European Space Components Coordination



# SINGLE EVENT EFFECTS TEST METHOD AND GUIDELINES

## ESCC Basic Specification No. 25100

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# 1 SCOPE

## 1.1 GENERAL

This specification defines the basic requirements applicable to the Single Event Effects (SEE) testing of integrated circuits and discrete semiconductors suitable for space applications.

## 1.2 PURPOSE

The purpose of this specification is to define the requirements for the testing of integrated circuits and discrete semiconductors for SEE arising from irradiation by energetic heavy ions or protons.

## 1.3 APPLICABLE DOCUMENTS

### 1.3.1 ESCC Specifications

No. 21300, Terms, Definitions, Abbreviations, Symbols and Units.

### 1.3.2 Other (Reference) Documents

ASTM F1192-11, Standard Guide for the Measurement of Single Event Phenomena (SEP) Induced by Heavy Ion Irradiation of Semiconductor Devices.

EIA/JEDEC JESD57, Test Procedures for the Measurement of Single Event Effects in Semiconductor Devices from Heavy Ion Irradiation.

EIA/JEDEC JESD89, Measurement and Reporting of Alpha Particle and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices.

EIA/JEDEC JESD234, Test Standard for the Measurement of Proton Radiation Single Event Effects in Electronic Devices.

MIL–STD–750, Method 1080, Single-Event Burnout and Single-Event Gate Rupture.

# 2 TERMS, DEFINITIONS, ABBREVIATIONS, SYMBOLS AND UNITS

The terms, definitions, abbreviations, symbols and units specified in ESCC Basic Specification No. 21300 shall apply. For the purpose of this specification, the following additional definitions shall apply.

- Electronic Stopping Power, or Linear Energy Transfer (LET)

  The electronic stopping power is the amount of energy lost by the incident ion along its path in the absorber medium when colliding with atomic electrons. It is expressed in units of energy per unit length, MeV/cm.

  In the present document, LET is the electronic stopping power divided by the mass density of the absorber medium, i.e. the mass electronic stopping power. LET is expressed in units of MeV/(mg/cm$^2$) or MeV.cm$^2$/mg. LET is the unit of reference for SEE irradiation with heavy ions.

- Effective LET

  The equivalent LET obtained by tilting the device under test with respect to the beam axis, hence increasing the path length of the ion and the total energy deposited. Effective LET = Incident LET x $1/\cos\theta$ where $\theta$ is the tilt angle of the device.

  Effective LET may also be used to refer to the actual LET in a sensitive volume after taking into account the energy loss in “dead layers” such as metallisation and passivation.

- Charge Transfer or Deposition

  The LET expressed as charge deposited per unit length (by electron-hole pair creation). Expressed in units of pC per µm.

  A LET of 97MeV.cm$^2$/mg will give 1pC per µm in silicon.

- Flux

  The number of ions passing through a unit area perpendicular to the beam, in one second. Units: ions/cm$^2$/sec.

- Fluence

  The flux integrated over time. Units: ions/cm$^2$.

- Cross-section

  The number of events per unit fluence, expressed in units of cm$^2$/device or cm$^2$/bit. In the event of the device being tilted at an angle $\theta$, the fluence must be corrected by multiplying the fluence by Cos $\theta$. See also Para. 4.2.7.

- Ion Species

  Type of ion being used for irradiation (e.g. oxygen, neon etc.).

- Range

  The distance travelled, without straggling, in the target material by the specified ion of given charge state and energy.

- Energy

  The energy imparted to the ion by the accelerator. This may be in units of total energy (MeV) or energy per nucleon (MeV/n). Energy is the unit of reference for SEE irradiation with high energy protons.

- Single Event Upset (SEU) also known as a Soft Error

  The change of state of a latched logic cell from one to zero or vice-versa. A single event upset is non-destructive and the logic element can be rewritten or reset.

- Multiple Cell Upset (MCU)

  The change of state of two or more logic cells induced by a single ion strike. The corrupted cells are usually, but not always, physically adjacent.

- Multiple Bit Upset (MBU) or single word multiple-bit upset (SMU)

  A particular case of MCU when the corrupted cells are in the same word. Note that MBU cannot be corrected by a simple (single-bit) error correction code.

- Single Event Transient (SET)
  A temporary voltage excursion (voltage spike) at a node in a logic, or linear, integrated circuit. Caused by a single energetic particle strike.

- Single Event Functional Interrupt (SEFI)
  A soft error that causes the component to reset, lock-up, or otherwise malfunction. SEFI typically occur in complex devices with built-in state/control sections like in modern memories (SDRAM, DRAM, NOR- and NAND-Flash, etc.), all types of processors, FPGA or ASICs, or mixed-signal devices. Two main types of SEFI are distinguished depending on the actions required to restore operability: reset by software or by power cycling. The stored data may or may not be lost.

- Single Event Latch-up (SEL)
  A permanent and potentially destructive state of the device under test whereby a parasitic thyristor structure is triggered by an ion strike and a low impedance, high current path is created.

- Single Event Snap-Back (SESB)
  A high current state and subsequent localized heating when the parasitic bipolar structure in a single MOS transistor is triggered by an ion strike.

- Single Event Hard Error (SEHE) or Stuck Bit
  Permanent or semi-permanent damage of a cell by an ion strike.

- Single Event Gate Rupture (SEGR) or Single Event Dielectric Rupture (SEDR)
  Destructive rupture of a gate oxide or any dielectric layer by a single ion strike. This leads to leakage currents under bias and can be observed in power MOSFETs, linear integrated circuits (with internal capacitors), or as stuck bits in digital devices.

- Single Event Burn-out (SEB)
  Triggering of the parasitic bipolar structure in a power transistor, accompanied by regenerative feed-back, avalanche and high current condition. SEB is potentially destructive unless suitably protected.

- Destructive events
  All single event effects resulting in the device's irreversible operational failure. This includes SEGR, SEDR, non-protected SEB and SEL, and SEHE or stuck bits in such numbers that they cannot be mitigated by error correction codes.

- Threshold LET or Energy
  The lowest LET or energy at which SEE occurs.

- Saturated Cross-section, also known as asymptotic cross-section
  The cross-section for which an increase in ion LET or proton energy does not result in an increased number of upsets. Note that in some cases the asymptotic cross-section is not reached due to MCU.

- Level of Interest
  A cross-section, energy, LET or fluence having some particular significance for a programme or project.

## 3 EQUIPMENT AND GENERAL PROCEDURES

The equipment shall consist of the radiation source, electrical measurement or monitoring system and test software, test circuit board(s), cable, interconnect board or switching system, test fixtures, and the appropriate dosimetry and diagnostic instruments.

Precautions shall be taken to obtain an electrical measurement or monitoring system which by use of sufficient insulation, ample shielding, line drivers and receivers, satisfactory grounding etc. shall yield suitably low levels of interference from mains power supplies, magnets, switching systems and other sources of noise. The magnitude of interference from each of these items shall constitute the test requirements.

### 3.1 RADIATION SOURCE AND DOSIMETRY

#### 3.1.1 Source, General

The radiation source used for SEE tests shall be a particle accelerator capable of delivering the required flux and fluence of heavy ions or protons of suitable LET and energy. The radiation field shall be uniform to ±10% over the area of the device(s) under test in terms of both fluence and energy. It is the User's responsibility to have exact knowledge of the location of the active surface of the tested component and all materials in the beam's path which will degrade the beam energy, and to make the appropriate adjustments in the energy and/or LET values when reporting the results.

#### 3.1.2 Source, Heavy Ions

The heavy ion accelerator shall be capable of delivering ions with a range of at least 40µm in silicon with variable flux ranging from a few 10 ions/cm$^2$/s to at least $10^5$ ions/cm$^2$/s on the device under test.

Unless the accelerator allows extraction of the beam in air, the accelerator beam-line shall be equipped with a suitable vacuum chamber allowing the irradiation of delidded components and accurate alignment of the device under test. Rotation of the axis of the component with respect to the beam is a desirable facility. The device under test shall be shielded from incident light during test.

#### 3.1.3 Source, Protons

In the case of high energy proton tests, SEE are induced by the ionizing by-products of nuclear interactions between incident high energy protons and the tested device. The high energy proton accelerator shall be capable of delivering protons in the energy range 20 to 200MeV with a variable flux ranging from $10^5$p/cm$^2$/s to at least $10^8$p/cm$^2$/s on the device under test. It is recommended that the primary energy of 200MeV is not degraded below 50MeV for SEE measurement to avoid excessive energy spreading. Below 50MeV, a primary beam shall be set at about 60-50MeV and degraded down to 20MeV. Irradiations under high energy protons may be performed in air without delidding the components. Exposure is usually performed with the device normal to the beam. However, some devices have been observed to be more sensitive at a grazing angle. It is recommended to check the effect of angle on the SEE sensitivity.

Modern components (90nm technology node or below) may also be sensitive to direct ionisation from low energy protons. It can be detected under primary proton energy typically less than 60-50MeV using degraders with well-controlled thicknesses. It is however recommended to use a low energy proton accelerator with a quasi-mono energetic beam to avoid the energy spread when using degraders at high energy. The low energy proton accelerator shall be capable of delivering protons in the energy range of few MeV with a narrow and tightly controlled energy spread and with a variable flux ranging from 100 to $10^8$p/cm$^2$/s on the device under test. The device under test shall be delidded if possible. It is advised to have an exact knowledge of the insulating and conducting overlayers, or any materials (thickness and location) above the device sensitive regions, in order to carefully assess the beam energy spectrum at the active surface of the tested device.

### 3.1.4 Dosimetry

Dosimetry shall allow the continuous monitoring of the flux at the device throughout the test with an accuracy of ±10%. The dosimetry technique shall be reported. The device under test shall be mounted at a calibrated position, where the facility ensures accurate dosimetry.

The total ionising dose to the device under test shall be calculated and recorded. The total ionising dose D received by the device under test is given by:

$$D = F \times LET \times 1.6\times10^{-5}$$

where D is the deposited dose in rad, F is the Fluence measured in the plane normal to the beam in ions/cm$^2$ and LET is expressed in MeV.cm$^2$/mg.

If degraders, or any other material, are used in the beam's path for proton or heavy ion testing the full energy spectrum shall be measured after the degrader. If not possible, it shall be measured before the degrader and calculated after the degrader.

It is the facility's responsibility to maintain a procedure for calibrating the provided beam. A calibration procedure shall be used each time the primary beam energy or the particle species is changed. Upon the User's request, the facility shall be able to provide the calibration data. This includes:

- beam purity and energy spectrum
- beam flux and fluence, and spatial uniformity

The User has to be vigilant that the beam conditions are according to specification. The use of a well-known "golden" part, or any dosimetry element, is recommended to check the delivered beam.

For heavy ion and low energy proton testing, the code and version used to express the LET values shall be provided when reporting results. In practice, preferred codes are SRIM (version 2003 or after) or codes developed or used by the facility.

3.2 TEST SYSTEM

3.2.1 Test Board and Cabling

The test board provides mechanical support for the device(s) under test and provides electrical connections to the feedthrough connectors which provide electrical connection from inside the vacuum chamber to the monitoring equipment cables. For certain testing the test board may be a full single board computer which provides all monitoring of the device under test. The full set-up of test board and cabling shall be proven to be noise free in the accelerator operating environment.

Inside the vacuum chamber a support frame is required for the test board, and the frame/test board assembly must allow positioning of the device(s) in the path of the beam. It is desirable that it also allows accurate rotation about the X or Y axis for modification of the effective LET. The frame is generally facility specific and provided by the accelerator laboratory.

3.2.2 Device Test System

The device test system shall be designed to cover the needs for characterisation of all single event effects of concern in the device under test.

3.2.3 Temperature

The temperature of the device under test shall be monitored and recorded unless otherwise agreed with the Customer.

**4 PLANNING AND PROCEDURES**

Further information on test planning is given in the guidelines (Appendix A).

4.1 SAMPLE SIZE, SELECTION AND PREPARATION

For the characterisation of non-destructive events (SEU, SEFI, SET, …), a sample size of 3 pieces is recommended, 2 pieces are required as a minimum. For the characterisation of destructive events (SEGR, SEB, …), a sample size of 3 pieces shall be used as a minimum to check the pass compliance for each test condition unless specific agreement has been made with the Customer. A larger number of pieces might be used for a better statistical determination of failure events. In all cases, the selected samples shall be of identical technology, i.e. same process and same diffusion mask set.

Delidding or substrate thinning is required for heavy ion and low energy proton testing when the beam energy degradation in the package induces a large uncertainty of the beam energy spectrum when reaching the die. In the case of flip-chipped devices, substrate thinning might also be necessary to ensure that the beam reaches the active surface of the die. After delidding and/or substrate thinning, a functional test shall be performed (care shall be taken to exclude all light during this test).

Delidding or substrate thinning is not required for high energy proton testing or for very high energy heavy ions, when the beam range is notably larger than the packaged device. However, the package and/or substrate material and thickness shall be carefully noted so that the beam energy and LET are calculated at the active surface of the die if the energy degradation is significant.

Each sample shall be clearly marked to facilitate traceability of test data. A photograph of the die and of the die marking shall be taken to aid in data analysis and evaluation. The die size shall be measured and any die identification or marking shall be recorded.

## 4.2 ELECTRICAL MEASUREMENTS

### 4.2.1 Single Event Upset

The device architecture shall be studied to identify functional blocks containing bistable elements such as registers or memory cells. Test hardware and software shall be designed to allow the monitoring of functional blocks, together with the possibility of writing different patterns (e.g. all zero's, all one's, checker board, random pattern, etc.) and the re-writing of an affected cell after an SEU. The test software shall be capable of logging the number of upsets, the location and the time. It shall be capable of identifying and logging MCU and MBU.

A device may well contain a number of bistables of different design, each having a different single event sensitivity. Test coverage should be such as to allow these different sensitivities to be identified.

### 4.2.2 Latch-up

Test hardware and software shall be designed for latch-up detection, protection and logging. The response time of latch-up protection shall ensure that there is no damage or degradation of the device under test. Software shall be tested to establish the percentage of "active time", that is the amount of time the device under test is in a condition sensitive to detectable SEE. The remaining time ("dead time") is used for software operations (device reset, reading, writing, logging etc.) during which SEE may occur without being detected. The percentage of active time shall be taken into account when calculating the cross-section of the device using raw fluence and event data. The beam flux shall be sufficiently low to minimize the dead time below 20% of the active time.

### 4.2.3 Single Event Transients

Analogue and mixed analogue/digital ICs may generate false outputs or transients as the result of SEE. Due to the fact that the bias, and input and output load conditions significantly impact both the device SET sensitivity and characteristics, the device shall be tested either in worst-case or in the application conditions. The test system shall be capable of monitoring and logging these single event transients. The polarity (positive or negative), waveform, duration and amplitude of the transients shall be recorded.

The beam flux shall be sufficiently low so that the risk of SET pileup is minimum. SET pileup shall be discarded or analysed separately by post-irradiation software analysis.

### 4.2.4 Single Event Functional Interrupt

The SEFI sensitivity depends on the device operating mode. The device shall be tested in all operating conditions potentially encountered in applications. Test hardware and software shall be designed for the detection, logging and correction of all SEFI types. This includes software programming flexibility and hardware capability for reset and power cycling.

### 4.2.5 SEB and SEGR test of power MOSFETs

Test hardware and software shall be designed in accordance with MIL–STD–750, Method 1080. The test sequence for characterization and verification tests of the SEB and/or SEGR sensitivity of power MOSFET transistors shall follow the MIL–STD–750, Method 1080 test method.

SEB testing is performed either in destructive or non-destructive mode. However, if performed in non-destructive mode with a resistance in the drain path, it shall be checked in two bias conditions as a minimum, in order that the resistance value is low enough for SEB to be correctly detected.

SEGR testing is performed in destructive mode only. SEGR produces catastrophic failure if a large gate bias is applied. However, if a relatively low gate bias is applied during irradiation (typically, less than 50% of the maximum rated gate voltage is considered low), SEGR produce latent defects only. Therefore, a post gate-stress test shall be performed after each irradiation step to reveal potential latent defects.

The post gate-stress test consists of applying a gate-to-source voltage Vgs, while the drain-to-source voltage Vds is at 0V. This test may use either a positive or negative Vgs, or tested to both conditions. The post gate-stress bias shall apply Vgs equal to the maximum rated gate voltage (±10%) and for a minimum of one second unless otherwise specified in the test requirements.

4.2.6 Test Conditions

The test conditions must be established to ensure that the SEE tests are performed with the conditions of a specific application or worst-case for each device type. This includes all electrical parameters applied on the device under test (supply voltages, stimulus inputs, temperatures, clock frequency, etc.) and the beam conditions.

In general, the device worst-case test conditions depend on the application requirements and the measured effects:

- SEU: minimum operating voltage and maximum clock frequency (if applicable).
- SET: worst-case or equivalent to application.
- Latch-up: maximum operating voltage and maximum operating temperature.
- SEB and SEGR: low operating temperatures. Room temperature is usually considered acceptable.

The beam shall also be chosen for worst-case test conditions.

- For high energy proton SEE tests, the worst-case is generally obtained at maximum proton energy. However a scan of the complete proton energy range (typically from 20MeV to 200MeV) is recommended.
- For heavy ion SEU, SET and SEFI tests in CMOS logic devices, a minimum range of 40µm in the target material is recommended. In linear devices and all devices with a relatively thick sensitive volume (>10µm like in bipolar, JFET, etc.), a minimum range of 60µm is recommended. If technology analysis is available the beam energy and range should be such that the Bragg peak is placed beyond the sensitive volume.
- For latch-up test under heavy ions a minimum range of 60µm in normal incidence shall be used unless it can be demonstrated that a lower range beam is sufficient to reach worst-case latch-up sensitivity.

- For SEB and SEGR tests under heavy ions, the ion beam energy shall provide sufficient penetration depth for a worst-case SEB and SEGR response. Note that for a given ion species, the ion beam energy has been shown to influence the SEGR failure thresholds. For SEGR, it was shown that the worst-case test condition occurs when the beam fully penetrates the epitaxial layer(s) with maximum energy deposition in the epitaxial layer(s). If technology analysis is available, the beam energy should be tuned to approach this worst-case energy condition. If technology analysis is unavailable, determination of the worst-case energy may require multiple irradiations with the same ion species at different energies. In both cases, the worst-case energy shall be experimentally checked. The worst-case angle of incidence shall also be assessed. For planar-type devices, the worst-case is generally at normal incidence. However, for trench-type, lateral diffusion MOS or other devices with a complex shape of the sensitive volume, the worst-case might occur in either positive or negative tilt or roll angles of incidence. These angle test conditions shall be assessed. For SEB and SEGR tests of power devices, using effective LET values when tilting the device is invalid and shall not be used. The ion species, energy and angle of incidence shall be used.

4.2.7 Units of Measure

The SEE sensitivity of the device under test is the cross-section σ and shall be expressed as the ratio of the number of events to the total particle fluence; that is, the number of events/particle/cm$^2$. The particle (ion or proton) fluence is measured in a plane normal to the beam.

$\sigma$ = number of events / fluence

For proton or heavy ion irradiation, the SEE cross-section is expressed as a function of, respectively, the proton energy or the ion LET at the active surface of the die. The proton energy or ion LET shall be corrected by taking into account the energy loss in all materials in the beam path. In any case, the beam energy shall be sufficient such that the ions can reach the active surface of the die.

In particular in the case of flip-chipped components under heavy ion irradiation, the LET value shall be corrected by taking into account the substrate thickness.

For heavy ion testing only, if the angle of incidence of the beam relative to the device under test is varied, an effective LET can be calculated as the normal incidence LET divided by the cosine of the angle:

LET (eff) = LET (normal incidence) / cos θ

where θ is the tilt angle of the device under test with respect to the beam axis. θ = 0 when the device surface is normal to the beam axis.

If the angle of incidence is varied, the effective fluence will also change; therefore, the measured fluence shall also be corrected and the cross-section shall be calculated as:

$\sigma$ = number of events / (fluence × cos θ)

where the fluence is measured in the plane normal to the beam.

Note that the effective LET is valid only if the depth of the sensitive volume is small compared to its lateral dimensions. More generally, the concept of effective LET shall be used with caution for components with complex shapes of sensitive volume. It is advisable to check the validity of the effective LET by comparison with normal incidence SEE results. In particular, in the event of an insensitive device, the device is commonly considered immune to SEE if tested in normal incidence at a minimum LET of 60MeV.cm$^2$/mg.

Excluding occasional cases of device degradation during SEE testing (see 4.3), SEE is a random phenomenon. The measured number of events during irradiation obeys a Poisson distribution. It is recommended to use error bars when reporting the measured number of events and the cross-section. The chosen confidence level and error bar calculation shall be reported. Preferably, and by default, a confidence level of 95% shall be used. An error bar formula is provided in Appendix A.

## 4.3 TEST PLAN

Prior to performing the tests, a Test Plan shall be prepared using the plan form found in the ESCC forms section of ESCIES (https://escies.org). Ion species and energies shall be chosen to cover the energy or LET range from SEE threshold to saturated cross-section for the device under test.

For LETs not directly available, the device may be tilted to give an increased “effective LET”, but with the precautions exposed in paragraph 4.2.7. For high energy proton testing only a range of energies needs to be specified (typically 20 to 200MeV) covering threshold to saturated cross-section. The device under test will be normal to the beam axis for all high energy proton testing.

For both heavy ion and proton testing, about 5 exposures (at different LET or Energy) are required to adequately plot a response curve.

The fluxes chosen should be such as to accumulate a meaningful, i.e. statistically significant number of events in one or multiple exposures of typical test time of 1 to 20 minutes each or, in the case of an insensitive device (as an example at LET 60MeV.cm$^2$/mg in normal incidence as defined in the ECSS-Q-ST-60-15), to accumulate a recommended fluence of $10^7$ ions/cm$^2$ for heavy ions, or $10^{11}$ protons/cm$^2$ for protons, or according to the MIL-STD-750 fluence requirements for power devices. Fluxes must be compatible with the response time of the device under test and the speed of test hardware and software.

The SEE response can degrade because of accumulated total dose or displacement damage or ageing. To verify the effect of the device degradation on its SEE response, it is recommended to monitor the device electrical parameters (e.g. supply current) and to frequently run a reference test condition during the SEE test campaign. The total fluence and ion species received by each sample shall be recorded.

For both proton and heavy ion testing, careful note shall be kept of the total ionising dose delivered to the device under test (see paragraph 3.1.4). The total dose may be significant and necessitate the use of new samples during the tests. It is suggested to perform total dose test before the SEE test. If the device is particularly sensitive to total dose, a larger number of samples shall be prepared for the SEE test.

## 5 DOCUMENTATION

### 5.1 GENERAL

For each SEE test to be performed 2, sets of documents are required:

(a) A Test Plan (prior to testing) defining the detailed requirements for the components to be tested including a description of the test hardware and a flow chart for the test software.
(b) A Test Report giving the actual test conditions and test results.

### 5.2 TEST PLAN

As a minimum, the Test Plan shall contain the information below. The information shall be entered (preferably type-written) in boxes in the plan form found in the ESCC forms section of ESCIES (https://escies.org) or using a software routine (ESA Radiation Effects Database Data - Collection Tool).

- Reference number of Test Plan (3 digits starting from 001).
- Reference (issue and revision with dates) of the Single Event Test Plan.
- Equivalent ESCC Component Number if existing.
- Component Designation and Description (e.g. quad 2-input exclusive OR gate) and commercial part number if necessary.
- Manufacturer/User Single Event Test Specification (number, issue, revision).
- Applicable ESCC Generic and Detail Specifications (numbers, issues, revisions).
- Type of radiation: Heavy Ions or Protons.
- Type of test: (SEU, SEFI, SET, SEL, SEB, SEGR, Other).
- Project or Programme requiring this test if possible or existing.
- Component Family.
- Component Group.
- Device package.
- Manufacturer’s name and address.
- Test House name and address.
- Originator of Test Plan (name and contact information).
- Name of facility and type of radiation source.
- Sample size and number of control devices.
- Type of Irradiation exposure (single or multiple).
- Device construction (technology): CMOS Bulk, CMOS EPI, CMOS SOS, CMOS SOI or other (specify). Enter also feature size/line width in µm or nm.
- Level of interest. (see Para. 2).
- Single exposure (when applicable): Specification of ion specie and charge state, energy in MeV, and, for heavy ions only, linear energy transfer.
- Multiple exposure (when applicable): Specification of ion specie and charge state, energy in MeV or MeV/n, and linear energy transfer for each exposure.
- Electrical conditions: Specification of test system used, cycle time, frequency or static condition, test pattern(s) used and supply voltage of device under test.
- Irradiation test sequence describing each step of each test to be performed and requirements related to these steps. Page 2 of the plan form is to be used as a continuation sheet as necessary.
- Any remarks containing items of special note or importance which should be considered during the test programme, especially the possibility of hard or soft latch-up, oxide rupture etc.

## 5.3 TEST REPORT

The Test Report shall be presented (preferably type-written) in accordance with the report form found in the ESCC forms section of ESCIES (https://escies.org) or using the ESA Radiation Effects Database Data - Collection Tool software, and provide the following information:

- Single Event Test Report number (plus page number and total number of pages).
- Reference (issue and revision with dates) of the Single Event Test report.
- Equivalent ESCC Component Number if existing.
- Component designation e.g. integrated circuit, quad 2-input exclusive or gate, and commercial part number if necessary.
- Manufacturer/User Single Event Test specification number, revision and issue.
- Component Family.
- Component Group.
- Device package.
- Applicable ESCC Generic and Detail Specifications (numbers, issues, revisions).
- Test facility, name and address.
- Single Event Test Plan number, revision and issue.
- Manufacturer's name and address.
- Type of radiation: Heavy Ions or Protons.
- Serial numbers of sample and control devices.
- Manufacturing date code and mask set.
- Pictures of package, die and die marking.
- Device construction (technology): CMOS bulk, CMOS EPI, CMOS SOS, CMOS SOI, or other (specify). Enter also feature size/line-width in µm.
- Die size in mm.
- Depth of active region, either measured or from Manufacturer's data.
- Type of test: (SEU, SEFI, SET, SEL, SEB, SEGR, Other).
- Test Conditions.
- Type of radiation source and dosimetry technique, ion specie and charge state, energy in MeV or MeV/n, linear energy transfer. temperature of device under test, tilt angle of device under test with respect to the beam axis, and effective linear energy transfer.
- Irradiation test sequence in the form of a large table detailing each test run. The test sequence shall be prepared before the test is started and shall be based on the test sequence proposed in the relevant Single Event Test Plan. When the test sequence is voluminous, it can be submitted as an Appendix which shall be referenced under "Results". The test sequence shall indicate the date, time and number of each run, beam species and conditions, the tested device and electrical conditions, the run duration, flux and fluence, the number and type of events, and all comments related to each test run.
- Name and telephone number of the person responsible for the test facility.
- Name and telephone number of the person responsible for the electrical testing.
- Plots of upset cross-section (per bit or per device) versus LET or energy, including error bars and confidence level.
- Any remarks: The estimated total ionising dose received during testing should be recorded in this section. Reference to any special occurrences during the test, such as soft or hard latches, software crashes or effect of total ionising dose (increased leakage etc.), should be made. Die markings may also appear in this section (see Para. 4.1).

# APPENDIX A

## 1 GUIDELINES FOR THE PERFORMANCE OF SEE TESTS

### 1.1 TEST BOARD AND CABLING

Figure 1 shows a typical test board design which is suitable for use in the SEE Facility at Brookhaven National Laboratory (Long Island, US). The ESA Proton Irradiation Facility (PIF) at the Paul Scherrer Institute (Villigen, Switzerland), the ESA Heavy Ion Facility (HIF) at the University of Louvain la Neuve (Belgium) and the ESA Radiation Effects Facility (RADEF) at the University of Jyväskylä (Finland) are compatible with this test board example. ESA actively encourages the use of this standard board for any new facilities in Europe. However Users should check the compatibility of their test board for each used facility by consulting the facility web site or contact person.

Cabling is also facility specific but many accelerator facilities may require a significant length of cabling (in the region of 20 to 30 metres): this should be borne in mind when designing the test and monitoring system. Some facilities allow fairly close access (3 to 5 metres) to the vacuum chamber when using certain ions and for both heavy ions and protons. It is generally possible to have test and monitoring equipment installed close to the beam line but this has to be remotely operated over the longer distances mentioned earlier.

### 1.2 THE DESIGN OF A DEVICE TEST SYSTEM

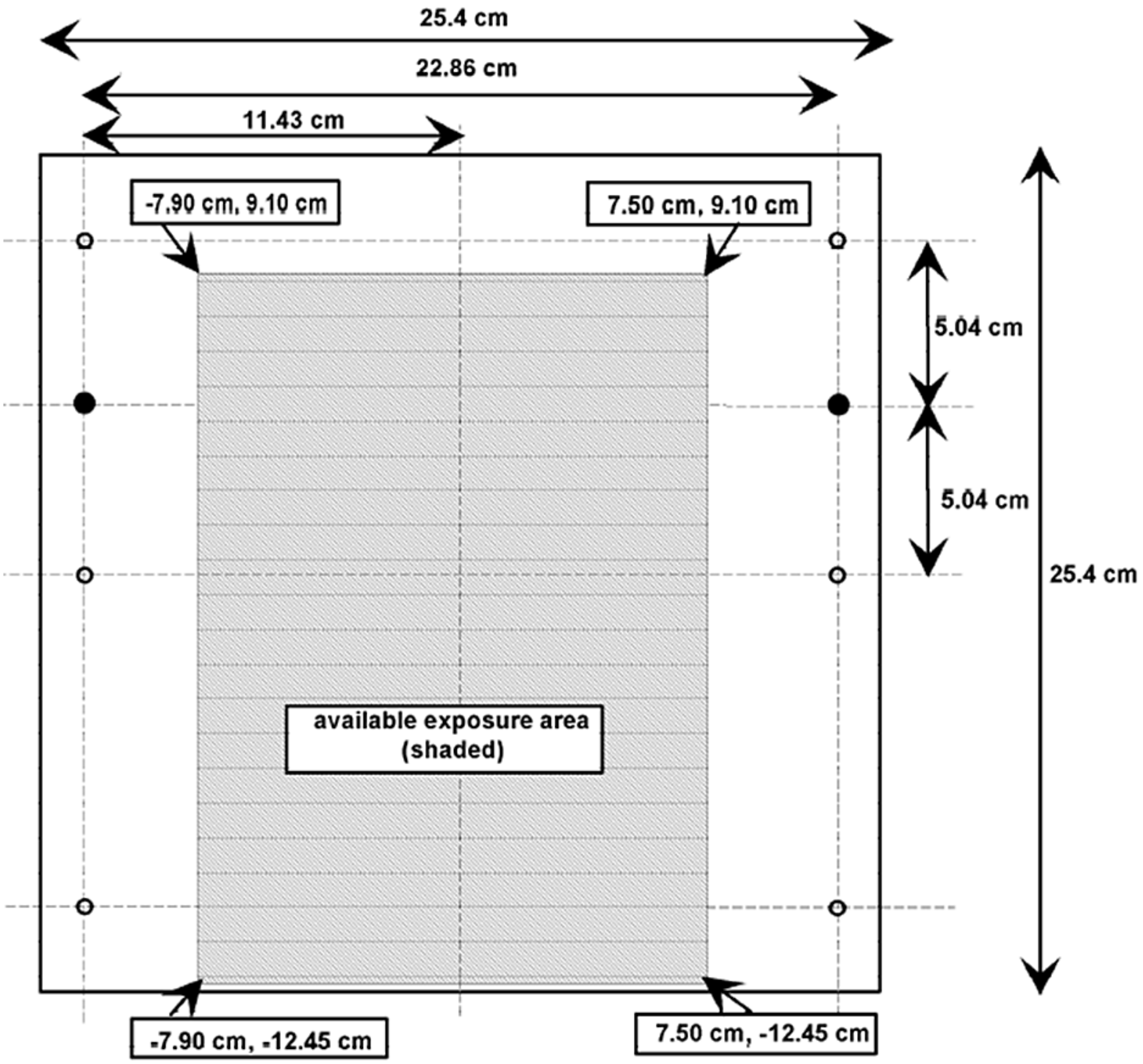
The Test System is device specific; however, there are a number of general principles which apply. The basic operations required of a Test System are:

(a) Device initialisation and function test.
(b) Device operation, dynamic or static, during exposure.
(c) Device latch-up protection, logging and re-initialisation.
(d) Detection of all types of errors or failures, logging and rewriting of an affected part of the tested device, software and hardware re-initialisation, and power control.
(e) Measurement and logging of the “duty cycle” (fraction of time the device is active and vulnerable to upset compared with the test time).
(f) Logging of test time, count rates, fluence and beam diagnostics to be attached to the test data.

The following additional features enhance test throughput and flexibility:

(a) Real time data processing, storage and retrieval.
(b) Reconfiguration under software control, particularly for the testing of different memory organisations.
(c) High operating speed and duty factor.
(d) Real time device under test data display.
(e) Data reduction while tests are in progress to allow test conditions to be modified depending on results achieved.

**FIGURE 1 – EXAMPLE OF AN SEE TEST BOARD**




1.3 ALTERNATIVE SOURCES

Alternative sources do not meet the requirements for SEE testing and shall not be used in place of heavy ions or protons for SEE qualification. However they can be used before or after heavy ion or proton SEE tests to validate or check the test hardware and software, and to investigate the device relative hardness or specific failure modes as a function of device operations.

1.3.1 Radioactive Source Californium-252

Californium-252 is a fissionable, transuranic radionuclide which decays by alpha particle emission with a half-life of 2.72 years. Californium-252 also undergoes spontaneous fission with a half-life of 85 years. The source emits alpha particles, fission fragments and fast neutrons.

The fission fragments are used for SEE testing and these have a mean LET of 43MeV.cm$^2$/mg (Si) with 95% of the particles having LETs between 41 and 45MeV.cm$^2$/mg (Si). The mean range of the fission particles in silicon is 14.2µm.

The source shall have a nominal activity in the range 1 to 5µCi and be used under vacuum (better than $10^{-3}$ Torr) with the component de-lidded. If the vacuum chamber is a glass bell-jar, this shall be fitted with a safety shield and a light tight cover. Sufficient feed through connectors shall be provided for the monitoring of the device under test. The source shall be calibrated at least once a year using a charged particle detector and pulse height analyser. The flux shall be measured at different distances from the source and a calibration curve of flux/distance constructed.

1.3.2 Focused Pulsed Laser

Laser facilities are characterized by the light wavelength, pulse energy range, pulse duration and repetition rate. Localised charges are generated in the tested devices by single photon or two photon absorption. Most SEE laser facilities have also position controlled stages to investigate the position dependence of particular failure modes, such as latch-up, transients, SEFI, or rare events located in a small part of the device surface area. In case of dense metals in the device overlayers, back side laser irradiation is recommended.

1.3.3 Other Alternative Sources

Examples of alternative sources are:

- Neutrons (e.g. 14MeV neutrons)
- Alpha sources (e.g. Am-241, Th-232)

1.4 LITERATURE AND RADIATION DATABASE SEARCH

Before the SEE test, the technology shall be studied with a view to estimating its likely sensitivity to SEE. This may be done by searching databases such as the ESA Components Radiation Effects Database, the NASA GSFC and NASA JPL databases, as well as recent Nuclear and Space Radiation Effects Conference Proceedings published annually in the December issues of the IEEE Transactions on Nuclear Science, and the RADECS proceedings and the Radiation Data Workshops from NSREC and RADECS. Ideally, there may be data available on devices in the same technology from the same Manufacturer. If not, then some “generic” estimates can be made according to technology (CMOS Bulk, CMOS Epitaxial, SOS, GaAs etc.), feature sizes and junction depths. Possession of such data allows more efficient use of accelerator time in terms of setting initial fluxes, ion species and energies.

1.5 FACILITIES COMMONLY USED FOR SEE TESTING

A list of facilities for SEE testing is provided in the ESA Radiation Database section of ESCIES (https://escies.org).

SEE facilities are subject to change and it is the User’s responsibility to verify that they still meet the requirements and needs of the specific test to be carried out.

## 1.6 SUGGESTED ERROR BAR FORMULA

Knowing that the SEE cross-section σ is given by (Paragraph 4.2.7):

$\sigma = N_{events} / F$

where $N_{events}$ is the number of events and F the fluence,

the uncertainty on the cross-section is given by:

$$\frac{\delta\sigma}{\sigma} = \sqrt{\left(\frac{\delta N_{events}}{N_{events}}\right)^2 + \left(\frac{\delta F}{F}\right)^2}$$

which can also be written as:

$$\delta\sigma \times F = \sqrt{(\delta N_{events})^2 + \left(N_{events} \times \frac{\delta F}{F}\right)^2}$$

1. The term δF/F is the uncertainty on the measured fluence (±10%, Paragraph 3.1.1). The used value shall be reported.
2. The term $\delta N_{events}$ is the variance on the measured number of events.

Assuming that SEE events are random, the probability of events follows a Poisson distribution. The variance on the number of events is calculated from the chi-square distribution for a given confidence level. Details of calculations can be found in JESD89. An example using Excel functions is given below as a function of the confidence level CL.

Lower limit of the confidence interval of $N_{events}$ ("Lower-$N_{events}$"):
If no event ($N_{events}$ = 0), the lower limit Lower-$N_{events}$ is 0.
If $N_{events}$ > 0, Lower-$N_{events}$ = 0.5*CHISQ.INV((1-CL)/2, 2×$N_{events}$)
where CHISQ.INV returns the inverse of the left-tailed probability of the chi-squared distribution.

Upper limit of the confidence interval of $N_{events}$ ("Upper-$N_{events}$"):
For all cases ($N_{events}$ ≥ 0), the upper limit is:
Upper-$N_{events}$ = 0.5*CHISQ.INV.RT((1-CL)/2, 2×($N_{events}$+1))
where CHISQ.INV.RT returns the inverse of the right-tailed probability of the chi-squared distribution.
Note that in the case of no event ($N_{events}$ = 0), the upper limit depends on the confidence level. For example, for a confidence level CL of 95%, the upper limit is 3.7.

When reporting SEE results, a confidence level CL of 95% shall preferably be used. The CL value shall be reported. The table below details an example of the calculation of error bars, assuming a fluence uncertainty of ±10% and a confidence level of 95%.

**TABLE 1 – CALCULATION OF ERROR BARS FOR 95% CONFIDENCE LEVEL AND 10% FLUENCE UNCERTAINTY**

| $N_{events}$ | $N_{events}$ | | $\delta N_{events}$ | | $\delta\sigma \times F$ | | $\sigma \times F$ | |
|---|---|---|---|---|---|---|---|---|
| | Lower | Upper | Lower | Upper | Lower | Upper | Lower | Upper |
| 0 | 0 | 3.69 | 0 | 3.69 | 0 | 3.69 | 0 | 3.69 |
| 1 | 0.025 | 5.57 | 0.975 | 4.57 | 0.980 | 4.57 | 0.020 | 5.57 |
| 2 | 0.24 | 7.22 | 1.76 | 5.22 | 1.77 | 5.23 | 0.23 | 7.23 |
| 3 | 0.62 | 8.77 | 2.38 | 5.77 | 2.40 | 5.78 | 0.60 | 8.78 |
| 4 | 1.09 | 10.2 | 2.91 | 6.24 | 2.94 | 6.25 | 1.06 | 10.3 |
| 5 | 1.62 | 11.7 | 3.38 | 6.67 | 3.41 | 6.69 | 1.59 | 11.7 |
| 6 | 2.20 | 13.1 | 3.80 | 7.06 | 3.85 | 7.08 | 2.15 | 13.1 |
| 7 | 2.81 | 14.4 | 4.19 | 7.42 | 4.24 | 7.46 | 2.76 | 14.5 |
| 8 | 3.45 | 15.8 | 4.55 | 7.76 | 4.62 | 7.80 | 3.38 | 15.8 |
| 9 | 4.12 | 17.1 | 4.88 | 8.08 | 4.97 | 8.13 | 4.03 | 17.1 |
| 10 | 4.80 | 18.4 | 5.20 | 8.39 | 5.30 | 8.45 | 4.70 | 18.4 |
| 20 | 12.2 | 30.9 | 7.78 | 10.9 | 8.04 | 11.1 | 12.0 | 31.1 |
| 30 | 20.2 | 42.8 | 9.76 | 12.8 | 10.2 | 13.2 | 19.8 | 43.2 |
| 40 | 28.6 | 54.5 | 11.4 | 14.5 | 12.1 | 15.0 | 27.9 | 55.0 |
| 50 | 37.1 | 65.9 | 12.9 | 15.9 | 13.8 | 16.7 | 36.2 | 66.7 |
| 60 | 45.8 | 77.2 | 14.2 | 17.2 | 15.4 | 18.2 | 44.6 | 78.2 |
| 70 | 54.6 | 88.4 | 15.4 | 18.4 | 16.9 | 19.7 | 53.1 | 89.7 |
| 80 | 63.4 | 99.6 | 16.6 | 19.6 | 18.4 | 21.1 | 61.6 | 101 |
| 90 | 72.4 | 111 | 17.6 | 20.6 | 19.8 | 22.5 | 70.2 | 113 |
| 100 | 81.4 | 122 | 18.6 | 21.6 | 21.1 | 23.8 | 78.9 | 124 |
| 200 | 173 | 230 | 26.8 | 29.7 | 33.4 | 35.8 | 167 | 236 |
| 300 | 267 | 336 | 33.0 | 35.9 | 44.6 | 46.8 | 255 | 347 |
| 400 | 362 | 441 | 38.2 | 41.2 | 55.3 | 57.4 | 345 | 457 |
| 500 | 457 | 546 | 42.9 | 45.8 | 66 | 68 | 434 | 568 |
| 600 | 553 | 650 | 47.1 | 50.0 | 76 | 78 | 524 | 678 |
| 700 | 649 | 754 | 50.9 | 53.8 | 87 | 88 | 613 | 788 |
| 800 | 746 | 857 | 54.5 | 57.4 | 97 | 98 | 703 | 898 |
| 900 | 842 | 961 | 57.8 | 60.8 | 107 | 109 | 793 | 1009 |
| 1000 | 939 | 1064 | 61.0 | 64.0 | 117 | 119 | 883 | 1119 |
| 2000 | 1913 | 2090 | 86.7 | 89.6 | 218 | 219 | 1782 | 2219 |
| 3000 | 2894 | 3109 | 106 | 109 | 318 | 319 | 2682 | 3319 |
| 4000 | 3877 | 4126 | 123 | 126 | 418 | 419 | 3582 | 4419 |
| 5000 | 4862 | 5141 | 138 | 141 | 519 | 519 | 4481 | 5519 |
| 6000 | 5849 | 6154 | 151 | 154 | 619 | 619 | 5381 | 6619 |
| 7000 | 6837 | 7166 | 163 | 166 | 719 | 719 | 6281 | 7719 |
| 8000 | 7826 | 8177 | 174 | 177 | 819 | 819 | 7181 | 8819 |
| 9000 | 8815 | 9188 | 185 | 188 | 919 | 919 | 8081 | 9919 |
| 10000 | 9805 | 10198 | 195 | 198 | 1019 | 1019 | 8981 | 11019 |

Error bars can be obtained for other values of fluence uncertainty and confidence level by using the formula above. Plots of the upper and lower limits of the error bars for a fluence uncertainty of 10% and confidence levels of 67%, 90% and 95% are shown below. Note that, with Excel, the limits of the error bars, as plotted below, use the absolute value of σ × F while the typical error bar plot uses the differential value δσ × F.

**FIGURE 2 – UPPER AND LOWER LIMITS OF THE ERROR BARS AS A FUNCTION OF THE NUMBER OF EVENTS AND FOR THREE VALUES OF CONFIDENCE LEVEL – 67%, 90% AND 95%. THE FLUENCE UNCERTAINTY IS 10%**