European Space Components Coordination

GUIDELINES FOR DISPLACEMENT DAMAGE IRRADIATION TESTING

ESCC Basic Specification No. 22500

Issue 2	October 2021

Document Custodian: European Space Agency – see https://escies.org

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DCR No.	CHANGE DESCRIPTION
DCR1455	Specification updated to incorporate changes per DCR.

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1 GENERAL

This guideline defines the requirements applicable to the displacement damage irradiation testing of integrated circuits and discrete semiconductors suitable for space applications.

This specification excludes the case of the solar cells. Requirements for displacement damage irradiation testing of solar cells are described in ECSS-E-ST-20-08.

Detailed requirements applicable to individual component types (e.g. test circuits) shall be specified in the relevant Test Plan and/or applicable Detail Specification.

The test shall be considered as destructive.

2 RELATED DOCUMENTS

2.1 APPLICABLE DOCUMENTS

The following ESCC specifications, at current issue, form part of and shall be read in conjunction with this specification:

- ESCC Basic Specification No. 21300: Terms, Definitions, Abbreviations, Symbols and Units
- ESCC Basic Specification No. 21500: Calibration System Requirements
- ESCC Basic Specification No. 22900: Total Dose Steady-State Irradiation Test Method

2.2 REFERENCE DOCUMENTS

- MIL-HDBK-814: Military Handbook: Ionising dose and neutron hardness assurance guidelines for microcircuits and semiconductor devices
- MIL-STD-883 Test Method 1017: Neutron Irradiation
- ECSS-E-ST-10-12: Methods for the calculation of radiation received and its effects, and a policy for design margins
- ECSS-E-ST-20-08: Photovoltaic assemblies and components

3 TERMS AND DEFINITIONS

The terms, definitions, abbreviations, symbols and units specified in ESCC Basic Specification No. 21300 shall apply. In addition, the following definitions and abbreviations are used:

Electronic Stopping Power, or Linear Energy Transfer (LET)	The electronic stopping power is the amount of energy lost by the incident particle along its path in the absorber medium when colliding with atomic electrons. It is expressed in units of energy per unit length, MeV/cm. For the purposes of this ESCC Basic Specification, 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 MeV/mg/cm^2
Flux	The number of particles passing through a unit area perpendicular to the beam, in one second. Units: particles/cm^2/s
Fluence	The flux integrated over time. Units: particles/cm^2

Equivalent Fluence	Quantity which represents the damage at different energies and from different species by a fluence of monoenergetic particles of a single species (ref. ECSS-E-ST-10-12) at the device level. This equivalent fluence is generally calculated assuming a Non-Ionising Energy Loss (NIEL) scaling.
Range	The distance travelled, without straggling, in the target material by the specified ion of given particle and energy.
Energy	The energy imparted to the particle (proton or neutron) by the accelerator. This is in units of total energy (MeV).
In-Situ Testing	The testing of devices which are physically located in the irradiation exposure chamber during electrical and/or electro-optical measurements. Bias is continuously applied to the devices, except for momentary interruptions of bias during electrical and/or electro-optical measurements. Measurements are made during or after each radiation exposure.
Remote Testing	The testing of devices after removal from the irradiation chamber for measurement. The reasons for removal are of two kinds: (a) Inability to pass signal leads from on-site measurement system into the irradiation chamber. (b) Necessity of transporting samples to an off-site (remote) measurement system. The time intervals between exposure, measurement and re-exposure may be very different for (a) and (b).
Displacement Damage	The disturbance of the semiconductor crystal by the dislodging or displacing of atoms from their lattice sites as frequently produced by energetic particles (e.g. protons, neutrons). The term is used to distinguish from ionisation effects or surface effects.
Level of Interest	The Level of Interest is a fluence value associated with a given particle type and energy value having a specific significance for the Test Authority. The value may be the anticipated fluence or equivalent fluence at a component's location within a spacecraft, the average tolerance level or the minimum required of a component. The maximum tested level is usually higher than the level of interest to allow for design margins and lot to lot variability.
Non-Ionising Energy Loss (NIEL)	The NIEL accounts for the amount of energy lost by a particle through a medium which was imparted to create atomic displacements.
Operational Conditions	The conditions of bias, temperature and light exposure of a device, as applicable, during a specific application.
Test Authority	The Customer (or their proxy) of the device under test

3.2 ABBREVIATIONS

DUT	Device Under Test
FWHM	Full Width at Half Maximum
LET	Linear Energy Transfer
NIEL	Non-Ionising Energy Loss
SRIM	Stopping and Range of Ions in Matter
TID	Total Ionising Dose

4 EQUIPMENT AND GENERAL PROCEDURES

The equipment shall consist of the radiation source, electrical and/or electro-optical parameter measurement system, optical sources, test circuit board(s), cabling, interconnect board or switching system, test fixtures and appropriate dosimetry instruments.

Precautions shall be taken to obtain an electrical parameter measurement system which, by use of sufficient insulation, ample shielding, satisfactory grounding etc., shall yield suitably low levels of interference from mains power supplies and other sources of noise and leakage. The magnitude of interference from each of these items shall be sufficiently small so as not to affect any electrical measurement.

4.1 RADIATION SOURCE AND DOSIMETRY

4.1.1 Source, general

The radiation source used for displacement damage tests shall be a particle accelerator capable of delivering the required flux and fluence of protons, preferably, or, if necessary, neutrons of suitable 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 Test Authority’s responsibility to have exact knowledge of the location of the active volume 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 values when reporting the results. The energy of the beam in the active volume should be constant within ±5%, and the spread in the FWHM of the beam energy shall be less than ±10%. Exposure is performed with the device normal to the beam.

In the case of proton irradiation, the total ionising dose shall be calculated (Gy(Si) and/or rad(Si)) at chip level. This dose shall be reported but should not be considered as a valid TID test. TID tests shall be performed according to ESCC Basic Specification No. 22900.

4.1.2 Source, Protons

During proton irradiation, the displacement damages are induced by the coulombic, nuclear elastic and nuclear inelastic interactions between incident high-energy protons and the tested device.

In the case of high energy proton tests (typically in the range of 20 to 200MeV), the primary energy should not be degraded such that the requirements of Para. 4.1.1 are no longer met.

In the case of low energy proton tests (i.e., below 20MeV), it is recommended to use a low energy proton accelerator with a quasi-mono energetic beam to avoid the energy spread when using degraders. The low energy proton accelerator shall be capable of delivering protons in the energy range of a few MeV with a narrow and tightly controlled energy spread.

NOTE:

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. For these reasons, for low energy proton tests (i.e., below 20MeV), it is advised to delid the device (particularly when the energy in the sensitive region is below 10MeV). It is also advised to irradiate the device in vacuum; otherwise, the impact of the air thickness between the output of the beam line and the device should also be considered.

The use of a proton spectrum may be considered if representativeness with respect to the application is demonstrated.

4.1.3 Source, Neutrons

During neutron irradiation, the displacement damages are induced by the nuclear elastic and nuclear inelastic interactions between incident high energy neutrons and the tested device. Generally, neutrons do not generate any significant ionisation dose. It is the responsibility of the test facility to give all the information about the dosimetry applied at the device level because of secondary particles.

It is advised that the accelerator provides a quasi-mono energetic beam with energies above 1MeV.

4.1.4 Dosimetry

Dosimetry shall allow the continuous monitoring of the flux and the fluence 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 test facility ensures accurate dosimetry.

For proton testing, 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:

$$D = F \times LET \times 1.6 \times 10^{-5}$$

where D is the deposited dose in rad, F is the Fluence measured in the plane normal to the beam in particles/cm² and LET is expressed in MeV/mg/cm². 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 test facility.

If degraders, or any other material, are used in the beam's path for proton testing, the full energy spectrum shall be measured after the degrader. If this is not possible, it shall be measured before the degrader and calculated after the degrader. It is the test 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 protons is changed. The test facility shall be able to show the calibration data. This includes:

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

It is the test facility's responsibility to ensure that that the beam conditions are according to specification. These condition shall be verified by the Test Authority.

4.2 RADIATION FLUENCES

The radiation fluences should be expressed as a fluence of a particle type and energy in the active volume of the device under test. The test devices shall be exposed to within 10% of the specified radiation fluence(s). This fluence shall be specified in the Test Plan.

NOTE:

The conversion of the fluence of a particle type and energy into a displacement damage dose implies the use of a NIEL table. It is the responsibility of the Test Authority to calculate the fluence(s) that shall be applied on the DUT and to report the NIEL table used for this calculation.

4.3 RADIATION FLUX

For proton and neutron irradiation, the flux should not be higher than 10^9 particles/cm²/s.

4.4 TEMPERATURE REQUIREMENTS

The devices under test shall be irradiated at the temperature specified in the Test Plan within ±10°C. Electrical and/or electro-optical measurements shall be performed at the temperature specified in the Test Plan with the corresponding accuracy. If the devices are transported to and from a remote electrical measurement site, the temperature of the test devices during transport shall not be allowed to increase by more than +10°C with respect to the temperature of the irradiation. The temperature of the device shall be monitored and recorded unless otherwise agreed with the Test Authority.

In order to prevent any annealing effect, it is advised to measure and irradiate the devices at the application temperature as soon as it is significantly lower than room temperature (negative temperature). In case of room or higher temperature application, the irradiation temperature shall be an ambient temperature of +20 ±10°C.

4.5 ELECTRICAL AND/OR ELECTRO-OPTICAL MEASUREMENT SYSTEMS

All instruments used for the electrical and/or electro-optical measurements shall have the stability, accuracy and resolution required for accurate measurement of the electrical and/or electro-optical parameters of the test devices as given in the Detail Specification. Any parts of the system required to operate within the irradiation chamber shall be insensitive to the required accumulated test doses or be shielded until that condition is achieved.

4.6 TEST FIXTURES

Devices to be irradiated shall be mounted on test circuit boards together with any associated circuitry necessary for application of bias during irradiation or for in-situ measurements. If the irradiation is performed in a vacuum chamber, 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.

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. The frame is generally test facility specific and provided by the accelerator laboratory. The beam shall be perpendicular to the diffusion face of the semiconductor chip.

Other than devices under test, components that are placed on the board(s) shall be insensitive to the required accumulated ionising and non-ionising test doses or be shielded so that that condition is achieved.

For the tests, the device terminals shall be electrically connected as prescribed in the Test Plan and/or Detail Specification. The geometry and materials of the completed board(s) shall allow uniform irradiation of the devices under test.

Design and construction practices shall be used to prevent damage by oscillation, and to minimise external noise pick-up and leakage currents and to obtain accurate measurements of device parameters. Only sockets which are radiation-resistant and do not exhibit any significant leakages (relative to the devices under test) shall be used to connect devices and associated circuitry to the test board(s). Similar precautions shall be taken in respect of cabling and switching systems. All equipment used repeatedly in radiation fields shall be checked periodically for physical and/or electrical degradation.

To assess interference and leakage, a circuit board shall be connected to the entire system with no test devices installed, all sources of noise and interference shall be operative, but with no radiation field applied. The current, as measured for the specified bias between any 2 terminals on each empty socket, shall not exceed 10% of the lowest current value given in the specification for pre-irradiation values.

4.7 TEST SET-UP AND SITE REQUIREMENTS

The Test Plan shall state whether electrical and/or electro-optical parameters shall be measured in the irradiation chamber (in-situ) or after the devices have been removed from the chamber (remote). The advantages of each method shall be carefully weighed against the disadvantages in order to take into account the post-irradiation effects (see Para. 4.8).

4.7.1 In-Situ Testing

Prior to being irradiated, each test device shall be checked for operation according to the Test Plan and/or Detail Specification. When the entire system is in place for the in-situ radiation test, it shall be checked for proper interconnections, leakage and noise level. The system shall be monitored for oscillations and current drain. The test devices shall remain in place on the test circuit board which itself shall remain in its irradiation location throughout the irradiation and measurement sequence (except for source types which require removal of the board from the irradiation location to end an irradiation).

To ascertain the proper operation and stability of the measurement system, a control device shall be measured with the measurement system before the insertion of test devices, and again upon completion of the irradiation and measurement series after removal of the test devices.

4.7.2 Remote Testing

Unless otherwise specified in the Test Plan, all terminals of the device under test shall be shorted together after removal from the irradiation bias fixture. The control devices shall be measured according to the Test Plan and/or Detail Specification requirements to confirm proper operation of the measurement system before and after all electrical and/or electro-optical measurements on irradiated devices.

4.7.3 Bias Conditions

The default bias conditions during irradiation shall be with all terminals of the device under test shorted together (known as the worst-case bias condition). Otherwise, the bias conditions shall be specified in the Test Plan.

When devices are biased during irradiation, the biasing condition, including the values of voltage, shall be maintained and monitored to remain within 10% of the conditions specified in the Test Plan and/or the Detail Specification. If these limits are exceeded the test shall be void.

The specified bias shall be maintained at all times on each device until removal of the device, except for the periods required for electrical and/or electro-optical parameter measurements. Devices to be annealed shall be mounted on boards providing the same bias condition as used for irradiation.

4.7.4 Light Exposure Conditions

When applicable, the default light exposure conditions during irradiation shall be total darkness. Otherwise, the light exposure conditions shall be specified in the Test Plan. If the devices are transported to and from a remote electrical measurement site, they shall be maintained in total darkness.

4.8 TIME INTERVALS FOR MEASUREMENT

The time interval from the completion of an exposure to the start of the measurement of parameters shall be specified in the Test Plan. It shall be recorded and reported for each sample. It is advised that the time interval shall be the same for all the samples whatever the particle type, energy and fluence. In order to avoid the effect of short time thermal annealing, a duration of less than 1 hour between consecutive exposures is advised.

Where measurements are performed remotely at a significant distance from the irradiation chamber, the time interval may vary between 24 hours and one month. In any case, it is advised to measure the devices one month after the end of the irradiation.

5 PROCEDURE FOR TESTING

5.1 TEST PLAN

The test devices shall be irradiated in accordance with the Test Plan. All electrical and/or electro-optical parameters to be tested and biasing conditions shall be clearly described. As a minimum, the Test Plan should contain the information listed in Section 6(a).

5.1.1 Particle Type and Energy

It is advised to irradiate the devices with the particle type that mostly contributes to the displacement damage during the mission of interest. Protons are the main contribution for most of the orbits around the Earth. In specific cases related to shielding and orbit, the contribution of electrons may dominate the degradation. The necessity of using neutrons instead of protons should be demonstrated prior to proposing the irradiation Test Plan, and shall be agreed with the Test Authority.

In the case of proton irradiation, for silicon devices, only one energy can be selected for the displacement damage irradiation Test Plan. For other materials, it is recommended to select at least 2 different energies, one below 40MeV and one over 100MeV. In the event that the results do not match with the available NIEL table (coulombic or total), either tests at other energies shall be performed or the worst case NIEL table shall be used.

The energies shall be chosen in order to evaluate the device in the range 10MeV - 200MeV. It is then advised that the lowest energy specified in the Test Plan should be below 40MeV.

5.1.2 Fluence Levels

The fluence levels shall be as specified in the Test Plan.

A minimum of 3 exposures are recommended, for which the increments in fluence levels may be F/2, F and 2×F, where F is the level of interest.

5.1.3 Test Conditions

A given test condition corresponds to a given temperature, bias, light exposure and fluence level, as applicable, applied on a test sample during the irradiation. In some cases of remote testing where the measurement systems are not available on the irradiation site, the electrical and/or electro-optical measurements are delayed and a given sample supports only one irradiation fluence level without intermediate fluence levels (multiple exposures).

5.2 SAMPLE SELECTION

The samples shall be selected at random from the procurement lot and samples should be selected from as many different wafers as possible. All sample devices shall have met all of the requirements of the applicable ESCC Generic and/or Detail Specifications up to the point of the selection and be individually identifiable for the purpose of pre- and post-irradiation identification and comparison.

The sample size depends on the device type and the number of test conditions. Unless otherwise specified in the Test Plan, it is advised to apply the following rules:

- A minimum of 6 (5 + 1 “unirradiated control”) test samples as defined in the Test Plan.
- When different samples are used per fluence level or different bias conditions are tested, a minimum of 3 samples per unique set of test conditions is recommended.
- For matrix devices (e.g., charge-coupled devices, bolometers…), due to the large number of individual sensitive elements and the high cost of the samples, the sample size may be reduced to one device per test condition (+ 1 “unirradiated control”).

If multiple exposures are required for a set of test devices, the post-irradiation electrical and/or electro-optical parameter measurements shall be performed after each exposure.

The devices shall be submitted to radiation tests in accordance with the test sequence specified in the Radiation Exposure and Test Sequence (Para. 5.4).

5.3 SAMPLE SERIALISATION

Immediately after selection, each individual sample device shall be serialised to facilitate pre- and post-irradiation data identification and comparison. The system of marking shall be such as to ensure that the samples are clearly identified by:

(a) Date code or lot identification of the samples.
(b) Their individual serial numbers.

5.4 RADIATION EXPOSURE AND TEST SEQUENCE

(a) Serialisation of all devices.
(b) Initial electrical and/or electro-optical testing of all devices at the test temperature (see Para. 4.3), with special emphasis given to parameters monitored during/after irradiation. All monitored parameters shall be recorded in the irradiation test report.
(c) Set-up of radiation source and bias of devices for irradiation as specified in Test Plan.
(d) Irradiation of devices to the specified exposure level.
(e) Post-irradiation electrical and/or electro-optical tests on exposed devices and control device.
(f) Steps (c), (d) and (e) shall be repeated (on the same sample or different ones, depending on the Test Plan) until the specified maximum fluence value specified in the Test Plan is reached. The time between the end of each exposure and the beginning of the electrical and/or electro-optical measurements shall be defined in the Test Plan (see Para. 4.8) and reported. The time between each exposure shall be reported.
(g) Room temperature anneal of 24 hours to 1 month, as defined in Para. 4.8. Unless otherwise specified in the Test Plan, the sample devices shall be unbiased. The duration of the annealing shall be reported.
(h) Final electrical and/or electro-optical characterisation at the application temperature.

5.5 ELECTRICAL AND/OR ELECTRO-OPTICAL MEASUREMENTS

The parameters to be measured and the test conditions shall be as stated below. If any part exceeds any allowable limit at the initial measurement, that part shall be rejected and replaced by an acceptable part for the sample selection for radiation test.

(a) Initial electrical and/or electro-optical measurements shall be performed in accordance with the Test Plan.

(b) Electrical and/or electro-optical measurements at intermediate points and at the end of exposure shall be performed in accordance with the Test Plan.

(c) Final electrical and/or electro-optical measurements shall be performed in accordance with the Test Plan.

5.6 REPORTING

Electrical and/or electro-optical test results and other observations shall be collected in a test report.

6 DOCUMENTATION

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

(a) A Test Plan (prior to irradiation testing) defining the detailed requirements of the irradiation testing to be performed.

As a minimum the Test Plan shall include the following:

- Part traceability information
- Full part type number
- Serial number
- Date code
- Wafer lot number
- Package type and marking
- Part technology/process
- Wafer number (if known)
- Die fab facility (if known)
- Irradiation conditions
- Irradiation test facility and radiation source type
- Type of radiation: protons or neutrons
- Irradiation test sequence with detail of irradiation and annealing steps
- Flux(es)
- Accuracy of the fluence levels
- Bias conditions during irradiation with identification of samples per bias conditions
- Electrical and/or electro-optical measurements conditions and acceptable limits
- Test sequence and schedule of the measurements

(b) A Test Report giving the actual test conditions and test results.

As a minimum the Test Report shall include the information of the Test Plan plus the following:

- Test date
- Test results (tabulated and figures) for each electrical and/or electro-optical parameter measured, showing the measurement results after each irradiation and annealing step of all irradiated parts and the control part
- Die picture
- Effective test sequence and schedule of the measurements
- Any anomalies that occurred during the test shall be reported and fully described.