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**Neutron irradiation test methods for
telecommunication equipment**

Recommendation ITU-T K.130



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Neutron irradiation test methods for telecommunication equipment

Summary

Recommendation ITU-T K.130 describes soft error test methods for the telecommunication equipment that composes carrier telecommunications networks. The objective of soft error tests of the telecommunication equipment using an accelerator-driven neutron source is described first. An overview of the soft error tests and operating principles of an accelerator-driven neutron source are then introduced. The requirements of the accelerator-driven neutron sources and test sites are specified. The test conditions including test set-up, operational conditions and error monitoring and test procedures for the telecommunication equipment are specified. Notes for determining specific detailed test methods, such as the neutron flux to be used for irradiation and conditions for counting as failures in estimation of the reliability are also described.

History

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Irradiation test, neutron, soft error.

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Introduction

The implementation of measures to mitigate faults caused by soft errors is essential to meet the reliability requirements for telecommunication equipment, which is composed of highly integrated, miniaturized semiconductor devices. However, since soft errors occur very infrequently in telecommunication equipment, at a frequency as low as once every few years or decades, the reliability cannot be checked under normal environmental conditions, which makes it difficult to verify the effects of the measures designed to reduce failures and to check conformity to requirements. Therefore, it is necessary to test by irradiating equipment with an intense flux of high energy neutrons produced by an accelerator-driven neutron source at a very high rate, such as several million to several tens of million times that which exists in the natural environment. This enables soft errors to be generated quickly and allows verification of conformity to reliability requirements and the effects of mitigation measures against failures caused by soft errors.

However, to evaluate the reliability of the equipment using a neutron irradiation installation, it is necessary to appropriately determine the irradiation site, the irradiation intensity of the neutron beam, the set-up of the equipment under test (EUT) and the method used to validate operation of the EUT at the time of the test.

This Recommendation describes the outline of the neutron irradiation test and requirements for accelerator-driven neutron sources, test sites, test set-ups and test procedures for testing telecommunication equipment regarding failures caused by soft errors.

Recommendation ITU-T K.130

Neutron irradiation test methods for telecommunication equipment

1 Scope

This Recommendation provides guidance on soft error test methods using an accelerator-driven neutron source for confirming the validity of soft error mitigation measures. It also describes the requirements for test conditions, such as the neutron generator, test site, test set-up and test procedure for testing conformity to the reliability requirements of the equipment. This Recommendation is applicable to telecommunication equipment installed at telecommunications centres for carrier networks, including core network equipment (link and node equipment) and access network equipment.

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 (2016), <i>Overview of particle radiation effects on telecommunication systems</i> .
[ITU-T K.131]	Recommendation ITU-T K.131 (2018), <i>Design methodologies for telecommunication systems applying soft error measures</i> .
[ITU-T K-Sup.11]	ITU-T K-series Recommendations – Supplement 11 (2017), <i>ITU-T K.131 – Soft error measures of field programmable gate arrays</i> .

3 Definitions

3.1 Terms defined elsewhere

None.

3.2 Terms defined in this Recommendation

This Recommendation defines the following term:

3.2.1 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.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

AE	Associate Equipment
AR	Alert Reliability
EUT	Equipment Under Test
MR	Maintenance Reliability
SR	Service Reliability

5 Conventions

None.

6 Advantages and objectives of neutron irradiation tests

Soft errors are caused by both high energy neutrons coming from outside of the equipment and alpha particles emitted from radioactive materials contained in semiconductor device packages. The occurrence rates of soft errors in semiconductor devices depend on their causes, i.e., the two kinds of particles; however, the phenomena and impact on the equipment do not vary regardless of the different causes. The failure modes after a soft error occurrence and the effects of the countermeasures do not vary regardless of the kind of particle causing the soft error in the telecommunication equipment. Since alpha particles do not penetrate deeply into solid material, it is difficult to test using alpha particles as it is necessary to remove the plastic packaging around the semiconductor devices to expose them to alpha particles. Thus, it is recommended to use neutrons for reliability tests for telecommunication equipment since their intensity is easily controlled during the test.

Neutrons are classified here into high energy neutrons and thermal neutrons and both types of neutron cause soft errors. The probability of the occurrence of soft errors caused by either type of neutron depends on the device type and feature size. However, considering the actual environment of telecommunication equipment, thermal neutrons are less likely to cause soft errors since cosmic-ray neutrons are mainly composed of high energy neutrons and thermal neutrons are shielded by the walls of telecommunications centres made of concrete etc.,. In addition, since soft errors generated by either type of neutron have the same effect on system operation, this Recommendation applies tests using high energy neutrons. The necessity for soft error tests using thermal neutrons is a subject for future study.

The purpose of this test using an accelerator-driven neutron source is to confirm the following by soft error tests:

- Conformity to the soft error reliability requirements
- Normal operation of soft error detection and correction functions
- Normal operation of alerts and event notification functions when soft errors occur
- Normal operation of functions (e.g., switching controls of redundant components, package reset start-up functions) in case of a failure caused by soft errors.

7 Overview of neutron irradiation test system for telecommunication equipment using an accelerator-driven neutron source

7.1 Configuration of neutron irradiation test facility

By using an accelerator, it is possible to generate a neutron flux which causes a soft error in a relatively short period of time. As shown in Figure 7-1, a particle accelerator facility that can be used for soft error tests consists of a cyclotron/linear accelerator chamber, a target chamber, a neutron irradiation chamber (some facilities do not have a separate one) and an accelerator control chamber. The cyclotron/linear accelerator chamber, target chamber and neutron irradiation chamber are designated as radiation controlled areas. The neutron flux is generated by a nuclear reaction by irradiating the target in the target chamber with protons / electrons accelerated by the accelerator in the cyclotron chamber. The neutron beam generated from the target directly irradiates the equipment under test (EUT) in the same room or is guided through the neutron flight tube in the shielding wall between rooms to irradiate the EUT in the next irradiation chamber.

The soft errors produced by the neutron irradiation are observed from the safely shielded accelerator control chamber by a control terminal to check the status of the EUT.

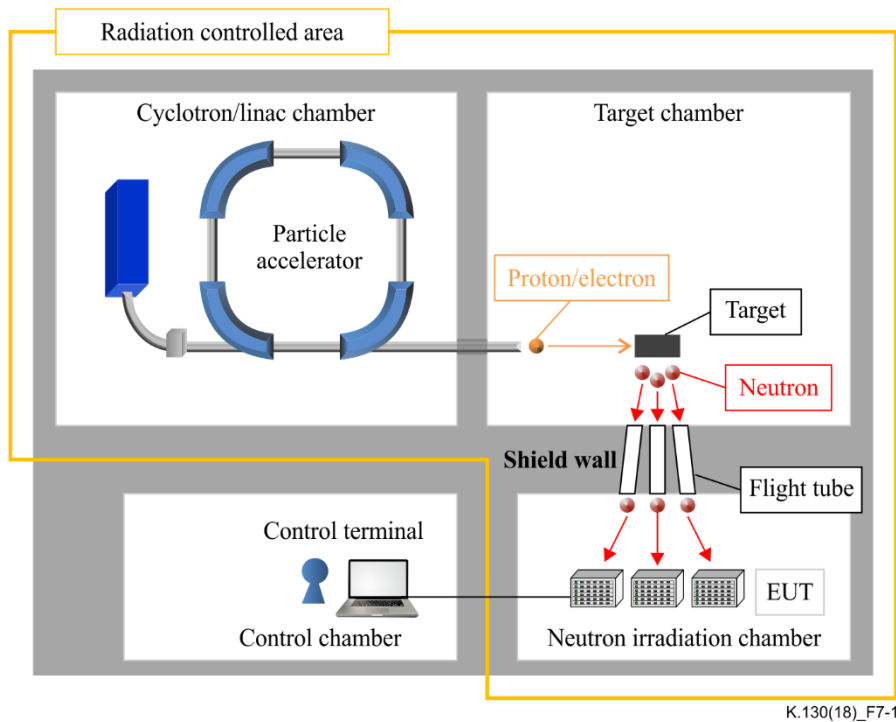


Figure 7-1 – Neutron irradiation test facility using an accelerator-driven neutron source

7.2 Target assembly requirements

When the target is irradiated with accelerated protons or electrons, high energy neutrons are produced through corresponding types of nuclear reactions. High energy neutrons are produced directly by a proton nuclear reaction, whereas electrons first produce gamma rays by reacting with the static electric field in the heavy metal atom and produce high energy neutrons through a photonuclear reaction.

In many facilities, as shown in Figure 7-2, thermal neutrons are generated by lowering the energy of high energy neutrons using a moderator (hydrogen-rich material), which is often employed in material research or neutron transmission imaging.

When performing a soft error test using an accelerator to which a moderator is usually attached for other purposes, the moderator as shown in Figure 7-3 shall be removed and the EUT shall be directly irradiated with high energy neutrons emitted from the target without deceleration.

There is also a method to increase the neutron flux to the EUT by reflecting neutrons traveling outside the path to the EUT by placing a reflector such as lead around the target.

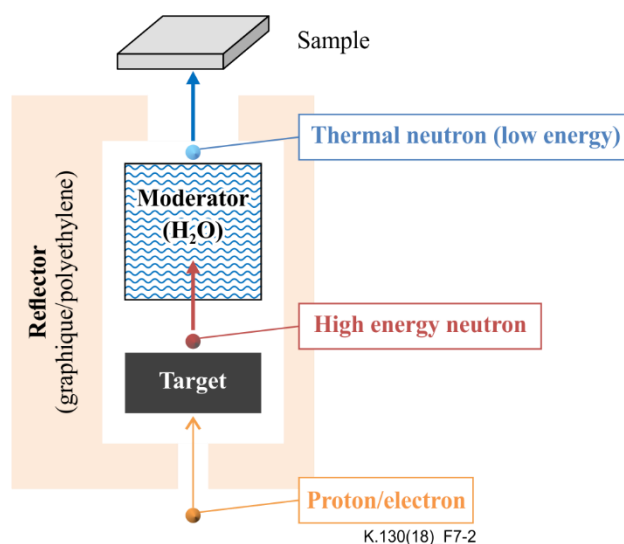


Figure 7-2 – Target assembly for thermal neutrons

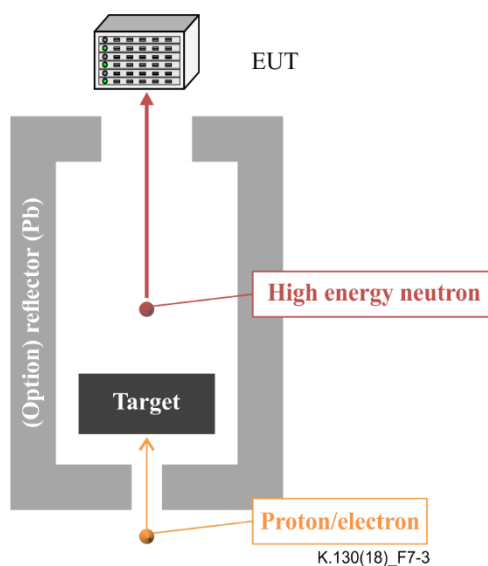


Figure 7-3 – Target assembly for soft error test

7.3 Requirements for accelerator-driven neutron source

Soft errors are caused by nuclear reactions between high-energy neutrons and the silicon nuclei in semiconductors. The stable composition ratios of silicon isotopes in the natural environment are ^{28}Si at 92.23%, ^{29}Si at 4.67% and ^{30}Si at 3.1%. Table 7-3 shows the nuclear reactions between each silicon isotope and neutrons, together with their threshold energies (the minimum energies required to cause a nuclear reaction). Since the majority of silicon is ^{28}Si , energy of about 4 MeV or more is required for tests in order to generate a specified number of soft errors.

A neutron in nature is caused by ultra-high energy particles travelling around the galaxy and includes ultra-high energy neutrons with energies up to several TeV. For this reason, a very large-scale accelerator is required, which can generate high energy neutrons to obtain a precise error rate in the natural environment very accurately; however, the numbers of and available time in this kind of facility are limited and the variable range of the irradiation area and beam intensity on such a very large-scale accelerator are narrow. Nevertheless, in telecommunication equipment installed at terrestrial telecommunication centres, soft errors due to neutrons having energy in the 4 to 10 MeV range and soft errors due to higher energy neutrons have been observed as nearly identical phenomena (memory bit inversion). Although there are some events with a very low probability

that cause permanent damage from high energy neutrons, such events are excluded from the scope of the neutron irradiation test since it is extremely rare for these specific situations to occur in telecommunication equipment.

It is recommended to use a relatively small accelerator facility capable of generating neutron energy of about 4 to 10 MeV, because the error rate of the natural environment can be reproduced with sufficient accuracy, the validity of the soft error measures can be confirmed and conformity to the reliability requirements regarding soft errors can be checked. An accelerator facility which has sufficient neutron energy to reproduce soft error should be selected based on the information of the neutron energy spectrum released by the accelerator facility, or calculation of the neutron energy spectrum from the configuration of an acceleration-driven neutron source. Figure 7-4 shows the neutron energy spectrum for accelerator facilities.

Table 7-3 – Si neutron reactions and threshold energies reaction with Si

Si - neutron reactions	E _{threshold}
$^{28}\text{Si} + n \rightarrow ^{28}\text{Al} + p$	3.999[MeV]
$^{28}\text{Si} + n \rightarrow ^{25}\text{Mg} + \alpha$	2.749[MeV]
$^{29}\text{Si} + n \rightarrow ^{29}\text{Al} + p$	3.009[MeV]
$^{29}\text{Si} + n \rightarrow ^{26}\text{Mg} + \alpha$	35[KeV]
$^{30}\text{Si} + n \rightarrow ^{30}\text{Al} + p$	8.040[MeV]
$^{30}\text{Si} + n \rightarrow ^{27}\text{Mg} + \alpha$	4.341[MeV]

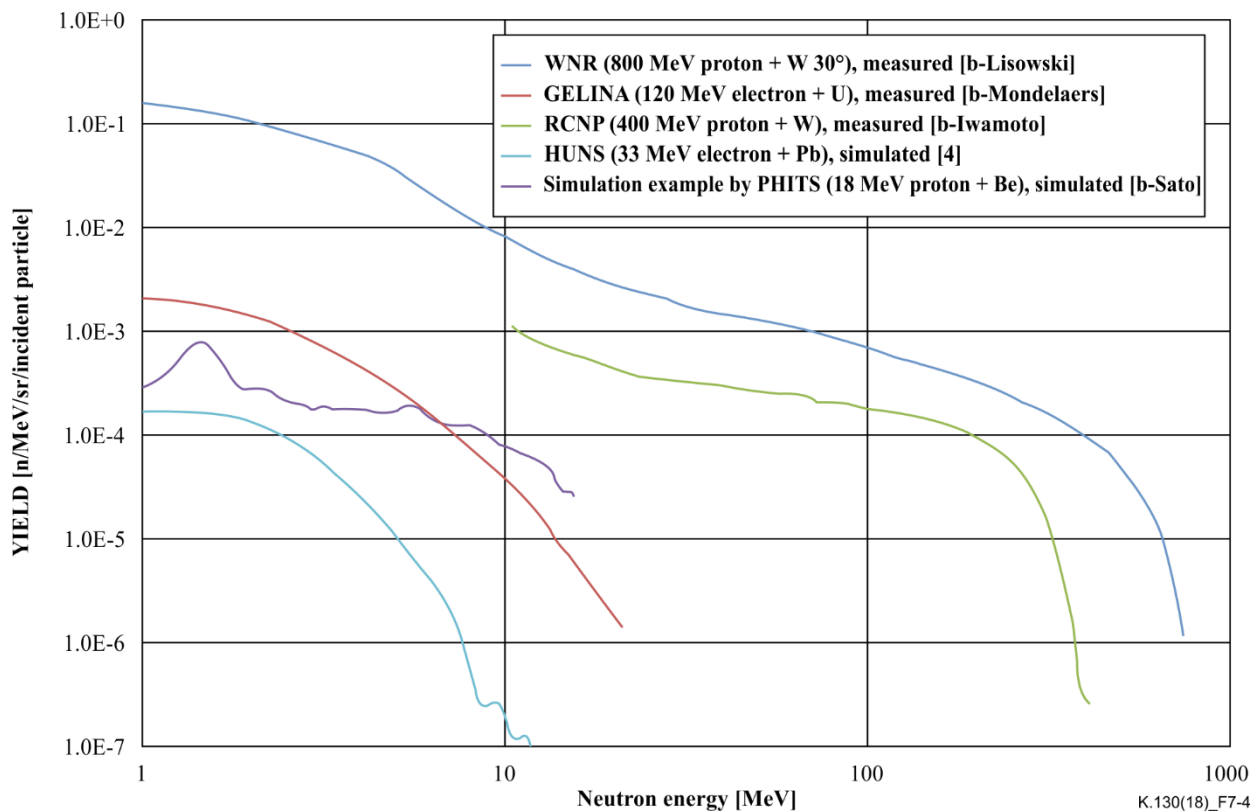


Figure 7-4 – Neutron energy spectrum for accelerator facilities

7.4 Elimination of unnecessary irradiation

In the neutron irradiation test, since only high energy neutrons, which are the major cause of soft errors, are to be irradiated, it is necessary to remove thermal neutrons and gamma rays that can cause permanent damage to semiconductors by shielding this unnecessary radiation. Also, from the viewpoint of improving test feasibility, the neutron irradiation area should be separated by appropriate shielding to reduce the induction of radioactivity in the irradiation chamber.

This clause lists the key issues for the shielding required to eliminate unnecessary irradiation to the EUT and outside of the irradiation field.

7.4.1 Shielding against thermal neutrons

In order to reduce the irradiation from thermal neutrons, shielding materials such as cadmium or boron, by which thermal neutrons are efficiently shielded but high energy neutrons are less affected, should be installed so that the EUT is not irradiated with thermal neutrons as shown in Figure 7-5.

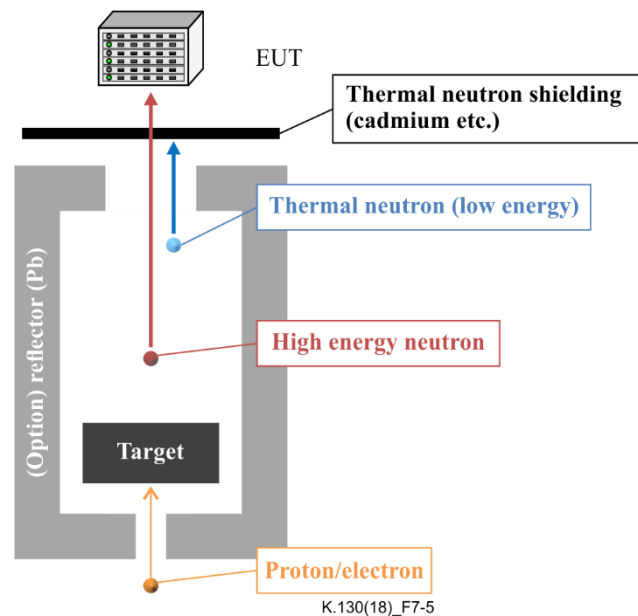


Figure 7-5 – Thermal neutron shielding

7.4.2 Shielding against gamma rays

When neutrons are generated by an electron accelerator, the target produces large amounts of gamma rays (greater than 10 Gy) [b-Eid]. Because gamma rays can physically damage semiconductors, lead blocks that shield gamma rays and easily transmit high-energy neutrons shall be installed. When using a proton accelerator, a shield for gamma rays is not necessary due to the minimal amount of gamma rays produced.

7.4.3 Separation between target chamber and neutron irradiation chamber

Even after the irradiation of protons or electrons to the target is stopped, the target, surrounding structures and air are radioactive, so nobody can approach immediately. On the other hand, during the neutron irradiation test of telecommunication equipment, the irradiation room frequently needs to be entered in order to confirm a failure situation that cannot be checked remotely, to reset the device manually and to replace a circuit pack, etc.

Therefore, the target and the neutron irradiation field should be in separate chambers and appropriate shielding should be installed between them. If a separate neutron irradiation chamber cannot be obtained, it is recommended to install appropriate shielding material around the target to reduce the number of neutrons other than to the EUT.

7.5 Simultaneous neutron irradiation of EUTs

In order to improve test efficiency, it is preferable to have facilities that can simultaneously irradiate multiple units of telecommunication equipment. It is possible to test multiple units simultaneously by placing them in front of multiple neutron beams emitted from a single target as shown in Figure 7-6.

In this case, it is preferable to have at least three neutron beam lines. Also, when multiple beam lines are used, each beam should be controlled independently. This can be achieved by installing shutters on the beam lines or by using remote-controlled lifts to move the EUTs up and down. When testing an EUT mounted on a lift, it is necessary to confirm the lift elevation accuracy.

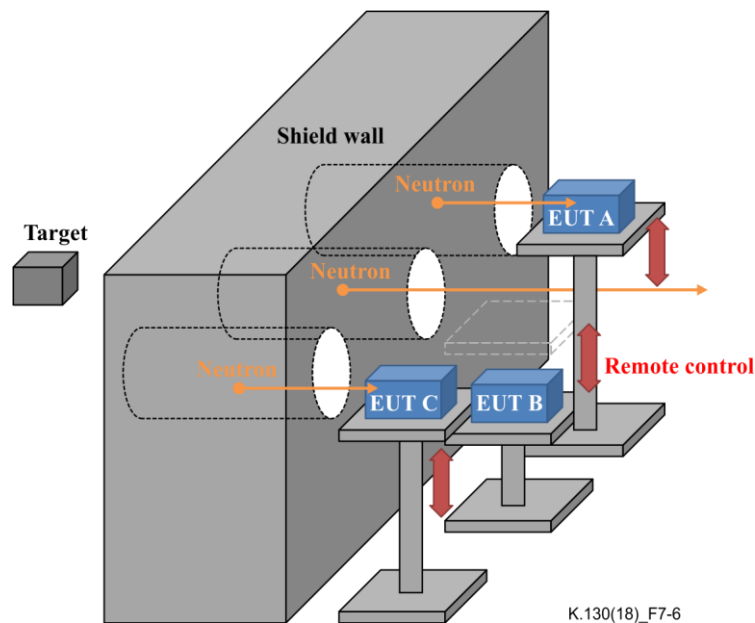


Figure 7-6 – An example of simultaneous irradiation to multiple EUTs using remote-controlled lifts

7.6 Irradiation area

If the irradiation area is small, it is necessary to change the irradiation position on the EUT and scan it to cover the necessary irradiation area, which increases the test time significantly. Hence, the irradiation area should be able to cover the entire EUT. As a result, it is possible to improve testing efficiency by irradiating neutron beams simultaneously to all the semiconductor devices in the EUT and thereby generating a soft error.

Taking into consideration the fact that ordinary telecommunication equipment is designed to be mounted on 19-inch racks and the height of modern units, it is recommended that the irradiation area is about 45 cm or more in width and height.

7.7 Uniformity of neutron flux

Since neutrons emit isotropically from the target, the neutron flux decreases in inverse proportion to the square of the distance. Figure 7-7 shows the neutron flux compared to distance from the target (the flux is normalized by the value at 1.0 m from the target). The flux can be increased in locations closer to the target, but flux change due to distance is also greater; for example, the flux reduces 30% when the separation increases by 20 cm from 1 m.

The position of the EUT should be 3 m away from the target in order to achieve a flux variation of less than 20% in the volume of an EUT whose depth is 30 cm. If a separation of 3.0 m cannot be achieved, the flux at the positions of components in the equipment shall be calculated carefully and

compensation should be applied to the reliability estimation since the difference in the flux within the EUT is too large.

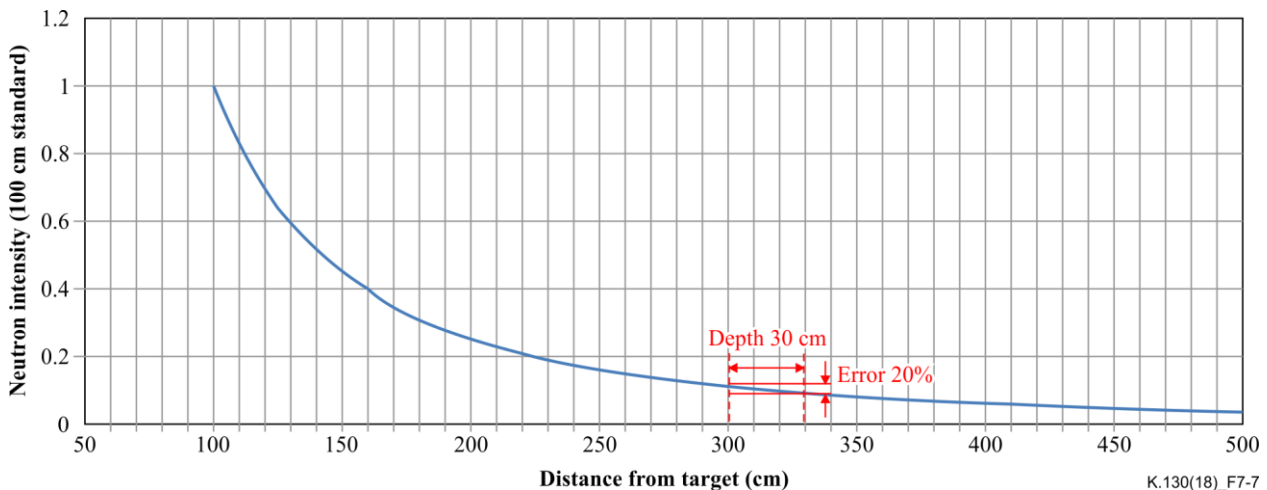


Figure 7-7 – Neutron intensity in relation to distance from the target

7.8 Miscellaneous notes

1) Power source for EUT

A power source is required in the irradiation chamber in order to operate the EUT. Sufficient power capacity must be available to operate the EUT.

For example, modern high-performance telecommunication equipment requires about 8000 W or more of power in the irradiation chamber. In addition, electric power of about 1500 W should be available for measurement equipment and control terminals in the control chamber.

2) Floor space for irradiation field

Enough space must be provided within the irradiation chamber to place a rack or other housing so that the EUT can be set up at the irradiation position. A floor space of about 80 cm × 80 cm is necessary for the test including the space for the DC power and associated equipment (AE).

8 Test set-up

8.1 Outline of test set-up

The test system consists of the EUT, terminals for monitoring and control of the EUT and AE.

The EUT is installed in the neutron irradiation chamber with all the installed packages to enable a comprehensive check of all the functions. The control terminal of the EUT is connected from the control room to the EUT and all functions which are used in normal operation should be installed. The following AE is installed: equipment to be normally connected to the EUT, signal measurement equipment for generating client signals and confirming signal normality and equipment for replicating the operational environment. It is desirable that the AE is installed outside the neutron irradiation chamber because it is out of the scope of the test, but in the case of installation in the neutron irradiation chamber due to cable and power supply restrictions, it is necessary to shield it from the neutrons with a concrete block, etc.

8.2 Configuration

The purpose of this test is to assess the reliability of the EUT in a manner that is consistent with its typical arrangement and use. Other arrangements may be used to check the entire area of the EUT

and/or to reduce test time, provided these arrangements can be shown not to have a significant effect on the performance of the EUT.

An EUT should include all types of packages, so that all functions can be comprehensively checked. The number of packages should depend on operating conditions. However, when there are many types of packages and it is not possible to mount all types of packages at once, it is also possible to install a part of them. In this case, the process is to change the package to be mounted, test multiple times and test all the packages in turn. In addition, when the physical size is large or the irradiation area is narrow and the entire package cannot be irradiated at once, it is also possible to irradiate a part of the EUT at a time. In this case, the entire EUT is covered by sequentially conducting the test while changing the irradiation position of the neutron beam.

Units and packages that do not irradiate in large systems (such as systems composed of multiple units) may be tested while they are in the irradiation room, or parts that are not irradiated may be placed in the control room and tested. The selection of these methods is based on whether the signal transmission and reception of the interface between the separated devices can be performed normally between the irradiation room and the control room.

If the EUT is a part of a system or can be connected to the AE, it should be connected to the necessary systems and AEs for testing compliance with all the types of reliability requirements.

The numbers of each package to be mounted, the configuration of the EUT including the irradiation chamber and the control room and the type and number of the AEs are decided from the range in which the error state propagates and the operating conditions.

8.3 Control terminals

The control terminal employed for this test should have all functions which are used in normal operation, e.g., receipt of all alarms and notifications from the EUT, confirmation of EUT status under test, execution of control functions and restoration of failures remotely.

Since these functions are subject to the soft error test, it is necessary to ensure that there is as little variation from normal operation as possible.

8.4 Positioning of EUT

The EUT should be mounted on a support base or rack and its position adjusted so that the neutron flux of interest is irradiated to the target area of the EUT. The material for the racks where the EUT and the communication device are installed is selected so that neutrons are not shielded or reflected. Also, it is recommended that there are no walls or doors covering the periphery of the EUT.

8.5 Control terminal and AEs installation

The AEs and a control terminal are not subject to the soft error test and their normality should be guaranteed. Therefore, these shall be installed in the control chamber of the test facility. If it is not possible to set up these devices in the control chamber, they shall be placed where the neutron flux is weak enough to avoid errors in the device, such as a position far from the neutron beam and be shielded by material such as concrete blocks.

8.6 Signal measurement equipment

To confirm operational normality during the irradiation test, the normality of client signals shall be checked using measurement equipment such as transmission signal test equipment. Client signals through all signal ports shall be measured since the occurrence probability depends on the signal port.

9 Operation of EUT and test procedure

9.1 Operation of EUT

From the perspective of client signal continuity and control/operational functionality in conjunction with telecommunication equipment functions, the following requirements must be met.

Client signal continuity perspective:

- Input traffic must be the maximum load possible with the test system configuration.
- Packet signals in the packet equipment must include packet lengths ranging from the minimum to the maximum length.
- Data patterns should be pseudo-random patterns.
- Monitoring of client signal error statuses for packet loss, packet errors and bit errors, etc., must be enabled.
- All notifications (alerts, warnings and events, etc.) from the EUT must always be able to be monitored.

Control and operational functionality perspectives (required for the functions that are implemented in the equipment):

- Switching controls of redundant component should be performed.
- Test functions should be performed (path continuity test, loopback test, etc.).
- Package reset and start-up functions should be performed.
- A firmware update should be performed.

All the types of data necessary to evaluate three kinds of reliabilities, i.e., service reliability (SR), maintenance reliability (MR) and alert reliability (AR), must be obtained. Combinations of measurement methods to reduce the testing time can be applied if this does not affect the normal operation of the EUT and evaluation of reliability.

9.2 Test procedures

Neutron irradiation test procedures are described below and Figure 9-1 part a) and part b) shows the flowchart for this soft error testing.

1. Connect the control terminal to the EUT and enable the EUT status and notification from the EUT to be monitored.
2. Pass through client signals to the EUT and enable the client signal continuity to be monitored.
3. Start monitoring the EUT status, notifications from the EUT and client signals.
4. Generate the neutron beam and record the time at which the neutrons are generated.

The following procedures vary depending on whether the event that occurred can recover autonomously if an abnormality occurs (such as detecting an alert or error on the client signal).

- a. When the event can recover autonomously:
 - 4a-1 Record the place where the soft error occurred, the period of continuous interruption of the client signals, the method used for recovery, notifications from the EUT and detected errors on the AE. (Notes 1, 2)
- b. When the event cannot recover autonomously:
 - 4b-1 Turn off the neutron beam and record the time at which the neutron beam is stopped.

- 4b-2 Record the place where the soft error occurred, the period of continuous interruption of the client signals, notifications from the EUT and detected errors on the AE. (Note 3)
- 4b-3 Remotely reset or restart the equipment to return it to its normal operational state and record the method used for recovery.
- 4b-4 Generate the neutron beam and record the time at which the neutrons are generated.

Repeat step 4 until the cumulative irradiation time of neutron beam becomes 25%, 50%, 75% and 100% of the irradiation time required to confirm conformance to the AR.

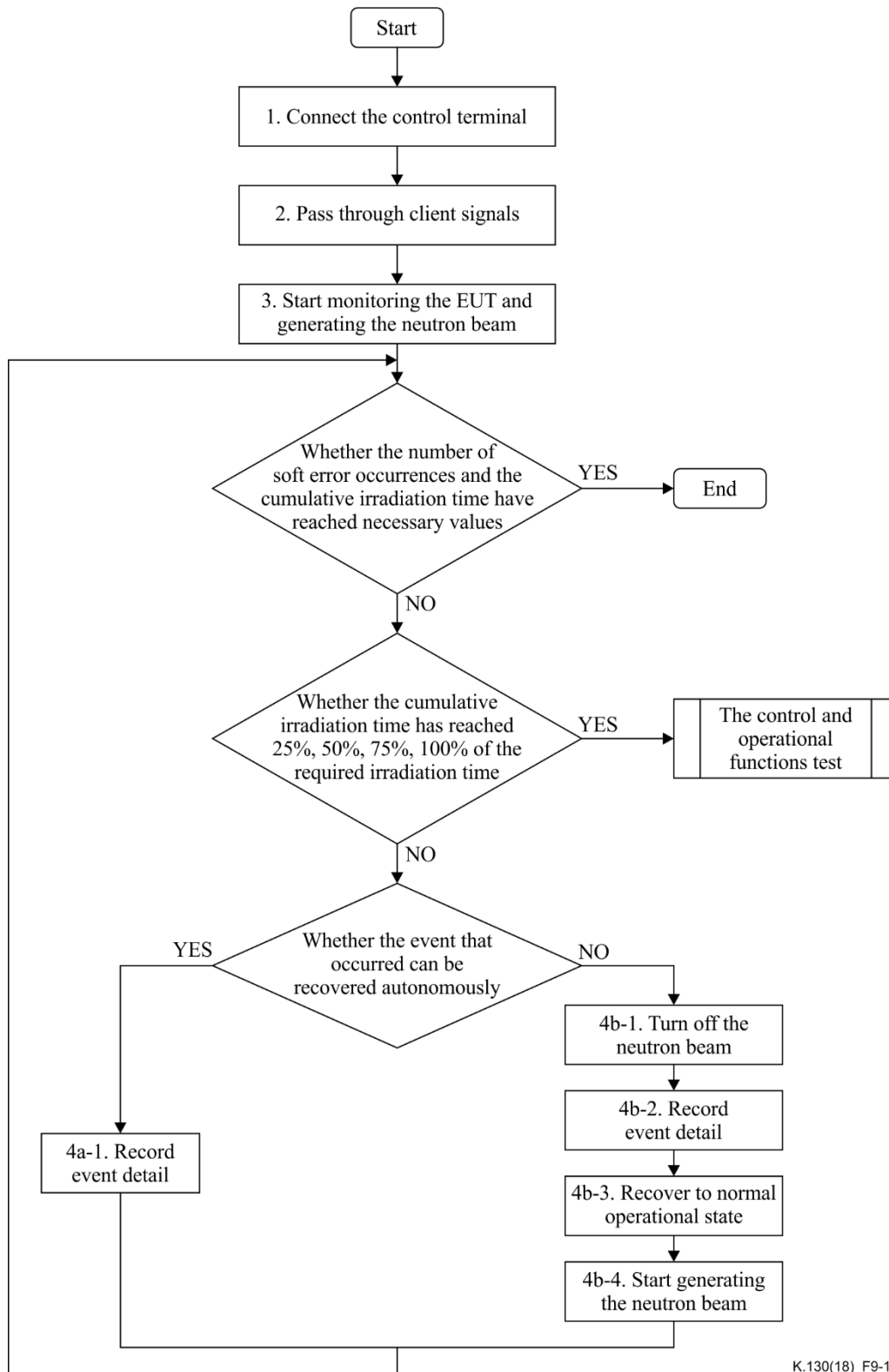
- 5. Turn off the neutron beam and record the time at which the neutron beam is stopped.
- 6. With the neutron beam stopped and client signals being passed through, perform the control and operational functions.
- 7. Record the place where the soft error occurred, the period of continuous interruption of the client signals, the method used for recovery, notifications from the EUT and detected errors on the AE if an abnormality occurs (such as detecting an alert, errors on the client signal or control failure, etc.). (Note 3)
- 8. Repeat step 7 until confirmation of all functionality defined in clause 9.1 is completed.

When confirmation of all functionality is completed, return to step 3 and repeat steps 3-8 until the cumulative irradiation time reaches the total irradiation time required to confirm conformance to the AR.

NOTE 1 – If the purpose of the testing is to confirm validity of soft error mitigation measures or to analyse soft error events in detail including autonomous recovery, the beam must be turned off and equipment logs retrieved.

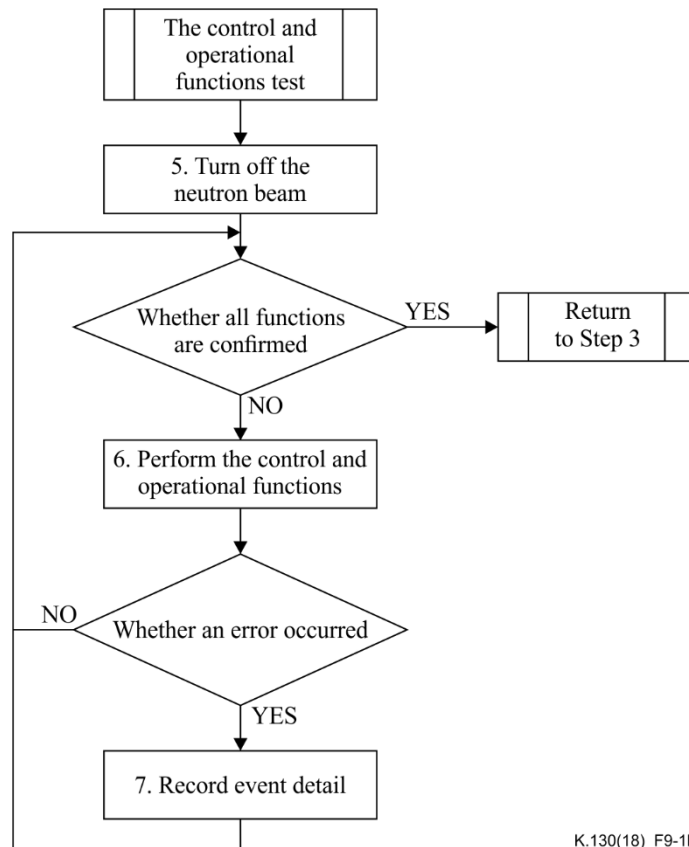
NOTE 2 – If the neutron beam irradiation is continued, soft errors may reoccur during autonomous recovery. However, because a soft error that reoccurs during the autonomous recovery cannot exist stochastically in the natural environment, this shall be ignored in the test results. Also, if the autonomous recovery requires a long time to complete, the neutron beam may be turned off.

NOTE 3 – The purpose of testing the control and operational functions is to confirm whether a soft error is actualized when each function is executed and an abnormality occurs. Thus, the neutron beam should be turned off when testing control and operational functions. Also, if a function that involves resetting the entire equipment is executed, soft errors that are present in the equipment will recover, so such a function must only be executed at the end of the test.



K.130(18)_F9-1a

(a)



K.130(18)_F9-1b

(b)

Figure 9-1 – Flowchart for neutron irradiation testing

9.3 Test report

In order to decide whether the reliability requirements (AR/SR/MR) are satisfied, the following items must be recorded in the test report.

1. Configuration of the EUT
2. Neutron energy spectrum
3. Irradiation area
4. Irradiation neutron fluence (calculated from the neutron energy spectrum, the total charge amount, the distance from the target, etc.) (See Appendix I)
5. Details of errors occurring during the irradiation test (information for evaluating the three types of reliability requirements)

Details of errors occurring during the irradiation test may include the period of continuous interruption of client signals, recovery time, whether the error recovered automatically, failure detection and issue of alert when a fault occurred, beam start time, beam stop time, etc.

Additionally, in order to reflect the test results in the design, it is recommended that the logs stored in the equipment be obtained and stored in an appropriate place and at an appropriate time so as not to be lost due to events such as equipment reset.

Appendix I

Method of calculation for neutron fluence

(This appendix does not form an integral part of this Recommendation.)

To evaluate the reliability specification for soft errors, the total number of neutrons (neutron fluence) irradiated to the communication device during testing and their energy distributions (neutron fluence energy spectrum) are required.

This clause describes the calculation method of the neutron fluence energy spectrum.

1. Obtain the total irradiation time $T_{\text{irradiation}}$ or total charge amount Q in the irradiation test.
In the case of an accelerator in which the current value (the number of accelerated particles per unit time) can be changed, the total charge amount is obtained.
In the case of an accelerator in which the current value cannot be changed, obtain the total irradiation time or the total charge amount.
2. Obtain the neutron flux energy spectrum $\Phi_A(E_n)$ of the accelerator at the irradiation position.
The neutron flux energy spectrum represents the number of neutrons of each energy passing through a unit area per unit time, per unit current, or per acceleration particle.
In the case of an accelerator in which the current value (the number of accelerated particles per unit time) can be changed, obtain a unit current or a neutron flux energy spectrum per accelerated particle.
In the case of an accelerator in which the current value cannot be changed, a neutron flux energy spectrum of any of unit time, unit current, or accelerated particle is obtained.
3. Calculate the neutron fluence H from the information obtained in steps 1 and 2 by the following formula.
 - a. When calculating from the total charge amount and the neutron flux energy spectrum per unit current.

$$H(E_n) = \frac{Q}{A} \times \Phi_A(E_n) \quad A: \text{unit current value}$$

- b. When calculating from the total charge amount and the neutron flux energy spectrum per accelerated particle.

$$H(E_n) = \frac{Q}{q} \times \Phi_A(E_n) \quad q: \text{elementary charge, } 1.6 \times 10^{-19} \text{ C}$$

- c. When calculating from total irradiation time and neutron flux energy spectrum per unit time.

$$H(E_n) = T_{\text{irradiation}} \times \Phi_A(E_n)$$

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