International Telecommunication Union

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

K.124
(01/2022)

SERIES K: PROTECTION AGAINST INTERFERENCE

Overview of particle radiation effects on telecommunication systems

Recommendation ITU-T K.124

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Summary

Recommendation ITU-T K.124 provides basic guidance on soft errors that are caused by particle radiation and that affect telecommunication systems. This Recommendation details the phenomenon of soft errors that arise from particle radiation. A brief explanation of the procedures for design, test and mitigation measures are also included in this Recommendation.

History

Edition	Recommendation	Approval	Study Group	Unique ID[*]
1.0	ITU-T K.124	2016-12-14	5	11.1002/1000/13140
2.0	ITU-T K.124	2022-01-13	5	11.1002/1000/14933

Keywords

Neutron, particle radiation, single-event upset, soft error.

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FOREWORD

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The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

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Introduction

As more highly integrated semiconductor devices are deployed in telecommunication equipment, soft errors caused by particle radiation occur more frequently on carrier telecommunication networks and have a more severe impact on network operations and the quality of signal transmission. Accordingly, measures to mitigate the effect of soft errors are required for telecommunication equipment. A large amount of telecommunication equipment is installed in remotely supervised telecommunication networks. A single soft error within a piece of telecommunication equipment can have a disastrous impact on services if the equipment is not appropriately designed to mitigate the effect of soft errors. Therefore, it is important during the design and development of telecommunication equipment to determine the impact of soft errors and to apply additional measures to mitigate this impact in order to achieve the target quality of the system.

Recommendation ITU-T K.124

Overview of particle radiation effects on telecommunication systems

1   Scope

This Recommendation presents an overview of the effects of particle radiation and design methods to mitigate the impact of soft errors. The Recommendation is applicable to the telecommunication equipment that composes a terrestrial carrier telecommunication network, including core network equipment (i.e., link and node equipment) and access network equipment that are installed in telecommunication centres.

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.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.138]   Recommendation ITU-T K.138 (2022), *Quality estimation methods and application guidelines for mitigation measures based on particle radiation tests*.

[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   neutron irradiation test: A means to evaluate soft error quality through the use of neutron irradiation emitted by a neutron source driven by a compact accelerator.

3.2.2   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 semiconductor device.

3.2.3   soft error rate: The number of occurrences of soft errors in a unit time.

4   Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

CRAM   Configuration Random-Access Memory

DICE	Dual Interlocked Storage Cell
ECC	Error Correction Code
FIT	Failure in Time
FPGA	Field-Programmable Gate Array
MCU	Multiple-Cell Upset
NE	Network Equipment
RCC	Replication, Comparison, Checkpointing
SCU	Single-Cell Upset
SEB	Single-Event Burnout
SEL	Single-Event Latch-up
SEU	Single-Event Upset
SRAM	Static Random-Access Memory
TMR	Triple Modular Redundancy

5 Conventions

None.

6 Mechanism by which particle radiation causes soft errors

A soft error does not damage the semiconductor device itself; instead, it is a phenomenon that affects the data within a device by reversing the value of one or more bits within the data. The semiconductor device itself is not damaged, therefore its operation will be restored to normal operating condition after the reversed bit is rewritten to the device or the semiconductor device is initialized in order to reset the data in memory to its default values. This Clause will explain the phenomena that produce particle radiation, which is the cause of soft errors, as well as the mechanism by which soft errors occur in semiconductor devices.

6.1 Particle radiation which causes soft errors

Soft errors are mainly caused by particle radiation of neutrons and alpha particles. Neutrons are generated by cosmic rays and alpha particles are generated by minute quantities of radioisotopes contained in materials used within the semiconductor devices.

6.1.1 Mechanism by which alpha particles cause soft errors

Materials for the packages and wiring that compose an integrated circuit contain minute quantities of radioisotopes such as uranium-238 or thorium-232. When an alpha particle produced by a radioisotope invades the interior of the material used in an integrated circuit, electron hole pairs are generated along the path of the alpha particle as shown in Figure 6-1. The electron hole pairs generated in and around the depletion layer drift and accumulate within the memory cell. Once the accumulated charge exceeds a threshold level specific to the semiconductor gate, the value of the bit within the memory cell is reversed (from 0 to 1 or 1 to 0).

The occurrence of soft errors caused by alpha particles can be reduced by using high purity materials such as low alpha particle plastics.
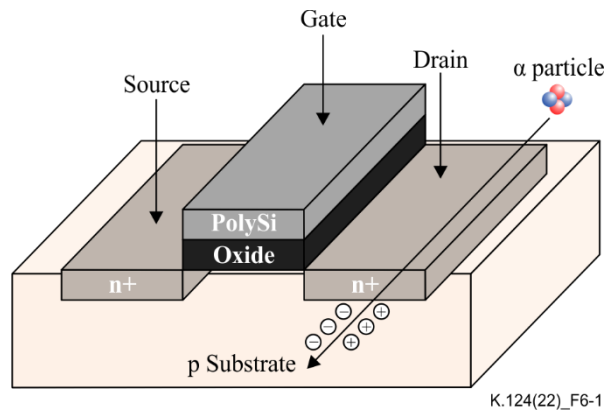
Figure 6-1 – Invasion of alpha particles in semiconductor material causes soft errors
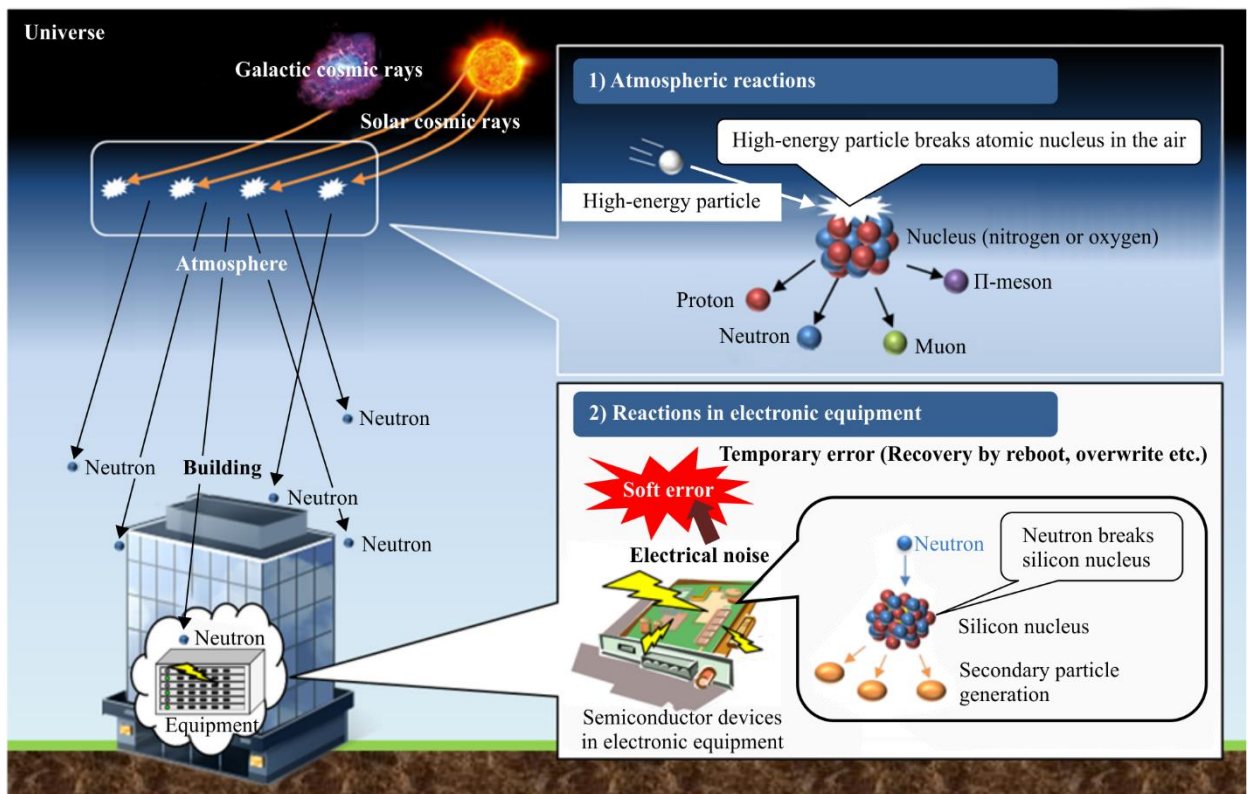
6.1.2 Mechanism by which cosmic rays cause soft errors

Ultra-high energy particles are included in cosmic rays that are flying about in cosmic space. As shown in Figure 6-2, two types of cosmic ray cause soft errors: solar cosmic rays produced by solar activity and galactic cosmic rays that originate outside the solar system. Both types of cosmic ray are composed of such elements as electrons, protons and alpha particles.

As cosmic rays enter the atmosphere of the earth, they collide with nuclei in the atmosphere and cause a nuclear reaction that produces secondary particles such as neutrons, π-mesons, electrons and protons. Unlike other types of particles, the energy and flux density of neutrons during travel in the atmosphere is not significantly reduced because a neutron does not have an electric charge. The energy spectrum of neutrons at the earth's surface is shown in Figure 6-3.

The mechanism by which neutrons generate soft errors in semiconductor devices differs depending upon neutron energy. High-speed neutrons with an energy of 1 MeV or higher cause nuclear reactions with the silicon nuclei in the semiconductor chip and the secondary ions produced in these reactions cause soft errors. Thermal neutrons with an energy of around 25 meV cause a capture reaction with the ^{10}B within the semiconductor device and generate alpha particles, which cause the soft error.

Figure 6-4 shows the mechanism by which high-speed neutrons cause soft errors. The collision of a high-speed neutron with an atom in the chip material (such as a silicon atom) has some probability of causing a nuclear reaction and when such a reaction occurs it generates secondary ions. Electron hole pairs are generated along the path of the secondary ions in the chip and a soft error occurs.

Figure 6-2 – Mechanism by which cosmic rays cause soft errors
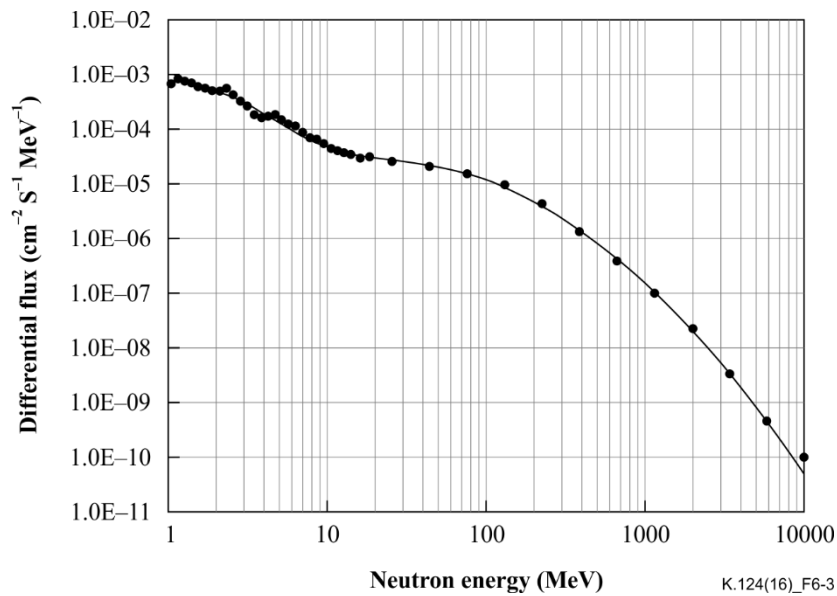
**Figure 6-3 – High-energy neutron spectrum at sea level in New York City
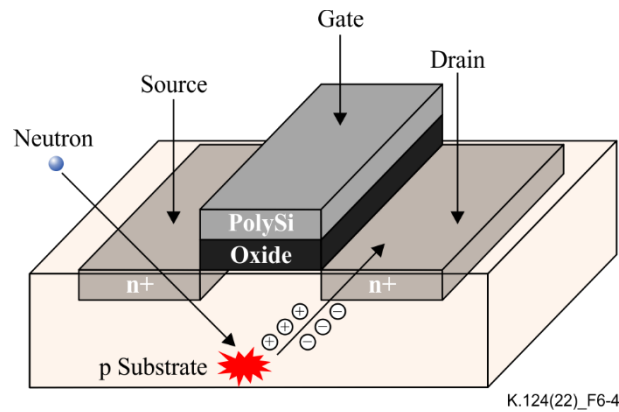[b-JEDEC-JSED89A]**

Figure 6-4 – Invasion of high-energy neutron causing soft errors

6.2 Effect of geographical conditions and solar activity on soft error rate

The flux level of neutrons from space differs depending on such factors as geographical conditions (i.e., location on the earth and altitude) and solar activity, and has an effect on the probability of generating soft errors. Neutron flux is higher at higher altitudes since neutrons are generated within the atmosphere at high altitudes and reduced in number as they travel to lower altitude locations. The relationship between neutron flux and altitude is shown in Figure 6-5.

The path of high energy protons in the cosmic rays that generate neutrons in the atmosphere is affected by the magnetic field since the high energy proton has a positive charge. The neutron flux generated by cosmic rays is lower at locations closer to the equator since the repulsive force of the magnetic field produced by geomagnetism is stronger and cosmic rays are repelled more. Conversely, the flux level at high latitudes near the North and South poles is higher since the repulsive force is weaker there. The ratio of neutron flux at major world cities compared to that of New York as a reference is shown in Table 6-1.

Neutron flux level also depends on solar activity, which periodically changes between high and low levels in an approximately 11-year cycle. During periods of high solar activity, less neutron flux is observed on the earth since solar magnetic flux, which reduces the amount of galactic cosmic radiation entering the solar system, is stronger than in other periods. In the event of a large-scale solar flare, the amount of neutron flux shows a temporary spike because the emitted solar cosmic radiation increases enormously at the time of such an event. The change in sunspot number and neutron flux is shown in Figure 6-6, which shows that solar activity increases when sunspot number increases.

The level of neutron flux depending on geographical conditions as well as solar activity can be obtained by computer simulations of the flying path of galactic rays and their reaction upon collision with atmospheric gases. As a result, the occurrence of soft errors for a specific location and degree of solar activity can be evaluated based on the ratio of cosmic-ray neutron-flux versus the reference level at New York.
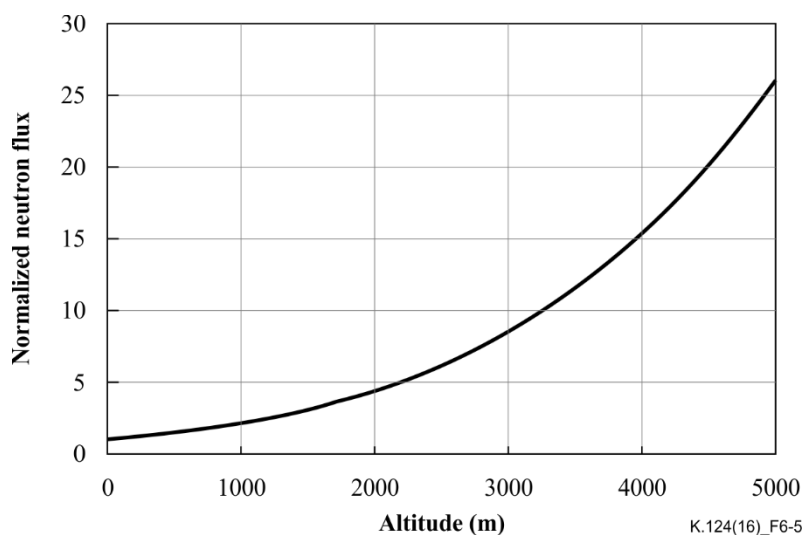
Figure 6-5 – Neutron flux variation with altitude

**Table 6-1 – Ratio of cosmic-ray neutron-flux level in cities relative to New York
[b-JEDEC-JSED89A]**

City or location	Lat. (°)	Long. (° E)	Elevat. (m)	Atm. depth (g/cm²)	Cutoff rigidity (GV)	Relative neutron flux		
						Active sun low	Quiet sun peak	Avg.
Bangkok, Thailand	13.4 N	100.3	20	1031	17.4	0.51	0.53	0.52
Beijing, China	39.9 N	116.4	55	1027	9.4	0.71	0.76	0.73
Berlin, Germany	52.5 N	13.4	40	1028	2.8	0.94	1.08	1.01
Bogotá, Colombia	4.6 N	285.9	2586	753	12.3	3.7	4	3.85
Chicago, IL, USA	41.9 N	272.4	180	1011	1.8	1.09	1.28	1.19
Denver, CO, USA	39.7 N	255	1609	851	2.8	3.43	4.08	3.76
Hong Kong, China	22.3 N	114.2	30	1030	16.1	0.53	0.56	0.55
Houston, TX, USA	30 N	264.6	15	1031	4.6	0.88	0.98	0.93
Johannesburg, S. Africa	26.2 S	28	1770	834	7.1	2.95	3.3	3.13
La Paz, Bolivia (Plurinational State of)	16.5 S	291.9	4070	623	12.2	8.59	9.39	8.99
London, UK	51.5 N	359.9	10	1032	2.9	0.91	1.05	0.98
Los Angeles, CA, USA	34 N	241.7	100	1021	5.3	0.89	0.99	0.94
Mexico City, Mexico	19.4 N	260.9	2240	787	8.4	3.75	4.16	3.96
Moscow, Russian Federation	55.8 N	37.6	150	1015	2.2	1.06	1.22	1.14
New Delhi, India	28.6 N	77.2	220	1007	14.1	0.66	0.7	0.68
New York, NY, USA (ref)	40.7 N	286	0	1033	2.08	0.927	1.073	1
Paris, France	48.9 N	2.3	50	1027	3.6	0.92	1.04	0.98
Seattle, WA, USA	47.6 N	237.7	50	1027	2	0.97	1.13	1.05
Seoul, Korea (Republic of)	37.6 N	127	50	1027	10.7	0.66	0.71	0.69
Sydney, Australia	33.9 S	151.2	30	1030	4.5	0.87	0.97	0.92

Table 6-1 – Ratio of cosmic-ray neutron-flux level in cities relative to New York [b-JEDEC-JSED89A]

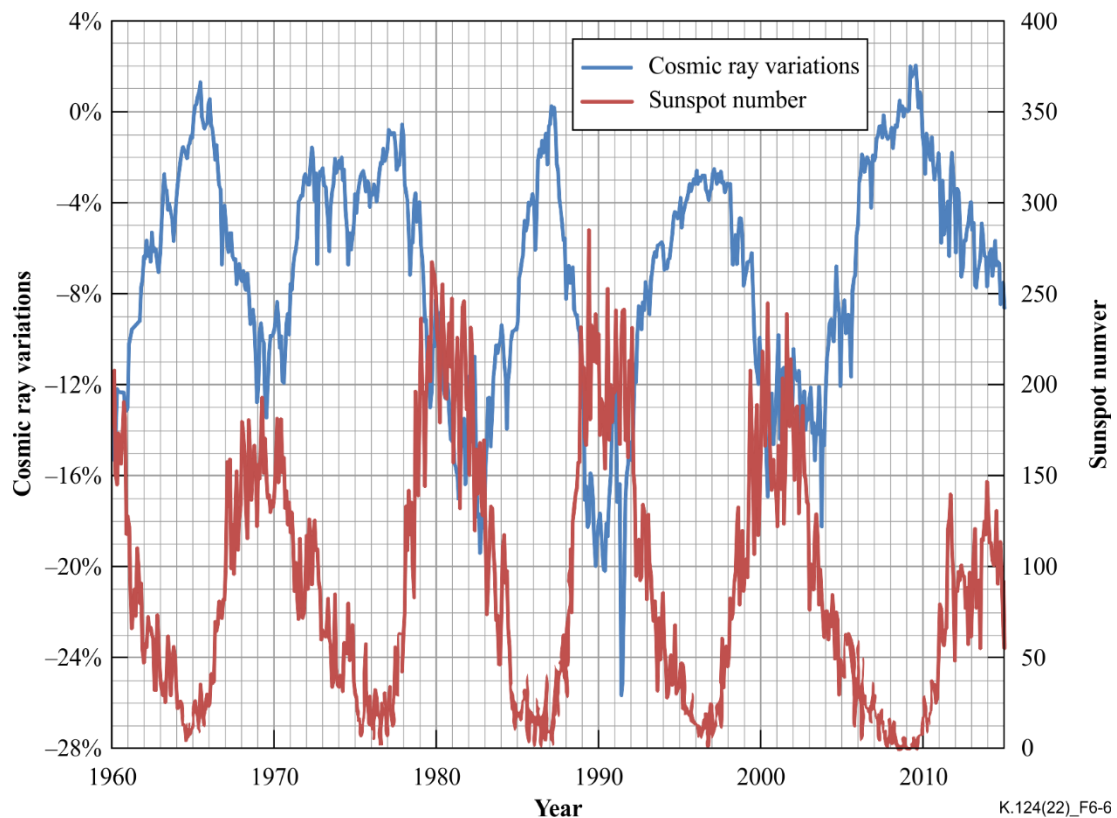| City or location	Lat. (°)	Long. (° E)	Elevat. (m)	Atm. depth (g/cm^2)	Cutoff rigidity (GV)	Relative neutron flux		
						Active sun low	Quiet sun peak	Avg.
Singapore City, Singapore	1.3 N	103.9	15	1031	17.2	0.51	0.53	0.52
Stockholm, Sweden	59.3 N	18.1	30	1030	1.4	0.96	1.12	1.04
Toronto, Canada	43.7 N	280.6	120	1019	1.5	1.04	1.22	1.13
Tokyo, Japan	35.7 N	139.8	20	1031	11.6	0.62	0.66	0.64

Figure 6-6 – Cosmic ray variations and sunspot number [b-SILS] [b-Moscow]

6.3 The effect of building and installation conditions on soft error occurrence in telecommunication equipment

Neutrons lose energy when travelling in materials that contain light elements such as hydrogen. Building walls and other structures made of concrete can reduce neutrons to some extent and lower the occurrence of soft errors. Figure 6-7 shows the normalized neutron flux level, which corresponds to the occurrence rate of soft errors, as obtained by computer simulation of an example telecommunication centre. The estimated occurrence of soft errors is lower on the lower floors of a building, values obtained on the third, second, and first floors are 70%, 60% and 40%, respectively, of the values outside the building. Additionally, the error rate is reduced more at the central parts of the building than near the exterior walls because there is more shielding against neutrons that enter in a direction inclined from the vertical. The effect of windows is negligible.
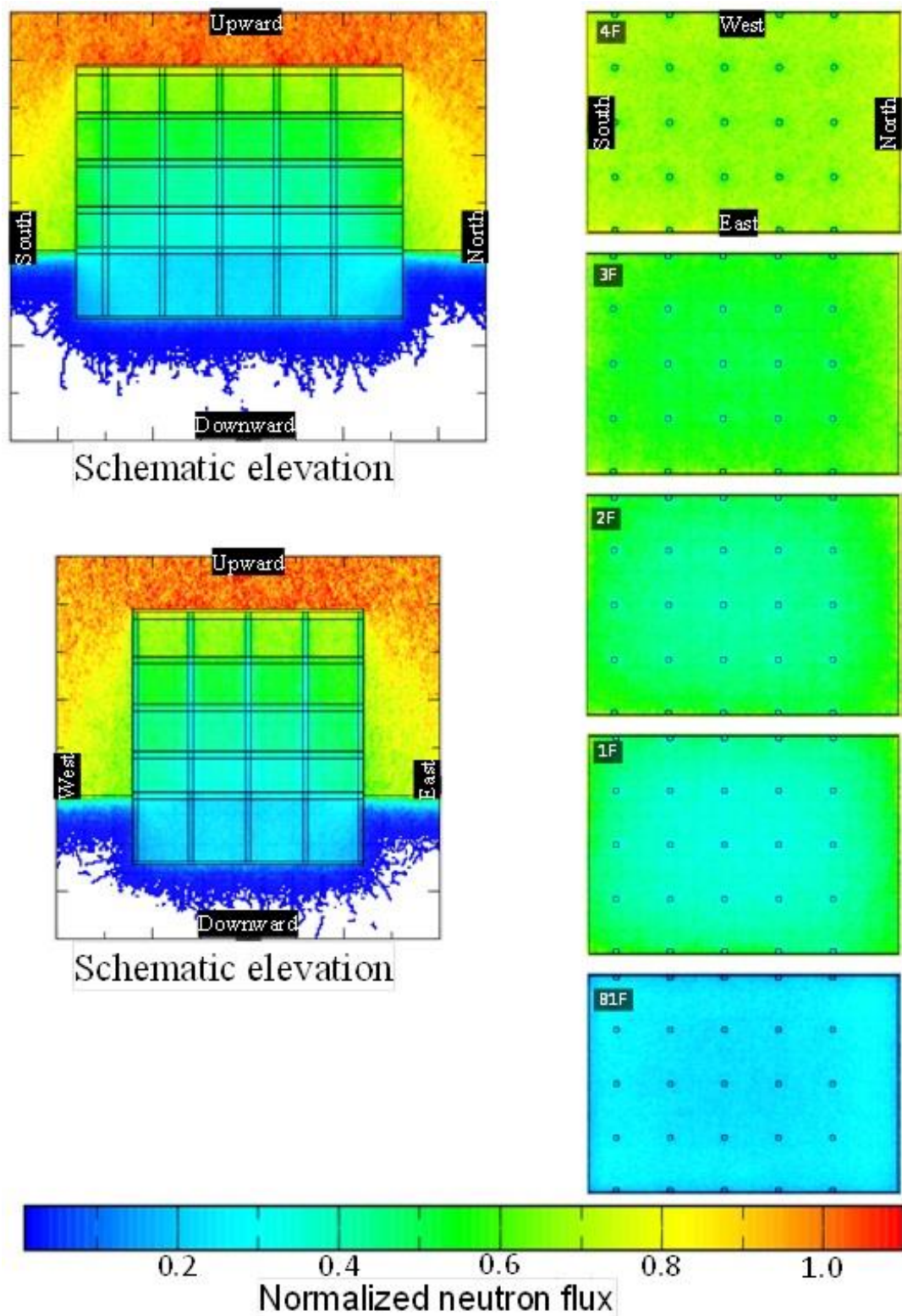
Figure 6-7 – Neutron flux in a telecommunication centre evaluated by computer simulations

(Normalized by the assessment of flux outside of the building)

In tall equipment, the neutron flux at the bottom part of the equipment is lower than that at the top part. However, it is very difficult to evaluate how much the upper part of the equipment reduces neutron flux, because precise calculations must take into account the complex structure of the equipment and the particle transport code for the materials of the devices within the equipment. Consequently, the reduction of neutron flux by the equipment is not considered in this Recommendation.

With regards to small telecommunication equipment, the installation direction, i.e., vertical or horizontal, of the equipment does not have a considerable effect upon the soft error rate. The reasons for this result are as follows:

1)   The equipment has a very slight shielding effect upon neutron flux.

2)   The soft error rate does not depend on direction in which the semiconductor devices are installed (either vertical or horizontal), because soft errors occur as a result of a nuclear reaction between neutrons and silicon nuclei and this reaction does not depend on the incidence angle of the neutrons.

6.4   Types of soft errors

The types of soft error caused by particle radiation are categorized as follows:

Single-event upset (SEU): An event that causes an error that changes the condition of a latch or memory cell which can be restored by a rewrite or initialization.

There are two kinds of SEUs:

–   Single-cell upset (SCU): An event that leads to single bit error.

–   Multiple-cell upset (MCU): An event that leads to multiple bit errors.

Single-event latch-up (SEL): An event that causes an error which cannot be recovered from by initialization or rewriting but must be restored by turning the power off and then on. The event occurs, for example, when a high energy particle encounters a thyristor on a semiconductor device and that situation produces excessive current in the semiconductor.

Single-event burnout (SEB): An event that causes a physical fault originated by a particle with extremely high energy that is sufficient to cause a high current flow which damages a piece of hardware.

SELs and SEBs are outside the scope of this Recommendation because their occurrence is extremely rare, and no problems have been reported concerning telecommunication systems.

7   Impact of soft errors generated in telecommunication equipment and mitigation methods

7.1   The increase of soft errors in telecommunication equipment

Recent progress in integration and microfabrication technologies has resulted in a dramatic increase in the occurrence of soft errors in contrast to hard errors, which permanently disable semiconductor devices. In particular, static random-access memory (SRAM) devices are easily affected by high-energy neutrons. Figure 7-1 shows the relationship between the design rule and FIT in the case of an SRAM-based FPGA [b-Iwashita].

For example, the error rate in the latest version field-programmable gate arrays (FPGAs) that include SRAM is larger than 10 000 FIT if mitigation measures are not applied; this is calculated from the error rate per unit of storage capacity (FIT/Mb) and memory capacity in the FPGA chip (Mb) [b-XILINX-1] [b-XILINX-2]. This means errors would occur 1.5 times a day in a telecommunication system made up of 1 000 pieces of equipment consisting of six FPGA chips each.
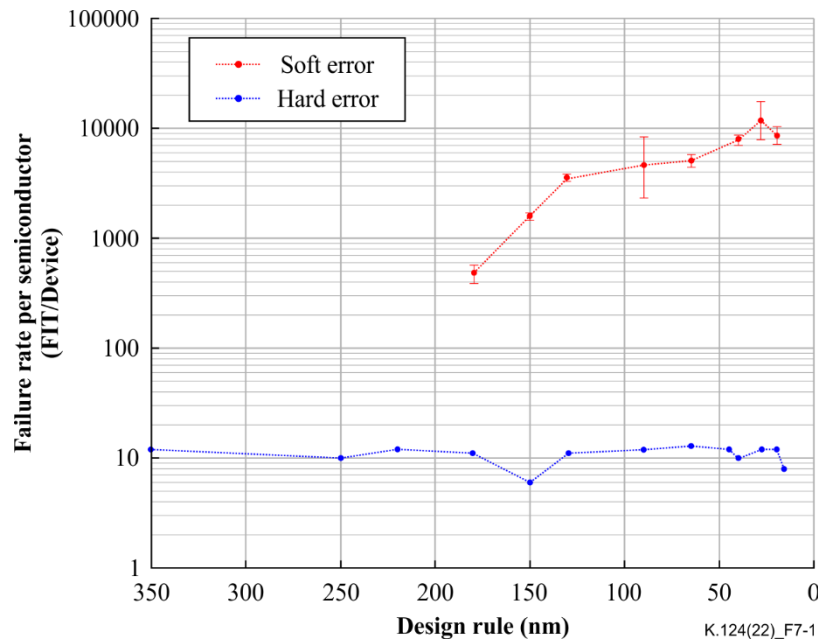
Figure 7-1 – Relationship between the design rule and FIT in case of an SRAM-based FPGA [b-Iwashita]

7.2 Impact of soft errors on operation of telecommunication systems

Failures in telecommunication equipment caused by soft errors can be classified as non-reproducible failures (those which cannot be reproduced in a laboratory and whose cause cannot be determined) and silent failures (those which are not detected by the operator before customer complaints arise).

Causes of non-reproducible failures are not usually uncovered in a laboratory or by the equipment manufacturer and can cause excessive costs related to investigation of the cause and equipment replacement.

Telecommunication equipment is usually designed to alert the operator when a failure occurs within a device in the equipment. However, soft errors can cause undetectable failures in equipment and can have long term effects, even with soft errors that rarely occur. These long-term failures can have serious adverse effects on society.

The following failures are experienced in telecommunications networks.

(1) Client signal interruption due to a failure in the destination information table.

Figure 7-2 is a schematic diagram of a client signal interruption by an error in the destination address table in the transmission equipment. When a soft error occurs in the destination address table in NE1 (where "NE" stands for network equipment), a wrong address is attached to the packet sent from NE1. The NE2 cannot read the correct address of the packet and will send the packet to the wrong destination or discard the packet. Consequently, the client signal is interrupted.
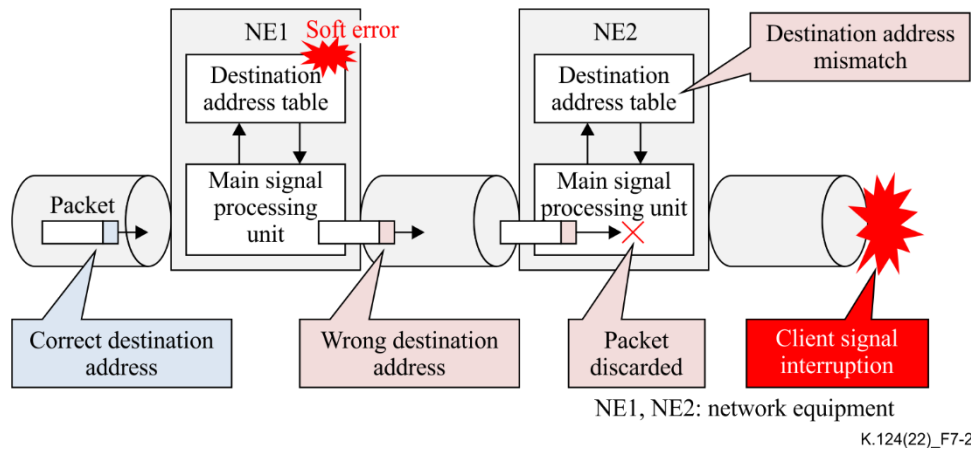
Figure 7-2 – Client signal interruption caused by an error in the destination table

(2)   Client signal interruption due to a failure of the bandwidth control unit.

Figure 7-3 is a schematic diagram of a client signal interruption by a soft error in the bandwidth control table in the transmission equipment. When a soft error occurs in the bandwidth control table, the bandwidth of the client signal processing unit is set to an inadequate value and the signal is interrupted at the unit.
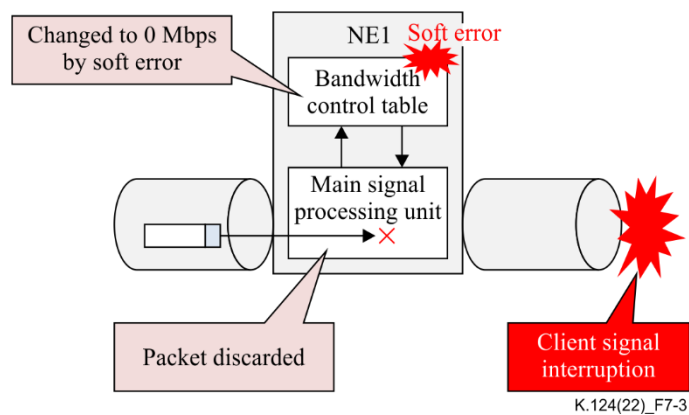
Figure 7-3 – Client signal interruption caused by an error in the bandwidth control table

(3)   Client signal interruption due to a failure of CRAM in FPGA.

Figure 7-4 is a schematic diagram of a client signal interruption by a soft error in configuration random-access memory (CRAM) in an FPGA in the transmission equipment. A soft error occurs in the client signal processing unit B and packet transmission stops at the unit. No alarm notification is generated because the unit is not monitored.

Figure 7-4 – Client signal interruption due to failure of CRAM in FPGA

(4)   Unsupervised situation arising from a failure in CPU cache memory.

Figure 7-5 is a schematic explanation of an unsupervised situation caused by a soft error. A soft error occurs in the CPU of a NE and then the signal connection is lost between NE and the operation system. The network equipment falls into an unsupervised state as a result of this error.
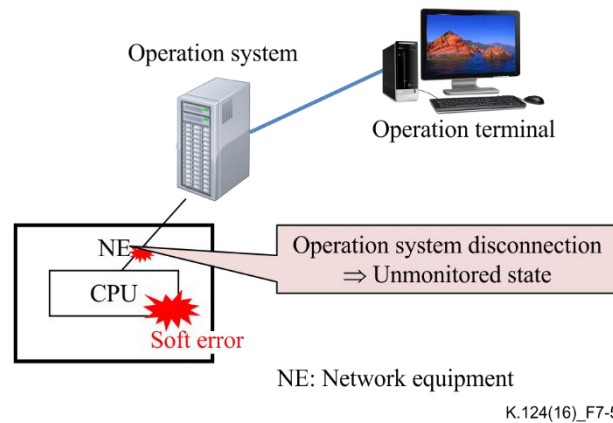
Figure 7-5 – Unsupervised situation arising from a failure in CPU cache memory

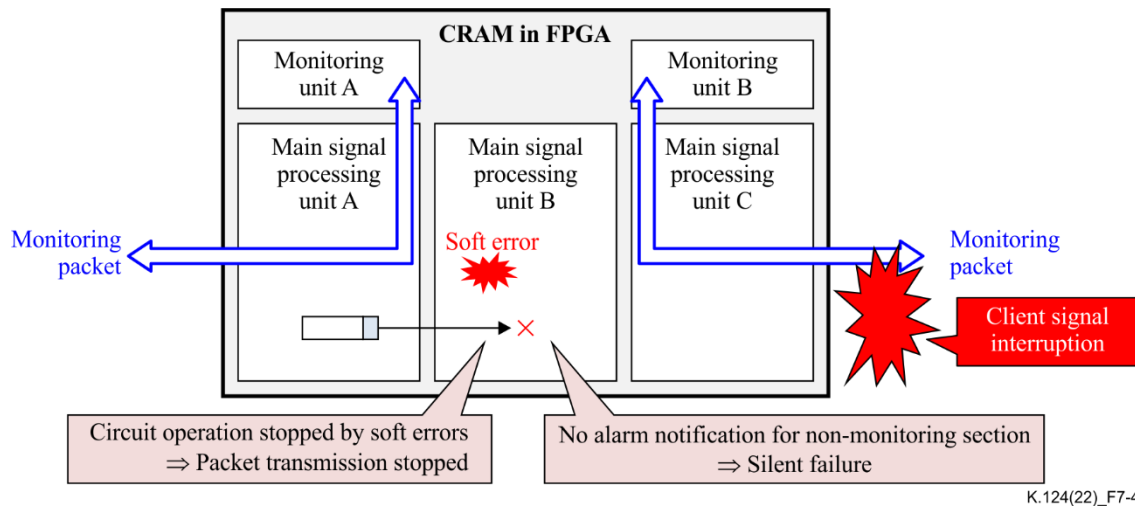### 7.3   Mitigation measures for soft errors in telecommunication equipment

There are three classes of mitigation measures for soft errors: (1) reduction, (2) isolation, and (3) correction.

(1)   Reduction

Reduction measures moderate the impact of soft errors by reducing the physical occurrence of the actual soft errors.

Examples include the following:

–   In place of semiconductors, using devices that operate magnetically and which as a consequence do not suffer from the effects of particles.

–   Using a 3D structure that reduces the soft error rate by reducing the area of the depletion layer between the drain and the silicon substrate where the charges generated by neutrons accumulate.

–   Applying replication, comparison, checkpointing (RCC) technology to semiconductor devices so that generated charges are absorbed by a dummy inverter circuit when high-speed ions collide with the silicon.

–   Reducing the amount of SRAM, the element in the equipment that is most easily affected by particles.

(2)   Isolation

Isolation measures avoid the effects upon a system by first activating a component that complements the operation of the component in which the soft error occurred and then isolating the component in which the soft error occurred. Examples include:

–   Applying a triplicated circuit configuration known as triple modular redundancy (TMR) so that an error in one component may then be isolated from the other two.

–   Using an interleaved memory configuration to lessen the impact on the MCU.

–   Ignoring soft errors that do not affect functionality by identifying whether or not each soft error will have an effect upon functionality.

(3)   Correction

Soft errors do not damage the actual semiconductor device; rather, they are errors in the data on the device. Therefore, one effective class of mitigation measures consists of those that correct data errors on the device and restore the device to normal condition by either overwriting the data with normal data or initializing the device. Three methods used for triggering the rewrite or initialization are:

–   An automatic correction function that is built into the semiconductor device.

–   An automatic correction function that is included in the equipment control program.

–   Manual operation by maintenance staff.

An automatic correction function can be realized in hardware by utilizing error correction code (ECC) functionality that overwrites memory circuits with normal data and by employing a dual interlocked storage cell (DICE) configuration that repairs soft errors which occur within a latch in logical circuits.

Manual operations for correcting a soft error are initiated when the system operator determines that the impact of the correction or initialization is less than that of the soft error itself. Only this kind of soft error impacts maintenance quality. On the other hand, soft errors that can be fixed by an automatic correction function in the control program for the device or equipment do not impact maintenance quality.

All of these corrective measures comprise two stages: soft error detection and then correction.

8   Necessity of this Recommendation for soft errors

As stated in clause 7, the occurrence of soft errors has been increasing rapidly. Even though there are measures to mitigate the impact of soft errors within a semiconductor device, it is not possible to prevent all soft errors within the actual semiconductor devices. Therefore, when soft error measures for telecommunication equipment are implemented, it is necessary to determine soft error measures adopted in devices, equipment and control systems by taking into consideration the evaluated quality, with respect to soft errors, of the semiconductor devices contained within the telecommunication equipment.

It is not necessary to implement soft error measures excessively when the amount of equipment to be installed is small. This is because soft errors only occur at the rate of once per several years, or even several decades, for each piece of equipment.

On the other hand, several soft errors may occur throughout a network every day if the network comprises several thousand pieces of telecommunication equipment. Therefore, when determining specifications, it is necessary to consider the number of equipment units to be installed as well as

service quality. Consequently, quality requirements must be determined against soft errors and measures to mitigate soft errors must be implemented during equipment design in order to achieve quality requirements.

In normal environments, the time required to observe soft errors is very long, so alternative methods are therefore needed to evaluate the effect of mitigation measures against soft errors. Some equipment is installed with functions that test for soft errors by inserting an error in a semiconductor device from an external controller connected to the equipment. Functions like this are referred to as error insertion functions in [b-ITU-T K.Sup11]. Particle accelerators can also generate soft errors in a device within a few minutes.

The correct operation of mitigation measures when a soft error occurs must first be checked before determining methods for such measures applied on either the device or the equipment. This makes it essential to have soft error tests for equipment using error insertion functions and particle accelerators.

In consideration of the situation described above, it is necessary to make Recommendations that include design procedures, quality requirements and test methods regarding soft errors. The standardized test methods and requirements will be helpful for both manufacturers and operators to select based on marketing or ordering based on their specifications.

9 Development procedures for telecommunication equipment

Figure 9-1 shows details of studying soft error measures during each development stage for telecommunication equipment.

During the study of specifications, it is recommended that the required quality level be determined by taking into account the required quality and reliability of the services provided by the equipment as well as the number of devices to be installed. The quality regarding soft errors can be determined by selecting the class of service quality and maintenance quality etc., according to [ITU-T K.139].

Next, during the design stage, it is recommended that the probability of soft error occurrence be estimated by theoretical means for the design of the initial unit of equipment. Then, measures shall be applied in order to satisfy the quality classes determined in the previous stage. Next, the theoretical estimation of occurrence probability shall be conducted for the second prototype. The mitigation measures should be evaluated, and additional ones developed, until the evaluated rate of occurrence satisfies the requirements for the class of quality. Details on the design methodologies are described in [ITU-T K.131].

Finally, it is recommended that the prototype equipment be tested by applying error insertion functions on actual equipment using tools provided by semiconductor vendors. Also, a neutron irradiation test according to [ITU-T K.130] should be conducted using an accelerator-driven neutron source and the equipment's quality class evaluated against soft errors. Details on quality estimation methods are described in [ITU-T K.138].
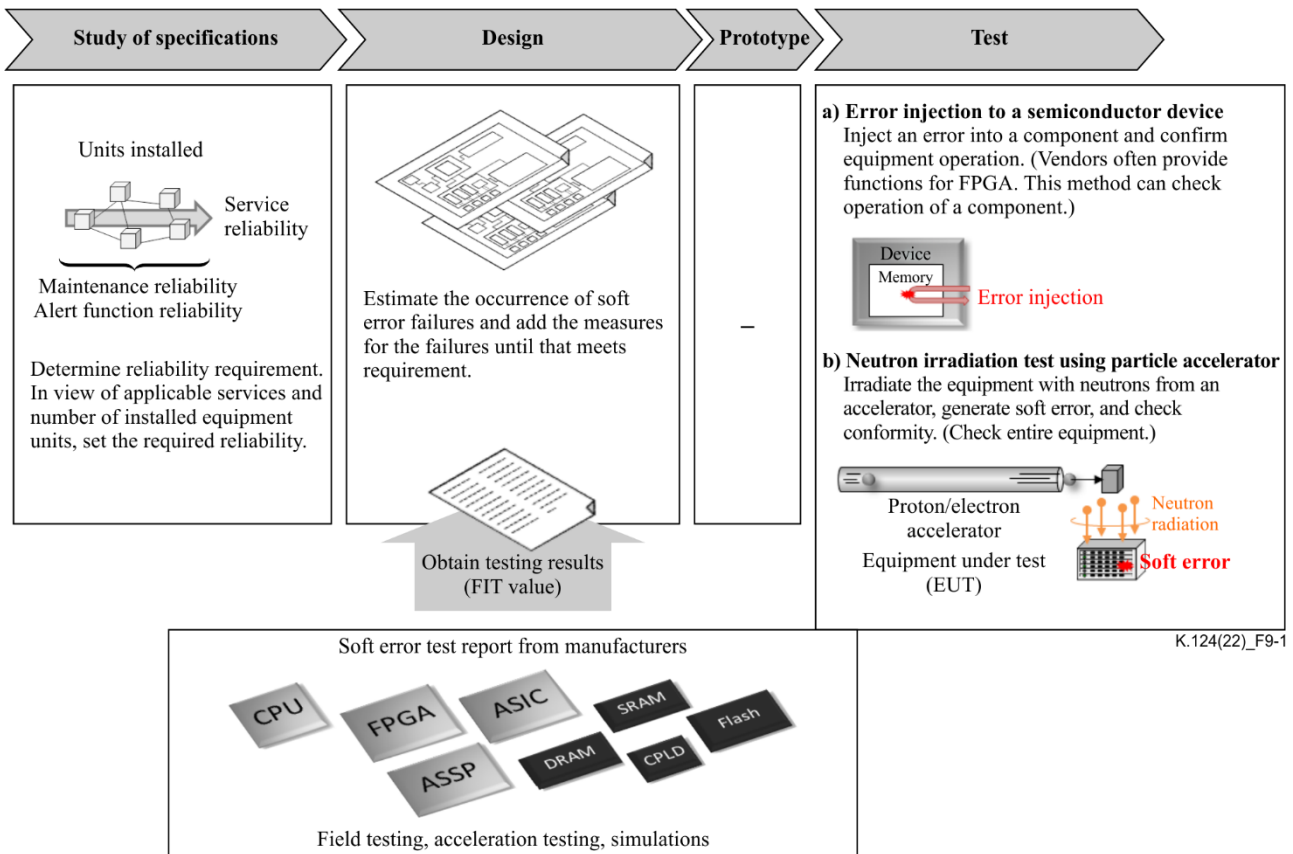
| Study of specifications | Design | Prototype | Test |

Study of specifications

Units installed

Service reliability

Maintenance reliability
Alert function reliability

Determine reliability requirement. In view of applicable services and number of installed equipment units, set the required reliability.

Design

Estimate the occurrence of soft error failures and add the measures for the failures until that meets requirement.

Obtain testing results (FIT value)

Prototype

–

Test

a) **Error injection to a semiconductor device**
Inject an error into a component and confirm equipment operation. (Vendors often provide functions for FPGA. This method can check operation of a component.)

Device
Memory
Error injection

b) **Neutron irradiation test using particle accelerator**
Irradiate the equipment with neutrons from an accelerator, generate soft error, and check conformity. (Check entire equipment.)

Proton/electron accelerator
Neutron radiation
Equipment under test (EUT)
Soft error

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Soft error test report from manufacturers

CPU
FPGA
ASIC
SRAM
Flash
ASSP
DRAM
CPLD

Field testing, acceleration testing, simulations

Figure 9-1 – Procedures for installation of soft error measures in development of equipment

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