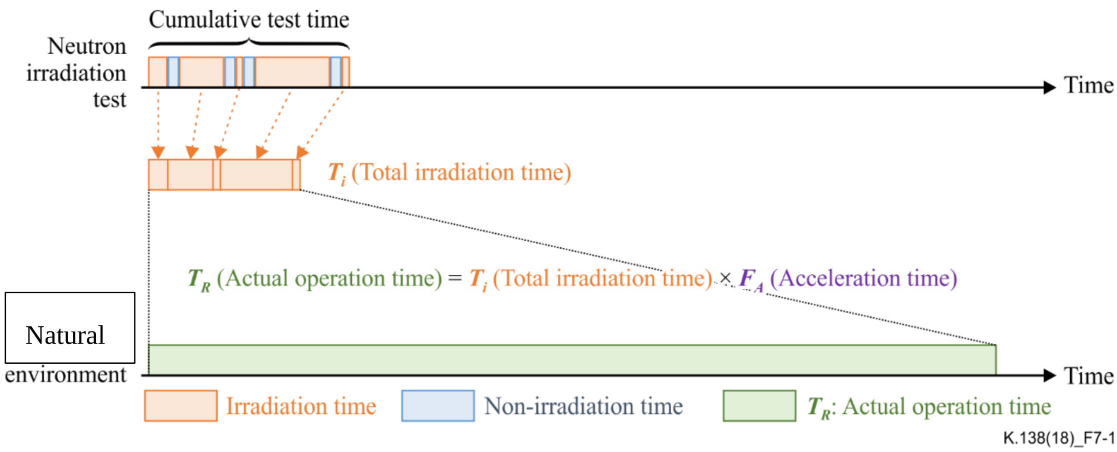

Figure 7-1 – Relationship between the irradiation time (T_i) and actual operation time (T_R)

8 Methods for evaluating the conformity to the reliability requirement

8.1 Selection of the relevant class from the classes of reliability requirements

Target class of reliability requirements should be set for each AR, SR and MR taking into account the applicable conditions and characteristics of each class of requirement with reference to [ITU-T K.139].

8.2 Examination of results of neutron irradiation test for conformity to the target reliability

In order to evaluate the results of the neutron irradiation test as defined in [ITU-T K.130], the events are classified and counted according to the following criteria.

a) Failure events involved in AR (no alert at the time of signal interruption)

When no alert is generated by the equipment despite the occurrence of a client signal interruption, the event is classified as an alert function failure (referred to as an AR failure) relating to AR, and the the number of events is defined as an N_{AR}. The details of the criteria for events which should be classified as an alert function failure are presented in clause 9.7 of [ITU-T K.131].

b) Failure events involved in SR (client signal interruption)

When a client signal interruption longer or equal to 0.2 second occurs during the neutron irradiation test, the event is classified as a service failure relating to SR (referred to as an SR failure). In addition, when the interruption duration is between 0.2 and 1.0 second, the failure is classified as an SR(M) failure, and the number of SR(M) failures is defined as an $N_{SR(M)}$. When the interruption duration is more than 1 second, the failure is classified as an SR(P) failure, and the number of SR(P) failures is defined as an $N_{SR(P)}$. When the interruption duration is less than 0.2 second, the result does not need to be recognized as a failure for SR evaluation.

A transmitter which sends signals of valuable packet length is necessary to check the customer signal continuity to conform the requirement described in clause 9.1 of [ITU-T K.130], i.e. "Packet signals in the packet equipment must include packet lengths ranging from the minimum to the maximum length". In this case, the number of failures classified as SR(M) should be determined from the average packet length and failure number since it is difficult to measure the interruption period less than one second.

Figure 8-1, for example, shows a case in which 0.1 second interruptions occurred three times within one second. This case should be recognized as one failure classified to SR(M) since totally a 0.3 second interruption occurred within one second and it is difficult to separate each 0.1 interruption.

Figure 8-2 shows a case in which 0.1 second interruptions are repeating in regular intervals. This case should be regarded as one SR(P) because although each interruption is less than 1 second some customers may recognize that the failure is continuing in this case.

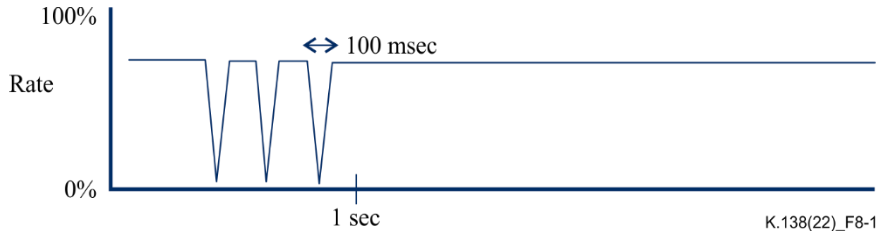

Figure 8-1 – Example of interruption included in SR(M)

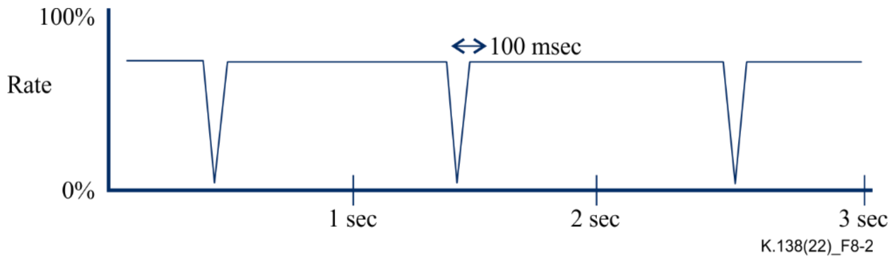

Figure 8-2 – Example of interruption included in SR(P)

c) Failure events involved in MR (request for recovery work)

When recovery from a soft error failure requires manual recovery work since the failure cannot be rectified automatically, the event is classified as a maintenance failure (referred to as an MR failure) relating to MR, and the number of events is defined as an N_{MR}. When recovery from a soft error failure is performed by automatic correction, the failure is not involved in an N_{MR}.

Examples of various failures relating to AR, SR and MR are shown in Table 8-1.

Table 8-1 – Classification examples for various events

No	a. Client signal interruption duration	b. Type of recovery	c. Presence of alert	Relating reliability type			
				SR		MR	AR
				SR(M): Momentary interruption (Interruption of client signal from 0.2 to 1.0 s)	SR(P): Prolonged interruption (Interruption of client signal for more than 1.0 s)		
1	0	Manual reset (On-site)	Y			✓	
2	10 s	Automatic recovery	Y		✓		
3	15 s	Automatic recovery	Y		✓		
4	300 s	Manual reset (On-site)	N		✓	✓	✓
5	0	Manual reset (Remote control)	Y			✓	
6	0.2 s	Automatic recovery	Y	✓			
7	0.5 s	Manual reset (On-site)	Y	✓		✓	
8	0.05 s	Automatic recovery	Y				
9	0.08 s	Manual reset (On-site)	Y			✓	
Number of occurrences				$N_{SR(M)}$	$N_{SR(P)}$	N_{MR}	N_{AR}

For example, in No. 1 of Table 8-1, there is no interruption to the client signal and the maintenance personnel have to perform the circuit pack reset recovery process. In this case, the event is classified as a maintenance failure. However, this event does not fall under SR(M) nor SR(P) since there is no interruption to the client signal.

In this way, the soft error failure events are classified as AR, SR(M), SR(P), and/or MR failure, and the number of events classified are counted as $N_{SR(M)}$, $N_{SR(P)}$, N_{MR} and N_{AR}.

8.3 Reliability evaluation methods for each type of requirement

First, as shown in Eq. 8-1, the actual operation time T_R should be calculated by the total irradiation time T_i and acceleration factor F_A because the reliability requirements in [ITU-T K.139] are defined relative to the soft error failure rate in the natural environment.

$$T_R = F_A \times T_i \qquad (8\text{-}1)$$

Then, conformity to each type of reliability requirement for the events that occur during the neutron irradiation test equivalent to the actual operation time T_R can be examined with reference to clauses 8.3.1, 8.3.2 and 8.3.3.

8.3.1 Method for examination of conformity to AR requirement

The EUT conforms to the AR requirement if no AR failure (silent failure) occurs during the neutron irradiation test of T_i which is calculated from T_R of the requirement.

Therefore, if an event corresponding to AR occurs even once in a shorter test than T_i, it is determined that the EUT does not conform to the AR requirement. In addition, AR events have a major impact on clients and maintenance personnel, so it is recommended that the causes be investigated, and soft error measures be implemented.

If it is found that an AR failure is caused by multiple soft errors that occurred simultaneously in different parts of the equipment (multiple failures), it may not fall under the definition for an AR failure since the occurrence of multiple failures is extremely rare in the natural environment. The determination of multiple failures should be estimated from the failure log in the EUT, etc.

8.3.2 Method for examination of conformity to SR requirement

The SR failure rates for SR(M) and SR(P), $\boldsymbol{Q_{SR(M)}}$ [FIT] and $\boldsymbol{Q_{SR(P)}}$ [FIT] respectively can be calculated from $\boldsymbol{T_R}$ [h] obtained in Eq. 8-1 and $\boldsymbol{N_{SR(M)}}$ and $\boldsymbol{N_{SR(P)}}$.

In this case, $\boldsymbol{Q_{SR(M)}}$[FIT] and $\boldsymbol{Q_{SR(P)}}$ [FIT] are calculated at the statistical confidence level (CL) of 68%. The upper limit of the confidence interval for the number of failures is calculated as $N_{SR(M)} + \sqrt{N_{SR(M)}}$ and $N_{SR(P)} + \sqrt{N_{SR(P)}}$. Then failure rates are calculated from Eq. 8-2 and Eq. 8-3 with FIT as a unit.

$$Q_{SR(M)}[FIT] = \frac{N_{SR(M)}+\sqrt{N_{SR(M)}}}{T_R[h]} \times 10^9 \tag{8-2}$$

$$Q_{SR(P)}[FIT] = \frac{N_{SR(P)}+\sqrt{N_{SR(P)}}}{T_R[\mathrm{h}]} \times 10^9 \tag{8-3}$$

If both $\boldsymbol{Q_{SR(M)}}$ [FIT] and $\boldsymbol{Q_{SR(P)}}$ [FIT] are below the specified value of the target class of the reliability requirement, it can be assumed that the EUT conforms to the reliability requirement.

The actual operation time $\boldsymbol{T_R}$ of a neutron irradiation test should be longer than 2,000 years. If the number of SR failures is low and the statistical error is large, the irradiation time may be increased as appropriate.

If an SR failure does not occur during the irradiation time, $\boldsymbol{Q_{SR(M)}}$ [FIT] and $\boldsymbol{Q_{SR(P)}}$ [FIT] can be calculated by Eq. 8-4 and Eq. 8-5 using $\boldsymbol{CL}$.

$$Q_{SR(M)}\ [\mathrm{FIT}] = \frac{-\ln(1-CL)}{T_R[\mathrm{h}]} \times 10^9 \tag{8-4}$$

$$Q_{SR(P)}\ [FIT] = \frac{-\ln(1-CL)}{T_R[\mathrm{h}]} \times 10^9 \tag{8-5}$$

For example, if no SR(P) event occurred during $\boldsymbol{T_R}$ of 17,520,000 hours (2,000 years), it can be calculated that $\boldsymbol{Q_{SR(P)}}$ is 65 FIT or less when CL is 68%.

8.3.3 Method for examination of conformity to MR requirement

The MR failure rate $\boldsymbol{Q_{MR}}$ [FIT] can be calculated from $\boldsymbol{T_R}$ [h] obtained in Eq. 8-1 and $\boldsymbol{N_{MR}}$.

In this case, $\boldsymbol{Q_{MR}}$ [FIT] is calculated at a CL of 68%. The upper limit of the confidence interval for the number of failures is calculated as $N_{MR} + \sqrt{N_{MR}}$. Then the failure rate is calculated from Eq. 8-6.

$$Q_{MR}\ [\mathrm{FIT}] = \frac{N_{MR}+\sqrt{N_{MR}}}{T_R[\mathrm{h}]} \times 10^9 \tag{8-6}$$

If $\boldsymbol{Q_{MR}}$ [FIT] calculated from Eq. 8-6 is below the specified value of the target class of the reliability requirement, it can be assumed that the EUT conforms to the reliability requirement.

The actual operation time $\boldsymbol{T_R}$ of a neutron irradiation test should be more than 2,000 years. If the number of MR events is low and the statistical error is large, the irradiation time may be increased as appropriate.

If an MR failure does not occur during the irradiation time, $\boldsymbol{Q_{MR}}$ [FIT] can be calculated by Eq. 8-7 using $\boldsymbol{CL}$.

$$Q_{MR}\ [\mathrm{FIT}] = \frac{-\ln(1-CL)}{T_R[\mathrm{h}]} \times 10^9 \tag{8-7}$$

For example, if no MR event occurred during $\boldsymbol{T_R}$ of 17,520,000 hours (2,000 years), it can be calculated that $\boldsymbol{Q_{MR}}$ is 65 FIT or less when CL is 68%.

9 Additional measures when the reliability does not conform to the requirement

If the reliability requirements cannot be achieved, it is necessary to implement additional soft error measures specific for the type of reliability. Details of the measures are described in [ITU-T K.131].

10 Events not classifiable as AR, SR or MR

During the neutron irradiation test, unintentional events may occur that do not have an influence on AR, SR or MR directly, see clause 10 of [ITU-T K.131] for details. However, these were events that were not intended at the time the equipment was designed and may potentially be a trigger for more severe events depending on the operation environment.

Therefore, it is recommended to apply appropriate measures if the following events occur during the neutron irradiation test even if they do not directly affect the reliability.

a) A failure which needs the attention of maintenance personnel but for which no alert was issued since there was no client signal interruption. This includes the following events.
   - No alert is issued even though the circuit pack did not restart completely.
   - No alert is issued even though an equipment cannot be controlled.

b) An unnecessary notification message to the operator is issued erroneously
   - A notification message requesting recovery by an operator is issued erroneously even though automatic correction is executed against a soft error that does not affect the client signal.

c) A failure that has an impact on failure event analysis
   - Failure events are not recorded in the log in a flash memory.
   - It is not possible to determine from the retrieved log if the failure was caused by a soft error, even though the failure is recorded in the log.

Annex A

Acceleration factors at accelerator facilities

(This annex forms an integral part of this Recommendation.)

A.1 Acceleration factor in the neutron irradiation test

In this Recommendation, the acceleration factor is referred to as the ratio of the SER in the neutron irradiation facility to that in the natural environment as defined in Eq. 7-1. The number of soft errors is not simply proportional to the number of neutrons. The number of soft errors per neutron number depends on the neutron energy. Therefore, it is necessary to consider the number of neutrons for each level of neutron energy and the SER produced by the neutrons of each energy level.

Consequently, the soft error rate can be evaluated by Eq. A.1 using $\boldsymbol{\Phi(E)}$ (the number of neutrons having energy level $\boldsymbol{E}$) and $\sigma(E)$ (the soft error rate produced by neutrons of energy level $\boldsymbol{E}$).

$$\mathrm{SER} = \int_0^{\infty} \Phi(E) \times \sigma(E) dE \tag{A.1}$$

The soft error rate $\sigma(E)$ produced by neutrons of each energy level is defined as the single-event upset (SEU) cross section that is roughly determined by the cross section of the nuclear reaction between the neutron and the Si nucleus as shown in Figure A.1, even though the cross section depends on the kind of semiconductor device involved.

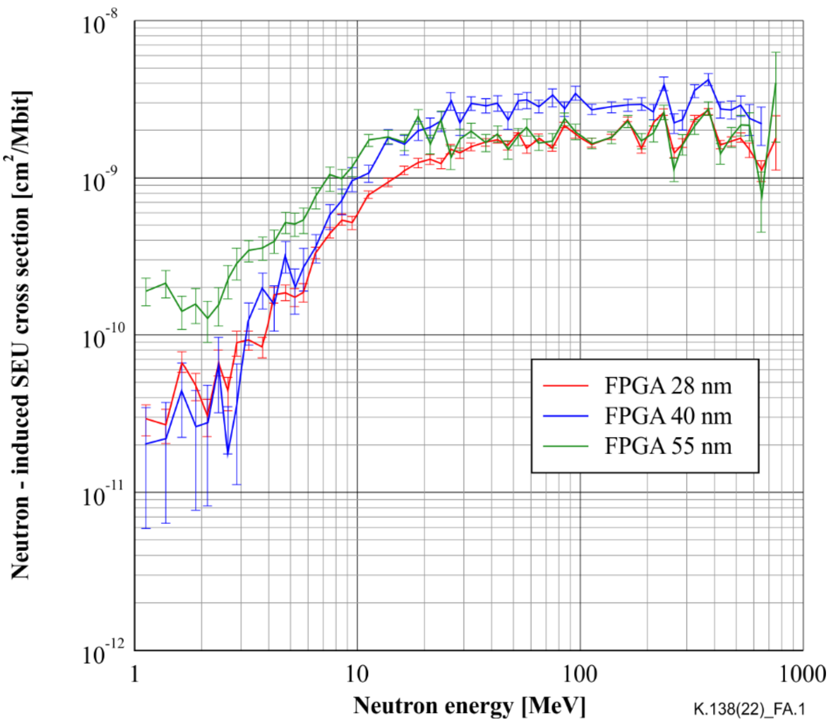

Figure A.1 – Measured neutron-induced SEU cross section of FPGAs [b-IEEE]

The acceleration factor $\boldsymbol{F_A}$ is calculated from the number of neutrons $\Phi_T(E)$ for each energy level in the natural environment, see Figure 6-3 of [ITU-T K.124], and the number of neutrons $\Phi_A(E)$ for each energy level in the neutron irradiation facility, see Figure 7-4 of [ITU-T K.130], by Eq. A.2.

$$F_A = \frac{ASER}{TSER} = \frac{\int_0^{\infty} \Phi_A(E) \times \sigma(E) dE}{\int_0^{\infty} \Phi_T(E) \times \sigma(E) dE} \tag{A.2}$$

If $\Phi_A(E)$ and $\Phi_T(E)$ have the same spectral shape, $\Phi_T(E)$ can be rewritten as $F\Phi_T(E)$. Then (A.2) can be rewritten as (A.3).

$$F_A = \frac{ASER}{TSER} = \frac{\int_0^\infty F\Phi_T(E) \times \sigma(E) dE}{\int_0^\infty \Phi_T(E) \times \sigma(E) dE} = F \quad \text{(A.3)}$$

In this case, the acceleration factor $\boldsymbol{F_A}$ does not depend on **σ(*E*)**.

However, if a comparatively low energy accelerator such as several 10 MeV is used, the spectrum shapes of $\Phi_A(E)$ and $\Phi_T(E)$ are significantly different from each other. Also, the soft error rate $\sigma(E)$ depends on the kind of device. Therefore, it is necessary to evaluate the acceleration factor of each accelerator facility taking the dependency on the spectrum shape and the kind of semiconductor devices into consideration.

The representative acceleration factors of accelerators are listed in Table A.1 determined from the acceleration factors for each device evaluated experimentally.

A.2 Representative acceleration factor of each accelerator facility

Table A.1 shows the representative acceleration factor of each accelerator facility. These acceleration factors are calculated from the TSER of various devices and are measured at the Weapons Neutron Research Facility (WNR) of Los Alamos in the U.S. that can irradiate with a neutron energy spectrum almost equivalent to that of the natural environment and from the irradiation test results of the soft error rate ASER of various devices which is measured at each accelerator facility. The TSER was calculated from the ratio of the neutron number above 10 MeV at WNR to the neutron number above 10 MeV in the natural world. The representative acceleration factor adopted is the minimum value of the acceleration factor because the soft error failure rate in the natural world calculated using the minimum value tends to be large. Therefore, if the soft error failure rate which is obtained with the minimum value is less than the class of reliability requirements, it can be determined that the class is definitely satisfied.

Table A.1 – Representative acceleration factor of each acceleration facility

Accelerator facility	Accelerated particle (Accelerated energy)	Maximum representative acceleration factor $\boldsymbol{F_{Amax}}$
ICE House at LANSCE	Proton (800 MeV)	Calculated according to JESD89A
TRIUMF	Proton (500 MeV)	
RCNP	Proton (400 MeV)	
GELINA	Electron (70-140 MeV)	1.3×10^6 ($\boldsymbol{I_{max}}$※1=40 µA, $\boldsymbol{D_R}$※2=7750 mm)
SHI-ATEX	Proton (18 MeV)	1.3×10^9 ($\boldsymbol{I_{max}}$=20 µA, $\boldsymbol{D_R}$=1000 mm)
NOTE 1 – $\boldsymbol{I_{max}}$: Maximum electric current – The acceleration factor is proportional to the electric current value. The electric current value can be adjusted by controlling the accelerator. For example, when irradiating at SHI-ATEX at I=10 µA, the acceleration factor is 0.65×10^9 ($F_A = \frac{I}{I_{max}} \times F_{Amax}$). NOTE 2 $\boldsymbol{D}$: Distance from neutron source – See [ITU-T K.130] clause 7.7. For example, when irradiating at SHI-ATEX at $\boldsymbol{D}$=2000 mm, the acceleration factor is 3.25×10^8 ($F_A = \frac{D_R^2}{D^2} \times F_{Amax}$).		

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