# ATLAS POLICY ON RADIATION TOLERANT ELECTRONICS

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***Distribution List***

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# ATLAS Policy on Radiation Tolerant Electronics

## GOALS

The first goal of ATLAS Policy on Radiation Tolerant Electronics is the general safety of the ATLAS materials and of the persons working on the experiment. Therefore, all components or systems which can cause fire or induce high and long-term radioactivity levels through radiation effects are forbidden.

The second goal of this policy is to help ATLAS sub-systems to build electronics complying with the levels of radiation tolerance necessary for their systems. These levels must be determined by the sub-systems. They represent the minimum doses and fluences tolerated by the electronics, and the maximum acceptable rate of soft, hard or destructive Single Event Effects (SEE). These levels of tolerance, which must be maintained during the 10 years of operation of the experiment, can be obtained either by qualifying ASICs developed with a suitable radiation-hard technology, or by selecting and qualifying standard electronics components (COTS) that comply with the radiation tolerance required for 10 years of operation, or by selecting *less* radiation tolerant COTS and making sure that replacement is possible, if necessary, after their predicted lifetime.

The third goal of this policy is to help sub-systems build electronics within the foreseen schedule. Therefore, it includes a strategy for pre-selection, qualification and purchase of components designed with the aim of reducing procurement risks.

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## Appendixes:

# I. ATLAS strategy for electronic components procurement

## I.1. Procurement of radiation tolerant COTS

*This subsection concerns only COTS (Commercial Off The Shelf) components, i.e. commercial standard non radiation-hard components.*

Step 1: Listing of all the radiation tolerant COTS components required by ATLAS sub-systems. The resulting list will be part of the ATLAS electronics components *database* (see section IV).

Step 2: Calculation of *Radiation Tolerance Criteria* (RTC) required for accepting components for use in a given ATLAS location (see section II and appendix 1).

Step 3: *Pre-selection* of the generic components (identified part number and manufacturer) which may satisfy the RTC. This pre-selection is based on the standard ATLAS test methods (see section III and appendix 2). It makes possible the identification of the part numbers and the manufacturers of the generic commercial components that may be used in ATLAS, but it does not select the physical components themselves.

Step 4: *Qualification* of batches of components to be mounted in ATLAS electronics systems. This qualification is based on the ATLAS standard test methods (see section III and appendix 2). It enables one to select the batches of physical components that satisfy the RTC and consequently that may be used in the foreseen ATLAS sub-system.

Step 5: *Purchase* of the qualified batches of components for ATLAS sub-systems. Ideally, this step takes place after step 4. This requires good relations with the vendor, who must agree to “freeze” homogeneous[1] batches and to provide samples for the customer to test before deciding to purchase or to reject the frozen batches. Frequently, vendors cannot “freeze” batches and step 5 must be done before step 4. This induces a risk of purchasing “bad” batches. In this case, to reduce the risk, the population sample in step 3 must be increased.

## I.2. Procurement of radiation hard ASICs

*This subsection concerns only ASICs (Application Specific Integrated Circuits) designed with a radiation-hard technology.*

Step 1: Listing of all the radiation hard ASICs required by ATLAS sub-systems. The resulting list will be part of the ATLAS electronics components *database* (see section IV).

Step 2: Calculation of *Radiation Tolerance Criteria* (RTC) required for accepting components dedicated to a given ATLAS location (see section II and appendix 1).

Step 3: *Selection of a technology* whose radiation hardness complies with RTC. Ideally, the manufacturer guarantees the radiation hardness level of the electrical parameters of the elementary components used for ASIC designs.

Step 4: *Development of the ASICs* using the selected radiation-hard technology, or using a radiation-soft technology plus a translation of advanced prototypes into the selected radiation-hard technology. Usually, when the customer makes the development, the robustness of the *architecture* and of the *design* against radiation are under its responsibility.

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[1] A homogeneous batch (or diffusion batch) is a batch of components issued from wafers manufactured together at the same time on a known manufacturing line.

The development phase usually includes radiation hardness tests made on advanced prototypes designed with the radiation-hard technology. The aim of these tests is to verify and if necessary to improve the robustness of the *architecture* of the circuit against radiation.

Step 5: *Qualification* of the radiation hardness of the final prototype designed with the radiation-hard technology. This qualification is based on the ATLAS standard test methods (see section III and appendix 2). The radiation hardness of the final prototype must satisfy the RTCs.

Step 6: *Purchase* of batches of ASICs manufactured with the selected radiation hard technology. Ideally, the manufacturer delivers each batch together with a document certifying that it complies with the guaranteed radiation hardness.

## II. ATLAS components radiation tolerance criteria

For COTS: The results of standard radiation tests must be compared to the Radiation Tolerance Criteria (RTCs) in order to pre-select or to reject generic components and to qualify or to reject batches of components.

For rad-hard ASICs: The results of standard radiation tests must be compared to the Radiation Tolerance Criteria (RTCs) in order to qualify the *architecture* and the *design* of the ASIC.

RTCs result from Simulated Radiation Levels (SRLs) multiplied by three safety factors (SF) representing SRLs inaccuracies, low dose rate effects and variations of radiation tolerance from lot to lot and within lots. Details about SRLs, SFs and RTCs are given in appendix 1.

SRLs are computed for each region of ATLAS sub-systems. An initial set of SRLs and SFs was given in the previous policy (revision 1). An improved set of SRLs and SFs computed for each location of ATLAS electronics (Rmin, Rmax, Zmin, Zmax) is given in appendix 1 of the revised policy (revision 2 *et seq*). This set of SRLs is available on the ATLAS Radiation Hard Electronics web page[2].

## III. ATLAS standard test methods

ATLAS standard test methods are derived from DOD or ESA test methods [1-3] for CMOS devices and from ref. [4] for bipolar or BiCMOS devices, with several adaptations that take into account the specificities of ATLAS radiation environment.

- ATLAS standard NIEL test method enables the effects of particles producing Non Ionising Energy Loss (NIEL) to be measured. These particles produce displacement damages in silicon, which degrade the electrical parameters of the electronic components. NIEL test method is based on neutron irradiation.
- ATLAS standard TID test methods enable the effects of Total Ionising Dose (TID), ie the cumulated ionising dose deposited in the oxides of the electronic components, to be measured. TID test methods are based on gamma or X-ray irradiation.
- ATLAS standard SEE test method enables the SEE rates (upset, latch-up, burnout, gate rupture, etc.) expected in a given ATLAS environment to be estimated. This test method is primarily based on proton irradiation, but it also can be performed using neutrons (with a high enough energy).

Details on these ATLAS standard test methods are given in appendix 2.

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[2] The address of this web page is: http://atlas.web.cern.ch/Atlas/GROUPS/FRONTEND/radhard.htm

## IV. ATLAS electronics component database

All the electronics components that will be exposed to radiation during its operation in ATLAS shall be listed together with relevant data in the *ATLAS electronics component database.* This database will help sub-systems to *reduce* the total number of generic components having the same functionality but different part numbers ("PN") or produced by different manufacturers, and to *reduce* the total number of manufacturers. Indeed, the variability of the radiation tolerance from PN to PN or from manufacturer to manufacturer is very large. A standardisation of a limited number of generic components having the same PN and of a limited number of manufacturers will greatly improve the reliability of the Radiation Hardness Assurance. It will also greatly reduce the amount of work required to pre-select generic components and to qualify batches.

ATLAS electronics components database is available on the "ATLAS Radiation Hard Electronics" web page. External data or test results obtained by ATLAS sub-systems will be progressively entered into this database.

Appendix 3 shows the forms used to enter the technical data and the radiation test results of each ATLAS component before they are placed in the ATLAS electronics component database. An electronic version of these forms will be available on the "ATLAS Radiation Hard Electronics" web page. ATLAS Sub-systems are invited to send the list of all the electronic components they will use in irradiated locations together with the related technical data and radiation test reports to the coordinator of the ATLAS Radiation Hardness Assurance Working Group (RHA-WG), who will enter them into the database.

## V. Radiation facilities

Appendix 4 gives a preliminary *list of radiation facilities*, including technical features, addresses, contact persons, etc. A copy of this list, periodically updated, is available on the "ATLAS Radiation Hard Electronics" web page. It will help Sub-systems to select the most appropriate radiation facilities and to co-ordinate their radiation testing work.

A *Radiation Test Agenda* is available on the "ATLAS Radiation Hard Electronics" web page. It will enable sub-systems to announce their radiation tests planning and then to co-ordinate their work. ATLAS Sub-systems are invited to provide regularly the RHA-WG convenor with the dates, places and purposes of the foreseen radiation test campaigns. The RHA-WG convenor will place this information in the Radiation Test Agenda.

## VI. General rule and exceptions

### General rule

The ATLAS Policy on Radiation Tolerant Electronics shall be systematically applied by ATLAS subsystems for the selection and the qualification of each electronic component that will be exposed to radiation during its operation in ATLAS. Radiation test results shall be written using the ATLAS Standard Report Document for Radiation Tests given in appendix III. The list of the tested components shall be written together with the related technical data and radiation test reports in the ATLAS electronics component data base. Regarding radiation hardness assurance, Design reviews and Production Readiness Reviews shall be done on the basis of results of radiation tests made using the ATLAS standard test method given in appendix 2, and analysed according to the radiation tolerance criteria given in appendix 1.

Exceptions

Exceptions to some rules of the Policy can exceptionally be granted when justified by strong technical or economic reasons, provided that the general principles of this policy are satisfied (safety of the materials and of the persons, robustness of the electronics with respect to the radiation constraint, minimum procurement risks, respect of the ATLAS schedule). Exception requests shall be submitted to the ATLAS Electronics Co-ordination as early as possible.

Exceptions resulting from an unexpected increase of the simulated radiation level
After the beginning or the completion of an ASIC production, or after purchase of COTS, if new simulations show a significant increase of the radiation level expected for the electronics components in a sub-system, a meeting of the sub-system team and the ATLAS Electronics co-ordination shall be organised as early as possible in order to decide on the procedure to be followed.

## VII. Revision procedures

Revision of the main document:

ATLAS Policy on Radiation Tolerant Electronics revision 2 shall be permanently available on the “ATLAS Radiation Hard Electronics” web page. Changes in this Policy can be proposed either by ATLAS subsystems or by ATLAS Electronics Co-ordination. ATLAS Electronics Co-ordination shall decide to accept or to reject the changes. Minor changes shall be written by ATLAS Electronics Co-ordination with their date in a corrigendum which shall be permanently available on the “ATLAS Radiation Hard Electronics” web page together with the Policy. After several minor changes or after a major change, ATLAS Electronics Co-ordination shall revise the Policy. The new revised Policy shall be permanently available on the “ATLAS Radiation Hard Electronics” web page. Previous revisions and corrigendum shall remain available on the same web page as archive documents.

Revision of the simulated radiation levels

ATLAS Policy on Radiation Tolerant Electronics revision 2 contains a table that summarises radiation levels simulated by experts for the location of the electronics of the ATLAS sub-systems. This table was up to date at the date of release of revision 2. A copy of this table shall be permanently available on the “ATLAS Radiation Hard Electronics” web page. A revision number and a date of revision shall identify this copy. Changes can be proposed either by simulation experts, by ATLAS subsystems or by ATLAS Electronics Co-ordination. ATLAS Electronics Co-ordination, on the basis of expert’s advice, shall decide to accept or to reject the changes. The new revised table shall be identified by a revision number and a revision date and then made permanently available on the “ATLAS Radiation Hard Electronics” web page. Previous tables shall remain available on the same web page as archive documents.

Information on revisions

ATLAS Electronics Co-ordination shall inform each subsystem as early as possible of any of the revisions mentioned above. This information shall be sent by Email to the project leader of each sub-system as well as to the representative of each subsystem in the ATLAS Radiation Hardness Assurance Working Group.

# APPENDIXES

## APPENDIX 1: Radiation Tolerance Criteria for ATLAS Components

### 1. Simulated radiation levels

Simulated Radiation Levels ("SRL") are the radiation levels computed for the various ATLAS regions. Table 1 defines the three types of SRL that are necessary for the *ATLAS strategy for radiation tolerant or radiation-hard component procurement*.

| **Simulated Radiation Level** | **Type of Radiation Constraint** | **SRL Unit** |
|---|---|---|
| $SRL_{tid}$ | Particles producing ***TID***<br>(Total Ionising Dose).<br>Example: photons. | Total Dose in 10 years:<br>***Gray*** |
| $SRL_{niel}$ | Particles producing ***NIEL***<br>(Non-Ionising Energy Loss).<br>Example: neutrons. | Total Fluence in 10 years:<br>***1 MeV eq. neutron.cm***$^{-2}$ |
| $SRL_{see}$ | Particles producing ***SEE***<br>(Single Event Effects).<br>Example: heavy fragments. | Total Fluence in 10 years:<br>***> 20 MeV hadron.cm***$^{-2}$ |

Table 1: Definition of the three types of simulated radiation levels

The relevance of the fluence of hadron of energy greater than 20 MeV for the estimation of *soft* SEE rates in an accelerator environment is demonstrated in reference [5]. This fluence of hadrons of energy greater than 20 MeV can also be used to estimate an upper limit of *hard* and *destructive* SEE rates. The definition of these soft, hard and destructive SEEs and the methods used to estimate their rate are given in section 2.2.

Table 2 and 3 give the values of $SRL_{tid}$, $SRL_{niel}$ and $SRL_{see}$, computed for various ATLAS regions [6].

Remark: Table 2 and 3 give values of $SRL_{tid}$, $SRL_{niel}$ and $SRL_{see}$ up to date at the date of release of the ATLAS Policy on Radiation Policy revision 2. As mentionned in this document in section VII page 6, subsequent updated values – if any - will be made available on the "ATLAS Radiation Hard Electronics" web page[3].

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[3] The address of this web page is: http://atlas.web.cern.ch/Atlas/GROUPS/FRONTEND/radhard.htm

| SYSTEM | SUB-SYSTEM | POSITION | | | | RAW SIMULATED RADIATION LEVEL | | |
|---|---|---|---|---|---|---|---|---|
| | | Z min (cm) | Z max (cm) | R min (cm) | R max (cm) | $\mathrm{SRL}_{tid}$ (Gy.10y$^{-1}$) | $\mathrm{SRL}_{niel}$ (1 MeV n.cm$^{-2}$.10y$^{-1}$) | $\mathrm{SRL}_{see}$ (>20 MeV h.cm$^{-2}$.10y$^{-1}$) |
| **Pixel barrel** | Layer 1 | 0 | 40.7 | 4.2 | 4.2 | 3.05E+06 | 1.84E+15 | 2.61E+15 |
| | Layer 2 | 0 | 40.7 | 9.3 | 9.3 | 5.61E+05 | 8.59E+14 | 1.02E+15 |
| | Layer 3 | 0 | 40.7 | 12.7 | 12.7 | 3.76E+05 | 5.18E+14 | 5.50E+14 |
| **Pixel discs** | disc 1 | 49.1 | 49.1 | 12.1 | 18.2 | 3.36E+05 | 4.17E+14 | 4.96E+14 |
| | disc 2 | 58.0 | 58.0 | 12.1 | 18.2 | 3.29E+05 | 4.10E+14 | 5.08E+14 |
| | disc 3 | 65.0 | 65.0 | 12.1 | 18.2 | 3.44E+05 | 4.14E+14 | 5.23E+14 |
| | disc 4 | 71.0 | 71.0 | 09.9 | 16.0 | 4.84E+05 | 5.61E+14 | 8.16E+14 |
| | disc 5 | 77.0 | 77.0 | 09.9 | 16.0 | 4.89E+05 | 5.60E+14 | 8.16E+14 |
| **SCT barrel** | barrel 1 | 0.0 | 75.0 | 30.0 | 30.0 | 1.07E+05 | 1.75E+14 | 1.43E+14 |
| | barrel 2 | 0.0 | 75.0 | 37.0 | 37.0 | 7.89E+04 | 1.48E+14 | 1.12E+14 |
| | barrel 3 | 0.0 | 75.0 | 45.0 | 45.0 | 5.55E+04 | 1.24E+14 | 8.25E+13 |
| | barrel 4 | 0.0 | 75.0 | 52.0 | 52.0 | 4.57E+04 | 1.06E+14 | 6.25E+13 |
| **SCT disc** | 1-silicon | 84.0 | 84.0 | 27.0 | 56.0 | 7.43E+04 | 1.47E+14 | 1.11E+14 |
| | 1-electronics | 84.0 | 84.0 | 34.0 | 48.0 | 7.27E+04 | 1.41E+14 | 1.02E+14 |
| | 2-silicon | 91.0 | 91.0 | 27.0 | 56.0 | 7.45E+04 | 1.46E+14 | 1.13E+14 |
| | 2-electronics | 91.0 | 91.0 | 34.0 | 48.0 | 7.36E+04 | 1.40E+14 | 1.05E+14 |
| | 3-silicon | 105.0 | 105.0 | 27.0 | 56.0 | 7.52E+04 | 1.44E+14 | 1.12E+14 |
| | 3-electronics | 105.0 | 105.0 | 34.0 | 48.0 | 7.44E+04 | 1.39E+14 | 1.04E+14 |
| | 4-silicon | 128.0 | 128.0 | 27.0 | 56.0 | 7.55E+04 | 1.41E+14 | 1.10E+14 |
| | 4-electronics | 128.0 | 128.0 | 34.0 | 48.0 | 7.50E+04 | 1.37E+14 | 1.04E+14 |
| | 5-silicon | 151.0 | 151.0 | 27.0 | 56.0 | 7.77E+04 | 1.46E+14 | 1.13E+14 |
| | 5-electronics | 151.0 | 151.0 | 34.0 | 48.0 | 7.65E+04 | 1.42E+14 | 1.07E+14 |
| | 6-silicon | 174.0 | 174.0 | 27.0 | 56.0 | 8.03E+04 | 1.52E++14 | 1.17E+14 |
| | 6-electronics | 174.0 | 174.0 | 34.0 | 48.0 | 7.88E+04 | 1.47+E14 | 1.09E+14 |
| | 7-silicon | 206.0 | 206.0 | 34.0 | 56.0 | 6.91E+04 | 1.50+E14 | 1.00E+14 |
| | 7-electronics | 206.0 | 206.0 | 40.0 | 48.0 | 6.93E+04 | 1.54+E14 | 1.05E+14 |
| | 8-silicon | 252.0 | 252.0 | 41.0 | 56.0 | 6.07E+4 | 1.77+E14 | 1.03E+14 |
| | 8-electronics | 252.0 | 252.0 | 40.0 | 48.0 | 7.67E+04 | 1.88+E14 | 1.14E+14 |
| | 9-silicon | 272.0 | 272.0 | 44.0 | 56.0 | 6.19E+04 | 1.86+E14 | 9.92E+13 |
| | 9-electronics | 272.0 | 272.0 | 40.0 | 44.0 | 8.63E+04 | 2.19+E14 | 1.27E+14 |

Table 2 : SRL values computed for 10 years of operation in various ATLAS locations

| **SYSTEM** | **SUB-SYSTEM** | **POSITION** | | | | **RAW SIMULATED RADIATION LEVEL** | | |
|---|---|---|---|---|---|---|---|---|
| | | **Z min (cm)** | **Z max (cm)** | **R min (cm)** | **R max (cm)** | **SRL$_{tid}$ (Gy.10y$^{-1}$)** | **SRL$_{niel}$ (1 MeV n.cm$^{-2}$.10y$^{-1}$)** | **SRL$_{see}$ (>20 MeV h.cm$^{-2}$.10y$^{-1}$)** |
| **TRT** | barrel | 79.0 | 79.0 | 56.0 | 107.3 | 1.59E+04 | 6.68E+13 | 2.99E+13 |
| | end-cap | 83.0 | 340.0 | 108.0 | 108.0 | 8.14E+03 | 6.92E+13 | 1.82E+13 |
| **LAR** | barrel | 300.0 | 350.0 | 290.0 | 340.0 | 4.87E+01 | 1.56E+12 | 7.67E+11 |
| | end-cap | 620.0 | 670.0 | 290.0 | 340.0 | 5.67E+00 | 1.45E+11 | 2.14E+10 |
| **TILE** | HV micro | 210.0 | 210.0 | 400.0 | 400.0 | 6.41E–01 | 4.35E+10 | 1.76E+09 |
| | HV opto | 200.0 | 200.0 | 400.0 | 400.0 | 8.80E–01 | 3.28E+10 | 1.27E+09 |
| | Mother | 275.0 | 275.0 | 410.0 | 410.0 | 2.54E+00 | 2.29E+11 | 5.66E+10 |
| | Integrator | 210.0 | 210.0 | 410.0 | 410.0 | 5.20E–01 | 3.70E+10 | 2.80E+09 |
| | Adder | 260.0 | 260.0 | 410.0 | 410.0 | 1.22E+00 | 1.40E+11 | 2.33E+10 |
| | Digitiser PC | 275.0 | 275.0 | 410.0 | 410.0 | 2.54E+00 | 2.29E+11 | 5.66E+10 |
| | S-link & interface | 150.0 | 150.0 | 410.0 | 410.0 | 2.25E–01 | 1.49E+10 | 6.32E+08 |
| **MUON CSC** | Start CSC 1 | 717.7 | 717.7 | 89.4 | 89.4 | 5.16E+03 | 5.41E+12 | 1.12E+12 |
| | End CSC 1 | 694.1 | 694.1 | 204.7 | 204.7 | 1.47E+01 | 1.03+E12 | 1.21E+11 |
| | Start CSC 2 | 735.3 | 735.3 | 89.4 | 89.4 | 1.67E+02 | 3.88+E12 | 7.50E+11 |
| | End CSC 2 | 711.7 | 711.7 | 204.7 | 204.7 | 1.51E+01 | 1.09+E12 | 1.55E+11 |
| | Start CSC 3 | 753.5 | 753.5 | 94.0 | 94.0 | 1.70E+02 | 2.96+E12 | 5.58E+11 |
| | End CSC 3 | 730.8 | 730.8 | 204.7 | 204.7 | 2.06E+01 | 1.11+E12 | 1.95E+11 |
| | Start CSC 4 | 771.1 | 771.1 | 94.0 | 94.0 | 1.91E+02 | 3.12+E12 | 4.54E+11 |
| | End CSC 4 | 748.4 | 748.4 | 204.7 | 204.7 | 2.52E+01 | 1.19+E12 | 2.23E+11 |
| **MUON RPC** | BMF | 63.1 | 872.2 | 839.1 | 847.1 | 3.02E+00 | 2.49E+10 | 4.69E+09 |
| | BML | 15.0 | 966.0 | 750.6 | 758.6 | 3.04E+00 | 2.82E+10 | 5.65E+09 |
| | BMS | 13.5 | 945.5 | 839.1 | 847.1 | 3.03E+00 | 2.50E+10 | 4.73E+09 |
| | BOF | 60.8 | 1267.9 | 1035.5 | 1043.5 | 1.19E+00 | 2.14E+10 | 4.08E+09 |
| | BOL | 15.0 | 1225.2 | 985.3 | 993.3 | 1.33E+00 | 2.20E+10 | 4.21E+09 |
| | BOS | 1.0 | 1383.2 | 1025.8 | 1033.8 | 1.26E+00 | 2.10E+10 | 4.10E+09 |
| **MUON TGC** | 1 | 1280.0 | 1290.0 | 715.0 | 1180.0 | 2.27E+00 | 2.58E+10 | 6.54E+09 |
| | 2 | 1470.0 | 1480.0 | 680.0 | 1180.0 | 2.49E+00 | 1.42E+10 | 4.53E+09 |
| **MUON MDT** | Barrel 1 | 0.0 | 650.0 | 520.0 | 520.0 | 4.69E+00 | 2.99E+10 | 5.43E+09 |
| | Barrel 2 | 0.0 | 900.0 | 720.0 | 720.0 | 2.76E+00 | 3.01E+10 | 5.70E+09 |
| | Barrel 3 | 0.0 | 1250.0 | 950.0 | 950.0 | 1.33E+00 | 2.41E+10 | 4.61E+09 |
| | End-cap 1 | 730.0 | 730.0 | 215.0 | 620.0 | 6.38E+00 | 2.94E+11 | 4.83E+10 |
| | End-cap 2 | 1350.0 | 1350.0 | 190.0 | 1100.0 | 6.22E+00 | 3.41E+10 | 8.74E+09 |
| | End-cap 3 | 2230.0 | 2230.0 | 260.0 | 1200.0 | 3.26E+00 | 1.75E+10 | 2.31E+09 |

Table 3 : SRL values computed for 10 years of operation in various ATLAS locations (cont.)

## 2. Radiation tolerance criteria

ATLAS electronics components must have radiation tolerances equal to or higher than minimum values called Radiation Tolerance Criteria (RTCs). Table 4 defines the three types of RTCs that are necessary for the *ATLAS strategy for radiation tolerant or radiation hard component procurement*.

| Radiation Tolerance Criterion | Type of Radiation Constraint | RTC Unit |
|---|---|---|
| $RTC_{tid}$ | Particles producing ***TID***<br>(Total Ionising Dose) | Total Ionising Dose:<br>***Gray*** |
| $RTC_{niel}$ | Particles producing ***NIEL***<br>(Non-Ionising Energy Loss) | Total Fluence:<br>***1 MeV eq. neutron/cm$^2$*** |
| $RTC_{see}$ | Particles producing ***SEE***<br>(Single Event Effects) | SEE rate:<br>***SEE/s*** |

Table 4: Radiation tolerance criteria

### 2.1. Radiation tolerance criteria $RTC_{tid}$ and $RTC_{niel}$

The radiation tolerance criteria for TID and NIEL are:

- $RTC_{tid} = SRL_{tid} \times SF_{sim} \times SF_{ldr} \times SF_{lot}$ (unit : Gray)
- $RTC_{niel} = SRL_{niel} \times SF_{sim} \times SF_{ldr} \times SF_{lot}$ (unit : 1MeV eq. neutrons / cm$^2$)

Table 5 define the safety factors (SFs) used to compute RTCs.

| Safety factor | Definition |
|---|---|
| $SF_{sim}$ | Represents SRL inaccuracies. |
| $SF_{ldr}$ | Represents low dose rate effects (LDRE). |
| $SF_{lot}$ | Represents the variation of radiation tolerance from lot to lot and within a lot. |

Table 5: definition of the safety factors required for RTC computations.

Table 6 and 7 give SF values for various ATLAS locations [6]. In these tables, columns (a) to (f) correspond to the following cases:

(a) Applies on $SRL_{tid}$ only, for COTS only, except if TID tests are made with accelerated ageing at elevated temperature (in this case, $SF_{ldr} = 1$);
(b) Applies on $SRL_{tid}$ only, for radiation-hard ASICs only, except if TID tests are made with accelerated ageing at elevated temperature (in this case, $SF_{ldr} = 1$);
(c) Applies on all SRL for the *pre-selection* of COTS issued from unknown[4] batches *if their qualification is to be done on unknown COTS batches*;
(d) Applies on all SRL for the *qualification* of unknown COTS batches;
(e) Applies on all SRL for *pre-selecting* COTS or ASICs issued from homogeneous[5] batches or from unknown batches, *only if their qualification is to be done on homogeneous batches*;
(f) Applies on all SRL for the *qualification* of homogeneous COTS or ASICs batches;

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[4] An unknown batch is a batch of components provided by a vendor without information on the production line, on the batch number, etc. (these components may be issued from different batches or different production lines).

[5] A homogeneous batch (or diffusion batch) is a batch of components issued from wafers manufactured together at the same time on a known production line.

| **SYSTEM** | **SUB-SYSTEM** | **$SF_{sim}$** | | | **$SF_{ldr}$** | | | | **$SF_{lot}$** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **SF applies on:** | | **$SRL_{tid}$** | **$SRL_{niel}$** | **$SRL_{see}$** | **$SRL_{tid}$ (a)** | **$SRL_{tid}$ (b)** | **$SRL_{niel}$** | **$SRL_{see}$** | **All SRL (c), (d)** | **All SRL (e)** | **All SRL (f)** |
| **Pixel barrel** | Layer 1 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Layer 2 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Layer 3 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| **Pixel discs** | Disc 1 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Disc 2 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Disc 3 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Disc 4 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Disc 5 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| **SCT barrel** | Barrel 1 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Barrel 2 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Barrel 3 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Barrel 4 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| **SCT disc** | 1-silicon | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 1-electronics | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 2-silicon | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 2-electronics | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 3-silicon | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 3-electronics | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 4-silicon | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 4-electronics | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 5-silicon | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 5-electronics | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 6-silicon | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 6-electronics | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 7-silicon | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 7-electronics | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 8-silicon | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 8-electronics | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 9-silicon | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 9-electronics | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |

Table 6: SF values for various ATLAS locations.

| **SYSTEM** | **SUB-SYSTEM** | **$SF_{sim}$** | | | **$SF_{ldr}$** | | | | **$SF_{lot}$** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **SF applies on:** | | **$SRL_{tid}$** | **$SRL_{niel}$** | **$SRL_{see}$** | **$SRL_{tid}$ (a)** | **$SRL_{tid}$ (b)** | **$SRL_{niel}$** | **$SRL_{see}$** | **All SRL (c), (d)** | **All SRL (e)** | **All SRL (f)** |
| **TRT** | barrel | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | end-cap | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| **LAR** | barrel | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | end-cap | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| **TILE** | HV micro | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | HV opto | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Mother | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Integrator | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Adder | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Digitiser PC | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | -link & interface | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| **MUON CSC** | Start CSC 1 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | End CSC 1 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Start CSC 2 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | End CSC 2 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Start CSC 3 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | End CSC 3 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Start CSC 4 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | End CSC 4 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| **MUON RPC** | BMF | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | BML | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | BMS | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | BOF | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | BOL | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | BOS | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| **MUON TGC** | 1 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | 2 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| **MUON MDT** | Barrel 1 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Barrel 2 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | Barrel 3 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | End-cap 1 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | End-cap 2 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |
| | End-cap 3 | 3.5 | 5 | 5 | 5 | 1.5 | 1 | 1 | 4 | 2 | 1 |

Table 7: SF values for various ATLAS locations (cont.).

Remark 1: the location (Rmin, Rmax, Zmin, Zmax) of the electronics of the sub-systems mentioned in tables 6 and 7 is given in tables 2 and 3.

Remark 2: Table 6 and 7 give values of $SF_{sim}$, $Sf_{ldr}$ and $SF_{lot}$ up to date at the date of release of the ATLAS Policy on Radiation Policy revision 2. As mentioned in this document in section VII page 6, subsequent updated values – if any - will be made available on the "ATLAS Radiation Hard Electronics" web page[6], together with the updated values of $SRL_{tid}$, $SRL_{niel}$ and $SRL_{see}$.

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[6] The address of this web page is: http://atlas.web.cern.ch/Atlas/GROUPS/FRONTEND/radhard.htm

## 2.2. Radiation tolerance criterion $\mathrm{RTC}_{\mathrm{see}}$

### 2.2.1. Definition of the three $\mathrm{RTC}_{\mathrm{see}}$:

The generic acronym SEE (Single Event Effect) represents at once SEU (Single Event Upsets), SEL (Single Event Latch-up), SEGR (Single Event Gate rupture) and SEB (Single Event Burnout). These various SEEs can be distributed in three categories:

- *Soft SEEs* (also called soft SEUs) are radiation induced bit flips that corrupt data or system configurations. They are *not permanent effects* (they are cancelled by resetting the system or rewriting data in a memory). Example: a “1” changed into a “0” in a combinatorial logic circuit, or in a register, or in a memory.
- *Hard SEEs* (also called hard SEUs) are radiation induced bit flip that corrupts data or system configurations. They are *permanent effects* (they are not cancelled by resetting the system or rewriting data in a memory). Example: a bit stuck to “1” in a memory cell.
- *Destructive SEEs* (SELs, SEBs, SEGRs) produce permanent short circuits. SELs are destructive SEEs, unless a robust architectural solution protects the circuit against thermal destruction resulting from latch-up. SEBs and SEGRs are always destructive SEEs.

The radiation tolerance criteria for soft, hard and destructive SEEs are defined in table 8:

| Radiation Tolerance Criterion | Category of SEE | RTC Unit |
|---|---|---|
| $\mathrm{RTC}_{\mathrm{see.s}}$ | soft SEE | Soft SEE rate:<br>***soft SEE / s*** |
| $\mathrm{RTC}_{\mathrm{see.h}}$ | hard SEE | Hard SEE rate:<br>***hard SEE / s*** |
| $\mathrm{RTC}_{\mathrm{see.d}}$ | destructive SEE | Destructive SEE rate:<br>***destructive SEE / s*** |

Table 8: Radiation tolerance criteria $\mathrm{RTC}_{\mathrm{see}}$

*The values of these RTCs must be defined by each ATLAS Sub-system for each electronic function.* They are the maximum rates acceptable for soft SEUs, for hard SEUs and for destructive SEEs.

Remark: destructive SEEs can induce fire in electronics systems. In ATLAS electronics systems, for safety reasons, components sensitive to destructive SEEs are not allowed unless a proven robust architectural solution protects the system against SEE induced fire.

### 2.2.2. Use of $\mathrm{RTC}_{\mathrm{see.s}}$ for the selection or the qualification of electronics components

a / Soft SEE rate foreseen in ATLAS sub-systems:

The study of SEU rates published in reference [5] shows that the probability of soft SEU production is almost identical for all hadron above 20 MeV, and that the contribution to soft SEE rate of hadrons below 20 MeV is much smaller than that of hadrons above 20 MeV. This enables one to extrapolate the soft SEE (or soft SEU) rate measured with 60 – 200 MeV proton to that produced by all the hadrons of energy greater than 20 MeV foreseen in a given ATLAS location, and so to predict the soft SEU rate in this location.

The prediction of soft SEU rate in a given ATLAS location by extrapolation of measurements made with 60 – 200 MeV protons can be done as follow:

$$\text{Soft SEU}_f = (\text{soft SEU}_m / \text{ARL}) \times (\text{SRL}_{see} / 10^8 s) \times \text{SF}_{sim}$$

Where:

- "Soft $\text{SEU}_f$" is the *foreseen <u>rate</u> of soft SEU* in a given ATLAS location (soft SEU / s);
- "Soft $\text{SEU}_m$" is the total *<u>number</u> of soft SEU measured* during the total duration of proton beam tests (use the worst case value measured among the 4 DUT);
- "ARL" is the *Applied Radiation Level* (total fluence of 60 – 200 MeV proton applied during SEE measurement, in hadron / $cm^2$);
- "$\text{SRL}_{see}$" is the *Simulated Radiation Level* (total fluence of hadrons of energy greater than 20 MeV foreseen in 10 years in the ATLAS location, in hadron / $cm^2$);
- $10^8$s represents the integrated beam time (in seconds) expected in 10 years of LHC operation.
- "$\text{SF}_{sim}$" is the safety factor explained and given in section 2.1.

b / <u>Interpretation of SEE tests:</u>

Soft SEE (or soft SEU) rates foreseen for each ATLAS electronics components in a given ATLAS location must be lower than the corresponding radiation tolerance criterion:

$$(1) \quad \text{Soft SEU}_f < \text{RTC}_{see.s}$$

The pre-selection of a generic component requires that all the tested components satisfy this relation.

### 2.2.3. <u>Use of $\text{RTC}_{see.h}$ and $\text{RTC}_{see.d}$ for the selection of electronics components</u>

a / <u>Hard SEE rate and destructive SEE rate foreseen in ATLAS sub-systems:</u>

The equivalence of the probability of producing SEE for all the hadrons of energy greater than 20 MeV, established in [5], concerns *soft* SEUs only. Up to now, no study has been done to estimate the rates of *hard SEUs or destructive* SEEs in an *accelerator environment*. Without such a study, it is very difficult to predict accurately the rates of hard or destructive SEE for ATLAS. However, it is possible to make an approximate estimation of an upper limit for these rates.

The production of hard SEUs or destructive SEEs requires a high local instantaneous energy deposition (higher than that required for producing soft SEUs). The deposition of this high energy requires particles having a high LET (Linear Energy Transfer, or dE / dX). In HEP experiments like ATLAS, particles with a high LET are produced by fission reactions induced by energetic hadrons on elements heavier than 170-180 AMU [7]. The range of these particles in silicon or in the material from the integrated circuit package is typically less than 10 µm, which means that only secondary particles from fission reactions occurring *in silicon* or *in the material from the package* can produce hard or destructive SEEs. The main elements constituting silicon integrated circuits (ICs) and their packages are listed in table 9. Among these elements, only five of them have an atomic number higher than 170. These elements are tungsten, tantalum, gold, lead and platinum. Tungsten is used in a relatively thin layer to build an inter-metal barrier in "via" (vertical link between two metal layers). Tantalum is (very rarely) used to build a conductive layer on the top of the CMOS gate oxides. Lead could be used to make SnPb ball bumps in some hybrid systems like Pixel Detectors[7]. Gold constitutes the wire bonds of most of the ICs. Platinum is (very rarely) used in a thin layer to build inter-metal barriers in "via". Among these five elements, tantalum and platinum are very rarely used, so the most probable contributors to fission reactions are tungsten, gold and lead. The cross sections of fission reactions induced by protons in these elements increase with the proton energy up to saturated values, which occur at about 300 MeV for lead, 500 MeV for gold, and more than 800 MeV for tungsten [8]. However, the fission cross section of tungsten bombarded with protons is much smaller than that of gold and lead, so we can neglect the increase of this cross section between 500 MeV and the saturation energy. It can be estimated that most of the fission reactions can be triggered by 500 MeV protons.

| Element | Relative abundance in silicon integrated circuits | Use | Atomic weight |
|---|---|---|---|
| Silicon | Large | Main semiconductor | 28 |
| Boron | Small (< 1E-3%) | Doping | 11 |
| Arsenic | Small (< 1E-3%) | Doping | *75* |
| Phosphor | Small (< 1E-3%) | Doping | 31 |
| Aluminium | Large (few µm thick) | Interconnection metal (AlCu) in ≥ 0.25 µm processes | 27 |
| Copper | Large (> 6000 Å) | Interconnection metal (Cu) in advanced processes | 64 |
| **Tungsten** | Small (~ 1000 Å) | Inter-metal barrier in via | **184** |
| Titanium | Small (few 100 Å) | Inter-metal barrier;<br>Gate conductive layer | 48 |
| **Tantalum** | Small (~ 1000 Å) | Gate conductive layer (very rarely) | **181** |
| Oxygen | Large ($SiO_2$) | Gate oxides, field oxides | 16 |
| Nitrogen | Possibly large ($Si_3N_4$) | Passivation nitrides | 14 |
| **Gold** | Large | Bonding wires | **197** |
| **Lead** | Possibly large | Bumping balls | **207** |
| Tin | Possibly large | Bumping balls | 118 |
| Indium | Possibly large | Bumping balls | 115 |
| **Platinum** | Small (few 100 Å) | Inter-metal barrier in via (very rarely). | **195** |

Table 9: Main elements constituting ICs and their package.

Now an approximate upper limit for the rates of hard SEUs and destructive SEE can be estimated, by assigning the maximum SEE production probability to all the hadrons having an energy higher than a minimum value below which neither hard SEUs nor destructive SEEs occur. As discussed above, the maximum SEE production probability is approximately that measured on ICs irradiated with *500 MeV* protons. For convenience, the minimum value under which neither hard SEUs nor destructive SEEs occur could be set at 20 MeV, which corresponds to the energy threshold used to estimate soft SEU rates.

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[7] For this reason, it is recommended to use indium bumps instead of SnPb bumps, whenever it is possible.

The estimation of the rates of hard SEUs and destructive SEEs in a given ATLAS location by extrapolation of measurements made with 500 MeV protons can be done as follow:

$$\text{Hard or destructive SEE}_f = (\text{hard or destructive SEU}_m / \text{ARL}) \times (\text{SRL}_{see} / 10^8\text{s}) \times \text{SF}_{sim}$$

Where:

- “Hard or destructive $\text{SEU}_f$“ is the *foreseen* *<u>rate</u>* *of hard or destructive SEU* in a given ATLAS location (hard or destructive SEU / s);
- “Hard or destructive $\text{SEU}_m$“ is the total *<u>number</u>* *of hard or destructive SEU measured* during the total duration of proton beam tests (use the worst case value measured among the 4 DUT);
- “ARL” is the *Applied Radiation Level* (total fluence of 500 MeV proton applied during SEE measurement, in hadron / $\text{cm}^2$);
- “$\text{SRL}_{see}$“ is the *Simulated Radiation Level* (total fluence of hadrons of energy greater than 20 MeV foreseen in 10 years in the ATLAS location, in hadron / $\text{cm}^2$);
- $10^8$s represents the integrated beam time (in seconds) expected in 10 years of LHC operation.
- “$\text{SF}_{sim}$” is the safety factor explained and given in section 2.1.

b / <u>Interpretation of SEE tests:</u>

The rates of hard SEUs or destructive SEEs foreseen for each ATLAS electronic component in a given ATLAS location must be lower than the corresponding radiation tolerance criterion:

$$\text{Hard SEU}_f < \text{RTC}_{see.h} \tag{2}$$

$$\text{Destructive SEU}_f < \text{RTC}_{see.d} \tag{3}$$

The pre-selection of a generic component requires that all the tested components fulfill this relation.

## Appendix 2: ATLAS standard test methods

### 1. NIEL test method:

### 1.1. NIEL test method:

This test method is derived from the DOD MIL STD 883 test method 1017.2 [1], with several adaptations. It is suitable both for pre-selecting generic components and qualifying batches. The main stages of this test method are:

a / Selection of a calibrated neutron facility (1 MeV equivalent neutrons / $cm^2$);
b / Selection of a set of 11 good devices (for test of homogeneous[8] batch) or 22 good devices (for test of unknown[9] batch);
c / Serialisation of all devices (see appendix 2 section 1.2.);
d / Electrical measurement performed at room temperature on each device;
e / Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated, it (they) will constitute the pre-radiation reference(s);
f / Irradiation of the 10 (or 20) other components up to the $RTC_{niel}$ required for the application (see details on RTCs in appendix 1);
g / Electrical measurements performed at room temperature on each irradiated device, plus anomaly inspection after deactivation;
h / Rejection of the generic component (if the test is made to pre-select a generic component) or rejection of the batch (if the test is made to qualify a batch) if any of the 10 (or 20) components fails below $\mathrm{RTC}_{\mathrm{niel}}$;
i / Writing of test results in a standard report document (see appendix 3);
j / Feed database with test results (see section IV p.5).

### 1.2. Advises applicable to NIEL test method for components pre-selection or batch qualification:

Preparation of the components to be tested:

- The initial set of un-irradiated components must contain only good devices. At this stage, any faulty or suspect device must be replaced by a good device.
- It is allowed to perform tests with more devices than recommended in this document
- Immediately after selection, each individual component shall be serialised to facilitate pre- and post-irradiation data identification and control. The system of marking shall be such as to ensure if possible that the samples are clearly identified as to date code[10] and manufacturer code[11] of the sample, and individual identification.

Measurement setup

- Two approaches can be used to perform irradiation and tests:
  a / Tests made using a dedicated test board: electrical measurement are made on the 11 (or 22) test components using a dedicated test board.
  b / Tests made using an entire system board: electrical measurement are made on all the components of an entire system board. In this case, the architecture of the board must enable one to check the operation of each of its individual components. The total number of test components having the same part number must be equal or larger than 11 (or 22) as recommended in 1.1.b /. If necessary, this can be obtained by performing irradiation and measurements on additional components (using a dedicated test board), or by testing several system boards.

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[8] A homogeneous batch (or diffusion batch) is a batch of components issued from wafers manufactured together at the same time on a known production line.

[9] An unknown batch is a batch of components provided by a vendor without information on the production line, on the batch number, etc. (these components may be issued from different batches or different production lines).

[10] Code of the date of manufacturing of the batch from which the sample is issued.

[11] Code of the production line from which the sample is issued.

- In case of on-line measurement, all the necessary precautions shall be taken to obtain an electrical measurement system which, by use of sufficient insulation, ample shielding, satisfactory grounding etc. shall yield suitably low level of interference from main 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 nor induce any damage on the device under test.
- In case of off-line measurement, all the leads of each device must be shorted together during irradiation and during transportation, either by insertion in conductive foam or by the use of an appropriate fixture.
- Only sockets that are radiation-resistant and do not exhibit any significant leakage shall be used to connect devices under test and associated circuitry to the test board. Similar precautions shall be taken with respect of cabling and switching systems. All equipment used repeatedly in radiation fields shall be checked periodically for physical and/or electrical degradation.

Irradiation:

- Two approaches can be used to perform irradiation:
  a/ If the electrical measurements are made using a dedicated test board, the irradiation of the 11 (or 22) test components shall be made on the same test board (for on line measurements) or on conductive foam or appropriate fixture(for off line measurement).
  b/ If the electrical measurements are made using an entire system board, the irradiation shall be performed simultaneously on all the components of the system board(s), or on conductive foam or appropriate fixture (off-line measurements).
- It is not necessary to apply NIEL test method on pure CMOS devices, which are naturally tolerant to displacement damage (damages produced by neutron in the semiconductor).
- Neutron fluence can be applied either in one single step or in several steps. In both cases, the cumulated neutron fluence must be equal to at least $RTC_{niel}$. In case of several steps, two methods can be used:
  1/ All the 10 (or 20) devices under test (DUT) are placed in the same location. Electrical measurements are performed on line during irradiation;
  2/ Several sets of 10 (or 20) DUT are placed in several locations which are chosen in order to obtain several neutron fluences ranging from a small value up to the $RTC_{niel}$. All the sets of components are irradiated together at the same time. Electrical measurements can be performed either on line (during irradiation) or off line (after irradiation).
- In the case of several irradiation steps, it is recommended to choose the steps in order to get an approximate linear progression of the cumulated neutron fluence in a logarithmic scale (example: 1, 3, 6, 10, 30, … ; or 1, 4, 10, 40, … ; or 1, 10, 100, … ).
- During irradiation, the temperature must be under control and recorded if necessary.
- During irradiation, in case of off-line measurement, all the leads of each devices must be shorted together.
- During irradiation, in case of on-line measurement, all the leads of each devices must be properly biased in order to enable measurements. Unconnected leads are not allowed.
- The devices under test shall be exposed to a radiation constraint at least as high as $RTC_{niel}$.
- The total fluence of fast neutrons applied on the devices under test must be measured using activation foils such as $^{32}Sr$, $^{54}Fe$ and $^{58}Ni$ placed on the devices under test during irradiation. The fluence at the DUT shall be measured to a resolution of better than 10% and the non-uniformity of the radiation field in the test area shall be a maximum of 10%. The field uniformity shall be verified if the geometry of the test setup is changed.
- Depending on the $RTC_{niel}$, the neutron flux shall be chosen in such a way that the errors in fluxes coming from timing errors and initial beam adjustment are kept below 5%. It shall be recorded in the standard test report document.

Electrical measurements

- The main AC or DC parameters relevant for the DUT shall be measured.
- Electrical measurements shall always be done at room temperature.
- Electrical measurements can be done either on line (during irradiation) or off line (after irradiation).

Results analysis

- The failure of a component can be either the death of the component or the shift of one or more of its main relevant parameters out of the specified limits or out of the acceptable limits for the targeted application.
- For both component pre-selection and lot qualification, the basic acceptance criterion is zero failure among the entire set of tested components. However, if only one device fails, the rejection or the acceptance of a lot can be discussed during PRR. The decision shall be based on an analysis of the failure mechanisms and on the criticality of the component in the system(s) where it will be used.
- Failure induced by mechanisms other than radiation damages must not be imputed to radiation. To avoid such mistakes, after irradiation, components which have failed below $RTC_{niel}$ shall be analysed in order to determine (if possible) the failure mechanism.

Safety

- Irradiation and post-irradiation operations must be made in accordance with the Radiation Safety Rules for Material Irradiation at CERN[12].
- For safety reasons (traceability of irradiated materials, etc.), each ATLAS sub-system shall inform the responsible of radiation safety in ATLAS[13] of each campaign of neutron irradiation of material.
- After neutron irradiation, clearance must be obtained from the health physicists at the test facility before handling irradiated devices.

## 2. TID test methods:

These test methods are derived from the ESA SCC basic specification no 22900 [2], with several adaptations to take the specificity of ATLAS radiation environment into account. Several methods are proposed to test the tolerance of electronic components to Total Ionising Dose (TID):

TID test method for the *pre-selection*[14] of generic components

- Extended TID test method for pre-selection of CMOS devices;
- Simplified TID test method for pre-selection of CMOS devices;
- Extended TID test method for pre-selection of bipolar devices;
- Simplified TID test method for pre-selection of bipolar devices.

TID test method for the *qualification*[15] of batches

- Extended TID test method for qualification of CMOS batches;
- Simplified TID test method for qualification of CMOS batches;
- Extended TID test method for qualification of bipolar or BiCMOS batches;
- Simplified TID test method for qualification of bipolar or BiCMOS batches.

Extended test methods include experimental low dose rate effect (LDRE) tests which enable one to set $SF_{ldre} = 1$ in $RTC_{tid}$ computations. Simplified test methods replace LDRE testing by setting $SF_{ldre} = 5$ in $RTC_{tid}$ computations.

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[12] These rules can be found in the CERN web site: http://psschedule.web.cern.ch/PSschedule/psinfo/prp17b.pdf.

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[14] See steps 3 and 4 in sections I.1 and I.2 page 3 and 4.

[15] See steps 3 and 4 in sections I.1 and I.2 page 3 and 4.

## 2.1. TID test method for the *pre-selection* of generic components:

For both CMOS and bipolar devices, there are two possibilities:

(1) The *safest* solution is to set $SF_{ldre} = 1$ for $RTC_{tid}$ computation and to apply the *extended* TID test methods summarised below;

(2) The *simplest* solution is to use $SF_{ldre} = 5$ for $RTC_{tid}$ computation and to apply the *simplified* TID test methods summarised below.

### 2.1.1. Extended TID test method for the pre-selection of CMOS devices:

The main stages of this test method are:

a/ Selection of a calibrated ionising dose facility ($\gamma$ or x-rays);

b/ Selection of a set of 11 good devices (for test made on components from homogeneous[16] lot) or 22 good devices (for test made on components from unknown[16] lot);

c/ Serialisation of all devices (see appendix 2 section 2.3.);

d/ Electrical measurements on each device at room temperature;

e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated; it (they) will constitute the pre-radiation reference(s);

f/ Irradiation of the 10 (or 20) other components at room temperature under bias in one or several step(s) up to the RTC required for the application (set $SF_{ldre} = 1$ to compute $RTC_{tid}$);

g/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*; rejection of the generic component if one of the 10 (or 20) components fails;

h/ After the last irradiation step ($TID = RTC_{tid}$), annealing under bias (168 hours at room temperature) plus electrical measurements (room temperature) at 24 hours and 168 hours; rejection of the generic component if one of the 10 (or 20) components fails;

i/ Accelerated ageing under bias (168 hours at 100 °C);

j/ Electrical measurements at room temperature; rejection of the generic component if one of the 10 (or 20) components fails;

k/ Writing of test results in a standard report document (see appendix 3);

l/ Feed database with test results (see section IV p.5).

### 2.1.2. Simplified TID test method for the pre-selection of CMOS devices:

The main stages of this test method are:

a/ Selection of a calibrated ionising dose facility ($\gamma$ or x-rays);

b/ Selection of a set of 11 good devices (for test made on components from homogeneous[16] lot) or 22 good devices (for test made on components from unknown[16] lot);

c/ Serialisation of all devices (see appendix 2 section 2.3.);

d/ Electrical measurement at room temperature on each device;

e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated, it (they) will constitute the pre-radiation reference(s);

f/ Irradiation of the 10 (or 20) other components at room temperature under bias in one or several step(s) up to the RTC required for the application (set $SF_{ldre} = 5$ to compute $RTC_{tid}$);

g/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*; rejection of the generic component if one of the 10 (or 20) components fails;

h/ After the last irradiation step ($TID = RTC_{tid}$), annealing under bias (168 hours at room temperature) plus electrical measurements (room temperature) at 24 hours and 168 hours; rejection of the *generic component* if one of the 10 (or 20) components fails;

i/ Writing of test results in a standard report document (see appendix 3);

j/ Feed database with test results (see section IV p.5).

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[16] See footnote (8) and (9) in page 18.

### 2.1.3. Extended TID test method for the pre-selection of bipolar devices:

The main stages of this test method are:

#### 2.1.3.1. Preparation of the test:

a/ Selection of a calibrated ionising dose facility (γ or x-rays);
b/ Selection of a set of (11+2n) good devices (for test made on components from homogeneous[17] batch) or (22+4n) good devices (for test made on components from unknown[17] batch). The 2n (or 4n) components will be used to determine the worst case temperature which will be set during the final radiation test in order to experimentally represent low dose rate effects (LDRE). The value of n shall be chosen in order to allow an estimation of the worst case temperature with a reasonable accuracy (chose at least n>3).
c/ Serialisation of all devices (see appendix 2 section 2.3.);
d/ Electrical measurement performed at room temperature on each device;
e/ Random selection of 1 component among the set of (11+2n) devices (or 2 components among the set of (22+4n) devices). This (these) component(s) will not be irradiated, it (they) will constitute the pre-radiation reference(s);

#### 2.1.3.2. Determination of the worse case temperature:

f/ Random selection of 2 devices (for test made on components from homogeneous[17] batch) or 4 devices (for test made on components from unknown[17] batch) among the set of remaining devices;
g/ Irradiation under bias at room temperature of the 2 (or 4) selected devices by steps up to the $RTC_{tid}$ required for the application (use $SF_{ldre} = 1$ to compute $RTC_{tid}$);
h/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*;
i/ Redo (n-1) times the steps e/, f/ and g/, each time with 2 (or 4) new devices heated during irradiation at (n-1) different temperatures comprised between 20°C and 90°C. After each of these e/ + f/ + g/ steps, perform electrical measurements at room temperature on each 2 (or 4) devices. Determine the irradiation temperature that produces the worst radiation damage;

#### 2.1.3.3. Final radiation test:

j/ Irradiation under bias at the worst case temperature (determined in stage i/) of the 10 (or 20) remaining components, in one or several step(s) up to the $RTC_{tid}$ required for the application (set $SF_{ldre} = 1$ to compute $RTC_{tid}$);
k/ Electrical measurements on each irradiated component, at room temperature *within 1 hour after the end of each dose step*. Rejection of the *generic component* if one of the 10 (or 20) components fails;
l/ Writing of test results in a standard report document (see appendix 3);
m/ Feed database with test results (see section IV p.5).

### 2.1.4. Simplified TID test method for the pre-selection of bipolar devices:

The main stages of this test method are:

a/ Selection of a calibrated ionising dose facility (γ or x-rays);
b/ Selection of a set of 11 good devices (for test made on components from homogeneous[17] batch) or 22 good devices (for test made on components from unknown[17] batch).
c/ Serialisation of all devices (see appendix 2 section 2.3.);
d/ Electrical measurement performed at room temperature on each device;

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[17] See footnote (8) and (9) in page 18.

e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated, it (they) will constitute the pre-radiation reference(s);
f/ Irradiation of the 10 (or 20) other components at room temperature under bias in one or several step(s) up to the RTC required for the application (set $SF_{ldre} = 5$ to compute $RTC_{tid}$);
g/ Electrical measurements on each irradiated component, at room temperature *within 1 hour after the end of each dose step*. Rejection of the *generic component* if one of the 10 (or 20) components fails;
h/ Writing of test results in a standard report document (see appendix 3);
i/ Feed database with test results (see section IV p.5).

### 2.2. TID test method for the *qualification* of batches:

Here also, for both CMOS and bipolar devices, there are two possibilities:
(1) The *safest* solution is to set $SF_{ldre} = 1$ for $RTC_{tid}$ computation and to apply the *extended* TID test methods summarised below;
(2) The *simplest* solution is to use $SF_{ldre} = 5$ for $RTC_{tid}$ computation and to apply the *simplified* TID test methods summarised below.

### 2.2.1. Extended TID test method for the qualification of CMOS batches:

The main stages of this test method are:
a/ Selection of a calibrated ionising dose facility (γ or x-rays);
b/ Selection of a set of 11 good devices (for qualification of homogeneous[18] lot) or 22 good devices (for qualification of unknown[18] lot);
c/ Serialisation of all devices (see appendix 2 section 2.3.);
d/ Electrical measurements on each device at room temperature;
e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated; it (they) will constitute the pre-radiation reference(s);
f/ Irradiation of the 10 (or 20) other components at room temperature under bias in one or several step(s) up to the RTC required for the application (set $SF_{ldre} = 1$ to compute $RTC_{tid}$);
g/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*; rejection of the generic component if one of the 10 (or 20) components fails;
h/ After the last irradiation step ($TID = RTC_{tid}$), annealing under bias (24 hours at room temperature);
i/ Accelerated ageing under bias (168 hours at 100 °C);
j/ Electrical measurements at room temperature; rejection *of the lot* if one of the 10 (or 20) components fails;
k/ Writing of test results in a standard report document (see appendix 3);
l/ Feed database with test results (see section IV p.5).

### 2.2.2. Simplified TID test method for the qualification of CMOS batches:

The main stages of this test method are:
a/ Selection of a calibrated ionising dose facility (γ or x-rays);
b/ Selection of a set of 11 good devices (for qualification of homogeneous[18] lot) or 22 good devices (for qualification of unknown[18] lot);
c Serialisation of all devices (see appendix 2 section 2.3.);
d Electrical measurements on each device at room temperature;

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[18] See footnote (8) and (9) in page 18.

e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated; it (they) will constitute the pre-radiation reference(s);
f/ Irradiation of the 10 (or 20) other components at room temperature under bias in one or several step(s) up to the RTC required for the application (set $SF_{ldre}$ = 5 to compute $RTC_{tid}$);
g/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*; rejection of the generic component if one of the 10 (or 20) components fails;
h/ After the last irradiation step (TID = RTC), annealing under bias (24 hours at room temperature);
i/ Electrical measurements at room temperature; rejection *of the lot* if one of the 10 (or 20) components fails;
j/ Writing of test results in a standard report document (see appendix 3);
k/ Feed database with test results (see section IV p.5).

### 2.2.3. Extended TID test method for the qualification of bipolar or BiCMOS batches:

The main stages of this test method are:
a/ Selection of a calibrated ionising dose facility ($\gamma$ or x-rays);
b/ Selection of a set of 11 good devices (for qualification of homogeneous[19] lot) or 22 good devices (for qualification of unknown[19] lot);
c/ Serialisation of all devices (see appendix 2 section 2.3.);
d/ Electrical measurements on each device at room temperature;
e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated; it (they) will constitute the pre-radiation reference(s);
f/ Irradiation of the 10 (or 20) other components *at worst case temperature* (determined during pre-selection tests, see section 2.1.3.) under bias in one or several step(s) up to the $RTC_{tid}$ required for the application (set $SF_{ldre}$ = 1 to compute $RTC_{tid}$);
g/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*; rejection *of the lot* if one of the 10 (or 20) components fails;
h/ Writing of test results in a standard report document (see appendix 3);
i/ Feed database with test results (see section IV p.5).

### 2.2.4. Simplified TID test method for the qualification of bipolar or BiCMOS batches:

The main stages of this test method are:
a/ Selection of a calibrated ionising dose facility ($\gamma$ or x-rays);
b/ Selection of a set of 11 good devices (for qualification of homogeneous[19] lot) or 22 good devices (for qualification of unknown[19] lot);
c/ Serialisation of all devices (see appendix 2 section 2.3.);
d/ Electrical measurements on each device at room temperature;
e/ Random selection of 1 component among the set of 11 devices (or 2 components among the set of 22 devices). This (these) component(s) will not be irradiated; it (they) will constitute the pre-radiation reference(s);
f/ Irradiation of the 10 (or 20) other components *at room temperature* under bias in one or several step(s) up to the RTC required for the application (set $SF_{ldre}$ = 5 to compute $RTC_{tid}$);
g/ Electrical measurements at room temperature *within 1 hour after the end of each dose step*; rejection *of the lot* if one of the 10 (or 20) components fails;
h/ Writing of test results in a standard report document (see appendix 3);
i/ Feed database with test results (see section IV p.5).

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[19] See footnote (8) and (9) in page 18.

## 2.3. Advice applicable to each TID test methods for components pre-selection or lot qualification:

Preparation of the components to be tested:

- The initial sets of un-irradiated components must contain only good devices. At this stage, any faulty or suspect device must be replaced by a good device.
- It is allowed to perform tests with more devices than recommended in this document
- Immediately after selection, each individual component shall be serialised to facilitate pre- and post-irradiation data identification and control. The system of marking shall be such as to ensure if possible that the samples are clearly identified as to date code[20] and manufacturer code[21] of the sample, and individual identification.

Measurement setup

- Two approaches can be used to perform irradiation and tests:
  - a/ Tests made using a dedicated test board: electrical measurement are made on the 11 (or 22) test components using a dedicated test board.
  - b/ Tests made using an entire system board: electrical measurement are made on all the components of an entire system board. In this case, the architecture of the board must enable one to check the operation of each of its individual components. The total number of test components having the same part number must be equal or larger than 11 (or 22) as recommended in 1.1.b/. If necessary, this can be obtained by performing irradiation and measurements on additional components (using a dedicated test board), or by testing several system boards.
- In case of on-line measurement, all the necessary precautions shall be taken to obtain an electrical measurement system which, by use of sufficient insulation, ample shielding, satisfactory grounding, etc., shall yield suitably low level of interference from main 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 nor induce any damage on the device under test.
- Only sockets which are radiation-resistant and do not exhibit any significant leakage shall be used to connect devices under test and associated circuitry to the test board. Similar precautions shall be taken with respect of cabling and switching systems. All equipment used repeatedly in radiation fields shall be checked periodically for physical and/or electrical degradation.

Irradiation:

- Two approaches can be used to perform irradiation:
  - a/ If the electrical measurements are made using a dedicated test board, the irradiation of the 11 (or 22) test components shall be made on the same test board.
  - b/ If the electrical measurements are made using an entire system board, the irradiation shall be performed simultaneously on all the components of the same system board(s).
- TID can be applied either in one or several irradiation steps. In the case of several irradiation steps, it is recommended to chose radiation steps in order to get an approximate linear progression of the cumulated ionising dose in a logarithmic scale (example: 1, 3, 6, 10 , 30, … ; or 1, 4, 10, 40, … ; or 1, 10, 100, …).
- In the case of several irradiation steps, the time interval from the completion of an exposure (i) to the start of the next exposure (i+1) shall be a maximum of 3 hours. If this cannot be achieved, devices shall be irradiated in one step.
- During irradiation, devices must be AC + DC biased using conditions representatives of their regular operation.

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[20] Code of the date of manufacturing of the batch from which the sample is issued.

[21] Code of the manufacturing line from which the sample is issued.

- During irradiation, the temperature must be under control and recorded.
- The devices under test shall be exposed to a radiation constraint at least as high as $RTC_{tid}$.
- The Total Ionising Dose (TID) applied on the devices under test must be measured using appropriate dosimeters. The dose at the devices under test shall be measured to a resolution of better than 10% and the non-uniformity of the radiation field in the test area shall be a maximum of 10%. The field uniformity shall be verified if the geometry of the test set-up is changed.
- Depending on the $RTC_{tid}$, the dose rate shall be chosen in such a way that the errors in dose coming from timing errors and initial beam adjustment are kept below 5%. It shall be recorded in the standard test report document.
- The radiation beam shall be perpendicular to the top face of the device under test.

Electrical measurements

- The main AC or DC relevant parameters for the DUT shall be measured.
- Electrical measurements shall always be done at room temperature.
- Electrical measurements can be done either on line (during irradiation) or off line (after irradiation).
- If devices have to be removed from their exposure sockets, then, during transport, the leads must be shorted together, either by insertion in conductive foam or by the use of an appropriate fixture.
- The time interval from the completion of an exposure to the end of the measurement of electrical parameters shall be a maximum of 1 hour.

Results analysis

- The failure of a component can be either the death of the component or the shift of one or more of its main relevant parameters out of the specified limits or out of the acceptable limits for the targeted application.
- For both component pre-selection and lot qualification, the basic acceptance criterion is zero failure among the entire set of tested components. However, if only one device fails, the rejection or the acceptance of a lot can be discussed during PRR. The decision shall be based on an analysis of the failure mechanisms and of the criticality of the component in the system(s) where it will be used.
- Failure induced by mechanisms other than radiation damages must not be imputed to radiation. To avoid such mistakes, after irradiation, components which have failed below RTC shall be analysed in order to determine (if possible) the failure mechanism.

## 3. Single event effects (SEE) test method:

In HEP detectors, SEE will be produced by secondary particles resulting of interactions of hadrons with the material constituting the integrated circuits (i.e. the semiconductor chip and the package). These secondary particles have a small range; they are produced inside the semiconductor or inside the package of the integrated circuits in which they will perhaps induce SEEs. SEE tests made using proton or neutron beam involve these mechanisms based on secondary particles; thus they are more representative of actual HEP detectors conditions than SEE tests made using heavy ion beam. Moreover, the only existing models suitable to estimate SEE rate in an accelerator environment are based on SEE tests made with a proton beam [5] or on SEE tests made with a neutron beam [9]. For these reasons, the test methods proposed below to estimate SEE rates in a given ATLAS environment are based on the use of proton beam or of neutron beam.

## 3.1. Single event effects (SEE) test method based on proton beam for the pre-selection of ICs:

Soft[22] SEE tests can be done with protons having energy equal or higher than 60 MeV. However, as discussed in appendix 1 section 2.2.3, 60 MeV protons are not energetic enough to trig hard[22] or destructive[22] SEEs. Global SEE tests (including soft, hard and destructive SEEs) requires energy ≥ 500 MeV. The test method proposed below is suitable to estimate soft, hard and destructive SEE rates in a given ATLAS environment, depending on the energy of the proton beam. For the estimation of soft SEE rates, the choice of the test beam (60 MeV) and the method for estimating SEE rates are based on advice from [5]. For the estimation of hard or for destructive SEE rates, the choice of the test beam (≥ 500 MeV) and the method for estimating SEE rates are based on the analysis given in appendix 2 section 2.2.3 and on advice from [7].

The main steps of this proton-based SEE test method are:

a/ Selection of a calibrated proton facility suitable to provide a proton beam with a constant energy (60 MeV < E < 200 MeV for soft SEE tests only, 500 MeV < E < 1 GeV for global SEE test including soft, hard and destructive SEEs).
b/ Selection of a set of 4 good devices issued from *several* homogeneous[23] lots, or issued from *one or more* unknown[23] lot;
c/ Serialisation of all devices (see appendix 2 section 3.3.);
d/ Electrical measurements on each device at room temperature;
e/ Irradiation of each Device Under Test (DUT) at a controlled temperature, with a constant proton flux, up to a total fluence large enough to produce a total number of SEEs large enough for relevant statistics.
f/ During irradiation: on line electrical operation and measurement on the 4 devices; on line record of the measurement results;
g/ After irradiation and deactivation: post-irradiation inspection;
h/ Using recorded test results, computation of the soft, hard and destructive SEE rates expected in the targeted application. Comparison of these rates with the $RTC_{see}$ using the relations (1), (2) and (3) given in appendix 1 sections 2.2.2. and 2.2.3. Rejection of the generic component if one or more of the tested components does not satisfy these relations.
i/ Writing of test results in a standard report document (see appendix 3);
j/ Feed database with test results (see section IV p.5).

## 3.2. Single event effects (SEE) test method based on neutron beam for the pre-selection of ICs:

The test method proposed below is suitable to estimate the rates of *soft* SEE in a given ATLAS environment. It is based on advises from [9]. It requires neutrons having energy tuneable from 5 MeV to at least 25 MeV. However, 25 MeV neutrons are not energetic enough to trig hard[17] or destructive[17] SEEs. Global SEE tests (including soft, hard and destructive SEEs) would require neutrons having an energy ≥ 500 MeV.

The main steps of this neutron-based SEE test method are:

a/ Selection of a calibrated neutron source suitable to provide a neutron beam with a constant energy tuneable from $E_{min}$ = 5 MeV to $E_{max}$ = 25 MeV. This neutron source can be a cyclotron with a proton or a deuteron beam impinging on a Beryllium target and producing neutrons via stripping reactions.

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[22] See definition in appendix 1 section 2.2.1.
[23] See footnote (8) and (9) in page 18.

b/ Selection of a set of 4 good devices issued from *several* homogeneous[24] lots, or issued from *one or more* unknown[24] lot;

c/ Serialisation of all devices (see appendix 2 section 3.3.);

d/ Electrical measurements on each device at room temperature;

e/ Irradiation by steps of each Device Under Test (DUT) at a controlled temperature, with a constant neutron flux having an energy set to $E_{test}$.
The total number of energy steps (n) must be chosen in order to obtain the required accuracy. For step i, $E_{test} = E_{min} + i \text{ x } (E_{max} - E_{min})/n$, with $1 \le i \le n$. For each step, the total neutron fluence must be large enough to produce a total number of SEEs large enough for relevant statistics.

f/ During each irradiation step: on line electrical operation and measurement on the 4 devices; on line record of the measurement results;

g/ After the last irradiation step and after deactivation: post-irradiation inspection;

h/ Using test results recorded during each step of neutron irradiation (energy $E_{test}$), computation of the soft SEE rates expected in the targeted ATLAS application:

- Comparison of the SEE rates measured at each neutron energy $E_{test}$ with the value of the integral $I_{BGR}$ given below, where the $BGR(E_n, E_r)$ curves can be found in [9] and references therein together with differential neutron energy spectrum dN/dEn (for each neutron energy $E_{test}$).

$$I_{BGR} = \int_{E_n} BGR(E_n, E_r) \times \frac{dN}{dE_n} dE_n$$

  For this comparison, a $\chi^2$ dependence of the recoil energy $E_r$, in the linear fit of the measured SEE rate versus $I_{BGR}$, is to be done. The optimal value $E_{r.opt}$ corresponds to the minimum value $\chi^2_{min}$. This optimal value $E_{r.opt}$ gives the optimal integral $I_{BGR.opt}$ that enables one to derive a constant C = measured SEE rate / $I_{BGR.opt}$.
- Computation of the integral $I_{BGR(ATLAS)}$ corresponding to a given location in ATLAS, using the differential neutron energy spectrum expected at this location.
- Computation of the rate of soft SEE expected in the targeted ATLAS application:

$$\text{Soft } SEU_f = C \text{ x } I_{BGR(ATLAS)}$$

i/ Rejection of the generic component if one or more of the tested components does not satisfy the relation (1) prescript in appendix 1 section 2.2.2.

j/ Writing of test results in a standard report document (see appendix 3);

k/ Feed database with test results (see section IV p.5).

### 3.3. Advice for the SEE test method:

- SEE test method given in 3.1. applies only to the pre-selection of generic components.
- SEE tests are *not required for the qualification of lots* because results of pre-selection SEE tests are supposed to be enough reproducible to make qualification SEE tests unnecessary.

Preparation of the components to be tested:

- The initial sets of 4 un-irradiated components must contain only good devices. At this stage, any faulty or suspect device must be replaced by a good device.
- It is allowed to perform tests with more devices than recommended in this document
- Deluding of the devices under test (DUT) is not required for SEE tests made with *protons* or *neutrons*. Deluding of the DUTs is mandatory for ion-based SEE tests.

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[24] See footnote (8) and (9) in page 18.

- Immediately after selection, each individual component shall be serialised to facilitate pre- and post-irradiation data identification and control. The system of marking shall be such as to ensure if possible that the samples are clearly identified as to date code[25] and manufacturer code[26] of the sample, and individual identification.

Measurement setup

- Irradiation and measurement shall be made with components on board, either using an actual ATLAS system board, or using a dedicated test board.
- If irradiation and measurements are made using an actual ATLAS system board, the architecture of the system board must enable to run and to measure the DUT.

Irradiation

- A global proton-based SEE test (including soft, hard and destructive SEEs) requires protons with an energy ≥ 500 MeV. However, protons with too high energy (>> 1GeV) could produce a lot of *small fragments* which will have a smaller LET than that of the few bigger fragments produced by 500 MeV – 1 GeV protons. For this reason, it is recommended to perform global SEE tests with protons having an energy comprised between 500 MeV and 1 GeV. Proton beams with an energy higher than 1 GeV can be used for SEE tests, however they must be calibrated before being used. The calibration must be done by comparing the rates of SEE (including destructive SEEs) produced by the proton beam under calibration to the rates of SEE (including destructive SEEs) produced by a proton beam with an energy selected in the range 500 MeV – 1 GeV.
- For the time being, there is no model that allows to estimate SEE rates *in HEP experiments* on the basis of SEE tests made using *heavy ions*. For this reason, it is recommended to use heavy ion tests *only* to identify and then *to reject* generic components which are sensitive to SEE. In this case, the threshold of sensitivity (threshold LET) below which generic components will be rejected must be determined by the ATLAS Sub-systems.
- The proton flux used for SEE tests must be high enough to allow a reasonable duration of the experiment, and low enough to allow an accurate identification of individual SEEs.
- Only the DUT must be irradiated. The other components must be protected from radiation using appropriate shielding.
- If the test is made using an actual ATLAS system board, during irradiation, all the board must be biased and operated in order to run and measure the DUT.
- If irradiation and measurement are made using dedicated test boards, then two methods can be used to operate and measure DUTs during irradiation:
  1/ Sequential operation and measurement of each DUT, one by one, using a dedicated test board. In this case, the other DUTs and the components from the board other than the DUTs (for instance MUXs, etc.) must be protected from radiation using shield or by placing them out of the beam;
  2/ Simultaneous operation and measurement of all the DUTs together using a dedicated test board. In this case, components from the board other than the DUTs must be protected from irradiation using a shield or by placing them out of the beam.
- During irradiation, temperature must be set and maintained at a value close to that foreseen in actual ATLAS operating conditions, and must be recorded.
- During irradiation, DUTs must be AC + DC biased using conditions representatives of those of their regular operation. All the necessary precautions must be taken in order to avoid any damage that could be produced by the measurement system (parasitic electrical pulses).

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[25] Code of the date of manufacturing of the batch from which the sample is issued.
[26] Code of the manufacturing line from which the sample is issued.

- During irradiation, DUTs that die[27] before the targeted total fluence is reached must be replaced by new good devices, then the irradiation must be pursued up to the targeted total fluence.
- If no SEE occurs with a total fluence equal to $SRL_{see}$, or if the total number of SEEs measured with a total fluence equal to $SRL_{see}$ is too small to provide relevant statistics, then the irradiation must be pursued up to two times $SRL_{see}$.

Electrical measurements

- During irradiation, digital circuits must be automatically and periodically written and read (search for temporary or permanent bit errors); analogue circuits must be automatically and continuously read (search for parasitic transient pulses), and power consumption must be automatically and continuously measured on both analogue and digital circuits (search for SEL, SEGR or SEB);
- During irradiation, all measurements must be automatically recorded on line.

Results analysis

- The failure of a component can be either the death of the component (destructive SEE) or a rate of soft or hard SEEs higher than the acceptable limits ($RTC_{see}$) for the targeted application.
- The basic acceptance criterion is zero failure among the set of 4 tested components. However, if only one device fails, the rejection or the acceptance of a generic component shall be discussed during PRR. The decision shall be based on an analysis of the failure mechanisms and of the criticality of the component in the system(s) where it will be used.
- Failure induced by mechanisms other than radiation damages must not be imputed to radiation. To avoid such mistakes, after irradiation, components which have failed below $RTC_{see}$ must be analysed in order to determine (if possible) the failure mechanism.
- Components that are sensitive to *destructive* SEEs shall not be used in ATLAS unless a proven robust architectural solution protects the system against thermal destruction.

Safety

- Irradiation and post-irradiation operations must be made in accordance with the Radiation Safety Rules for Material Irradiation at CERN[28].
- For safety reasons (traceability of irradiated materials, etc.), each ATLAS sub-system shall inform the responsible of radiation safety in ATLAS[29] of each campaign of irradiation of material.
- After irradiation, clearance must be obtained from the health physicists at the test facility before handling irradiated devices.

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[27] The death of these devices could result from the TID, from the NIEL, from destructive SEEs or from parasitic electrical pulses.

[28] These rules can be found in the CERN web site: http://psschedule.web.cern.ch/PSschedule/psinfo/prp17b.pdf.

[29] Shaun Roe, phone +41 22 767 80 54, Email Shaun.Roe@cern.ch

## Appendix 3: ATLAS Standard Reports for Radiation Tests

### ATLAS STANDARD NIEL TEST REPORT (neutron test)

**Page 1/2**
**Ref. DB:**

| | | |
|---|---|---|
| **COMPONENT:**<br>Type: | **Name:**<br>Function: | Manufacturer part number:<br>ATLAS Part number: |
| COTS [ ] | ASIC [ ] | Design centre (if known): |

Main specifications of the component:

| | |
|---|---|
| Manufacturer name:<br>Address: | Manufacturer phone:<br>E-mail:<br>Web: |
| # of tested components (irradiated):<br># of un-irradiated reference components: | Origin of the components:<br>homogeneous batch [ ] unknown batch [ ] |
| Manufacturing date code (for a homogeneous batch): | Manufacturing line code (for a homogeneous batch): |
| Foreseen ATLAS application(s): | ATLAS contact person(s):<br>E-mail: |

**TECHNOLOGY:** Name: Bipolar [ ] BiCMOS [ ] AsGa [ ]

| | | |
|---|---|---|
| Minimum geometry (µm): | # of interconnection layers: | Date of first availability : |

**PACKAGE:** Type: Part number: # of pin: Ceramic [ ] Plastic [ ]

**RADIATION TEST:** ATLAS standard NIEL test method [ ] Other NIEL test method [ ]

Which test method if not ATLAS standard NIEL test method?

| | |
|---|---|
| Experimenter name:<br>Institute:<br>E-mail: | Radiation facility name:<br>Address:<br>Responsible: Phone: |

**RADIATIONS:** Radiation type: Radiation energy:

| | | |
|---|---|---|
| Radiation source: | Flux applied (1 MeV equivalent n.cm$^{-2}$.s$^{-1}$): | Total fluence applied (1 MeV eq. n.cm$^{-2}$): |

Dosimetry / calibration method:

**TEMPERATURE:**

- Temperature during irradiation (°C):____________________________________________
- Temperature during electrical measurements (°C):__________________________________

**BIASING:**

- Supply voltage during irradiation: Y [ ] N [ ] Value if yes (V): ____________________
- AC operation during irradiation: Y [ ] N [ ] Frequency if yes (MHz): ______________
- On line measurement: Y [ ] N [ ]

**IRRADIATION STEPS:**

If several irradiation steps are applied on components placed at the same location, give the value of the cumulated neutron fluence (1 MeV eq. neutron / cm$^2$) reached at each irradiation step:

| | | | | | |
|---|---|---|---|---|---|
| Step 1: | Step 2: | Step 3: | Step 4: | Step 5: | Step 6: |

If a single radiation step is applied on the components and if they are not at the same location during irradiation, give the value of the cumulated neutron fluence (1 MeV eq. neutron / cm$^2$) reached at each irradiation location:

| | | | | | |
|---|---|---|---|---|---|
| Location 1: | Location 2: | Location 3: | Location 4: | Location 5: | Location 6: |

**OPERATION AND MEASUREMENT:**

Concise description of the AC operations performed during measurement

# ATLAS STANDARD NIEL TEST REPORT, cont.

**Page 2/2**
**Ref. DB:**

**OPERATION AND MEASUREMENT, cont.**

| Main electrical parameters measured | Corresponding rejection criteria |
|---|---|
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |

**RESULTS:**

| | | | | | |
|---|---|---|---|---|---|
| a) Serial number of each DUT: | 1) | 2) | 3) | 4) | 5) |
| b) failure fluence (1 MeV eq. $n/cm^2$): | | | | | |
| a) Serial number of each DUT: | 6) | 7) | 8) | 9) | 10) |
| b) failure fluence (1 MeV eq. $n/cm^2$): | | | | | |
| a) Serial number of each DUT: | 11) | 12) | 13) | 14) | 15) |
| b) failure fluence (1 MeV eq. $n/cm^2$): | | | | | |
| a) Serial number of each DUT: | 16) | 17) | 18) | 19) | 20) |
| b) failure fluence (1 MeV eq. $n/cm^2$): | | | | | |

Failure mechanism(s) if failure:

[ ] Component(s) dead. For each dead component, indicate the serial number and the origin(s) of the death:

[ ] Component(s) out of specification(s). For each component out of specification(s), indicate the serial number and the violated specification(s):

**COMMENTS:**

# ATLAS STANDARD TID TEST REPORT (photon test)

**Page 1/2**
**Ref. DB:**

**COMPONENT:** **Name:**
Type: Function:
Manufacturer part number:
ATLAS Part number:
COTS [ ] ASIC [ ]
Design centre (if known):
Main specifications of the component:

Manufacturer name:
Address:
Manufacturer phone:
E-mail:
Web:

# of tested components (irradiated):
# of un-irradiated reference components:
Origin of the components:
homogeneous batch [ ] unknown batch [ ]
Manufacturing date code (for a homogeneous batch):
Manufacturing line code (for a homogeneous batch):

Foreseen ATLAS application(s):
ATLAS contact person(s):
E-mail:

**TECHNOLOGY:** Name: CMOS [ ] Bipolar [ ] BiCMOS [ ] AsGa [ ]
Minimum geometry (µm):
# of interconnection layers:
Date of first availability :

**PACKAGE:** Type: Part number: # of pin: Ceramic [ ] Plastic [ ]

**RADIATION TEST:** ATLAS standard TID test method [ ] Other TID test method [ ]
Which test method if not ATLAS standard TID test method?
Experimenter name:
Institute:
E-mail:
Radiation facility name:
Address:
Responsible: Phone:

**RADIATIONS:** Radiation type: Radiation energy:
Radiation source:
Dose rate (Gray/s):
Total dose (Gray):
Dosimetry/calibration method:

**TEMPERATURE AND TOTAL DOSE:**

Only for the extended TID test method for the pre-selection of bipolar devices (appendix 2 section 2.1.3.2):

- Number of irradiation pre-tests performed to determine the worse case temperature:________________
- Temperatures applied during irradiation for these pre-tests (°C):________________
- Temperature applied during electrical measurements for these pre-tests (°C):________________

For all the other TID tests and for the final radiation test described in appendix 2 section 2.1.3.2:

- Temperature applied during irradiation (°C):________________
- Temperature applied during electrical measurements (°C):________________
- If several irradiation steps are applied, value of the cumulated dose (Gray) reached after each irradiation step:

| Step 1: | Step 2: | Step 3: | Step 4: | Step 5: | Step 6: |
|---|---|---|---|---|---|
| | | | | | |

**OTHER INFORMATION**

- Supply voltage during irradiation: Y [ ] N [ ] Value(s) if yes (V): ________________
- AC operation during irradiation: Y [ ] N [ ] Frequency(ies) if yes (MHz): ________________
- On line measurement: Y [ ] N [ ]

- Post-irradiation annealing: Y [ ] N [ ] Temperature if yes (°C): ________________
- Supply voltage during annealing: Y [ ] N [ ] Value if yes (V): ________________
- AC operation during annealing: Y [ ] N [ ] Frequency if yes (MHz): ________________

- Post-irradiation accelerated ageing: Y [ ] N [ ] Temperature if yes (°C): ________________
- Supply voltage during ageing: Y [ ] N [ ] Value if yes (V): ________________
- AC operation during ageing: Y [ ] N [ ] Frequency if yes (MHz): ________________

**OPERATION AND MEASUREMENT:**

Concise description of the AC operations performed during irradiation

## ATLAS STANDARD TID TEST REPORT, cont.

**Page 2/2**
**Ref. DB:**

**OPERATION AND MEASUREMENT, cont.**

Concise description of the AC operations performed during measurement

| Main electrical parameters measured | Corresponding rejection criteria |
|---|---|
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |

**RESULTS:**

| | | | | | |
|---|---|---|---|---|---|
| a) Serial number of each DUT: | 1) | 2) | 3) | 4) | 5) |
| b) if failure before annealing: dose (*Gy*): | | | | | |
| c) failure after annealing (Y / N): | | | | | |
| d) failure after ageing (Y / N): | | | | | |
| a) Serial number of each DUT: | 6) | 7) | 8) | 9) | 10) |
| b) if failure before annealing: dose (*Gy*): | | | | | |
| c) failure after annealing (Y / N): | | | | | |
| d) failure after ageing (Y / N): | | | | | |
| a) Serial number of each DUT: | 11) | 12) | 13) | 14) | 15) |
| b) if failure before annealing: dose (*Gy*): | | | | | |
| c) failure after annealing (Y / N): | | | | | |
| d) failure after ageing (Y / N): | | | | | |
| a) Serial number of each DUT: | 16) | 17) | 18) | 19) | 20) |
| b) if failure before annealing: dose (*Gy*): | | | | | |
| c) failure after annealing (Y / N): | | | | | |
| d) failure after ageing (Y / N): | | | | | |

Failure mechanism(s) if failure:

[ ] Component(s) dead. For each dead component, indicate the serial number and the origin(s) of the death:

[ ] Component(s) out of specification(s). For each component out of specification(s), indicate the serial number and the violated specification(s):

**COMMENTS:**

## ATLAS STANDARD SEE TEST REPORT (single event test)

**Page 1/2**
**Ref. DB:**

| | |
|---|---|
| **COMPONENT:** **Name:**<br>Type: Function: | Manufacturer part number:<br>ATLAS Part number: |
| COTS [ ] ASIC [ ] | Design centre (if known): |
| Main specifications of the component: | |
| Manufacturer name:<br>Address: | Manufacturer phone:<br>E-mail:<br>Web: |
| # of tested components (irradiated):<br># of un-irradiated reference components: | Origin of the components:<br>homogeneous batch [ ] unknown batch [ ] |
| Manufacturing date code (for a homogeneous batch): | Manufacturing line code (for a homogeneous batch): |
| Foreseen ATLAS application(s): | ATLAS contact person(s):<br>E-mail: |

**TECHNOLOGY:** Name: Bipolar [ ] BiCMOS [ ] AsGa [ ]

| | | |
|---|---|---|
| Minimum geometry (µm): | # of interconnection layers: | Date of first availability : |

**PACKAGE:** Type: Part number: # of pin: Ceramic [ ] Plastic [ ]

**RADIATION TEST:** ATLAS standard SEE test method [ ] Other SEE test method [ ]

Which test method if not ATLAS standard SEE test method?

| | |
|---|---|
| Experimenter name:<br>Institute:<br>E-mail: | Radiation facility name:<br>Address:<br>Responsible: Phone: |

**RADIATIONS:** Radiation type: Radiation energy:

| | | |
|---|---|---|
| Radiation source: | Flux applied ($cm^{-2}s^{-1}$): | Total applied fluence ($cm^{-2}$): |

Dosimetry / calibration method:

**TEMPERATURE:** Temperature during irradiation and electrical measurements (°C):____________________

**BIASING:** Supply voltage during irradiation (V): ________ Operation frequency (MHz): _______

**OPERATION AND MEASUREMENT:**

Concise description of the AC operations (write, read, etc) performed during measurement under irradiation

| Main electrical parameters measured | Corresponding rejection criteria |
|---|---|
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |
| - | - |

## ATLAS STANDARD SEE TEST REPORT, cont.

**Page 2/2**
**Ref. DB:**

**RESULTS:**

| | | | | |
|---|---|---|---|---|
| a) Serial number of each DUT: | 1) | 2) | 3) | 4) |
| b) # of soft SEE measured up to the total fluence | | | | |
| c) # of hard SEE measured up to the total fluence | | | | |
| d) Total fluence producing destructive SEE | | | | |
| a) Serial number of each DUT: | 5) | 6) | 7) | 8) |
| b) # of soft SEE measured up to the total fluence | | | | |
| c) # of hard SEE measured up to the total fluence | | | | |
| d) Total fluence producing destructive SEE | | | | |

Mechanism of destructive SEE (if such SEE occurs):

[ ] SEL (Single Event Latch-up)
[ ] SEB (Single Event Burn-out)
[ ] SEGB (Single Event Gate Rupture)
[ ] Undetermined

Effects of destructive SEE (if such SEE occurs):

**COMMENTS:**

## Appendix 3, continued

## Few explanations about ATLAS STANDARD RADIATION TEST REPORTS

### Component:

- Name: usual name (if any). Examples: ABCD, Pentium, etc.
- Type: Chose among the following list: Analogue device; data transmission component; linear device; memory; microprocessor or peripheral, opto-electronic component; power device; programmable device; other (give a name).
- Function: Chose among the following list: ADC; amplifier; analog memory; analogue multiplexer; comparator; DAC; DC-DC converter; EEPROM; FIFO; FPGA; gate array; laser; LED; micro-controller; microprocessor; modulator / demodulator; operational amplifier; other (give a name).
- Design Centre: if the device is an ASIC, give the name of the laboratory(ies) which have developed this ASIC.
- Homogeneous batch: batch of components issued from wafers manufactured together at the same time on a known production line.
- Unknown batch: batch of components provided by a vendor without information on the production line, on the batch number, etc. (these components may be issued from different batches or different production lines).
- Manufacturing date code (for a homogeneous batch only): code giving the date of manufacturing of the batch from which the tested components are issued.
- Manufacturing line code (for a homogeneous batch only): code representing the manufacturing line from which the tested components are issued.

### Technology:

- Name: Examples: RICMOS-IV, DMILL, AVLSI-RH, etc…
- Minimum geometry: minimum CMOS gate length; or minimum bipolar emitter size.
- Number of interconnection layers: give both the number of metal layers (M) and the number of polysilicon layers (P). Example for 2 metal and 1 polysilicon: 2M, 1P.
- Date of first availability: date of first *commercial* availability.

### Package:

- Type: example: DIL40, JLCC 84, …

### Radiation:

- Radiation type:  example: gamma; neutrons, protons, pions, …
- Radiation source: example: 60Co, fission reactor; accelerator, …

## Appendix 4: Preliminary List of Radiation Facilities

**GAMMA IRRADIATIONS FACILITIES**

| | |
|---|---|
| **FACILITY: DELTA** | Institute: DEIN |
| Contact:<br>Jean-Pierre LE GAC<br>☎ +33 (0)1 69 08 67 45<br>Jean-Pierre.Legac@cea.fr | Address:<br>CEA Saclay<br>F-91191 Gif-sur-Yvette<br>France |
| Source: $^{60}$Co | Activity: 0,340 Curie (in January 2000) |
| Volume available: 100 dm3 | Dose rate available: 0.015 Gy/h to 1.5 Gy/h |
| **FACILITY: SIGMA** | Institute: DEIN |
| Contact:<br>Jean-Pierre LE GAC<br>☎ +33 (0)1 69 08 67 45<br>Jean-Pierre.Legac@cea.fr | Address:<br>CEA Saclay<br>F-91191 Gif-sur-Yvette<br>France |
| Source: $^{60}$Co | Activity: 100 Curie (in January 2000) |
| Volume available: 40 dm3 | Dose rate available: 23 Gy/h to 260 Gy/h |
| **FACILITY: IRMA** | Institute: IPSN |
| Contact:<br>Jean-Pierre LE GAC<br>☎ +33 (0)1 69 08 67 45<br>Jean-Pierre.Legac@cea.fr | Address:<br>CEA Saclay<br>F-91191 Gif-sur-Yvette<br>France |
| Source: $^{60}$Co | Activity: 9510 Curie (in January 2000) |
| Volume available: 24 m3 | Dose rate available: 25 Gy/h to 8000 Gy/h |
| **FACILITY: PAGURE** | Institute: ORIS / CIS-Bio Industrie |
| Contact:<br>Alexandre BATTUNG, ☎ +33 (0)1 69 85 71 17<br>M. DUVAL,☎ +33 (0)1 69 85 71 80<br>Fax +33 (0)1 69 08 74 35 | Address:<br>CEA Saclay<br>F-91191 Gif-sur-Yvette<br>France |
| Source: $^{60}$Co | Activity: 10000 Curie (in January 2000) |
| Volume available: 25 m2 x 3m high | Dose rate available: 1 Gy/h to 20 kGy/h |
| **FACILITY: GALAXIE** | Institute: ORIS / CIS-Bio Industrie |
| Contact:<br>Alexandre BATTUNG, ☎ +33 (0)1 69 85 71 17<br>M. DUVAL,☎ +33 (0)1 69 85 71 80<br>Fax +33 (0)1 69 08 74 35 | Address:<br>CEA Saclay<br>F-91191 Gif-sur-Yvette<br>France |
| Source: $^{60}$Co | Activity: 8 Curie (in January 2000) |
| Volume available: diameter 40 cm, hight 50 cm | Dose rate available: 2 kGy/h to 5 kG/h |
| **FACILITY: BRIGITTE** | Institute: CEN-SCK |
| Contact:<br>Benoit BRICHARD, ☎ +32 (0)14 33 26 40<br>Bbrichar@sckcen.be | Address:<br>Boeretang 200,<br>B-2400 Mol<br>Belgium |
| Source: $^{60}$Co, or irradiated fuel | Activity: |
| Volume available: diameter 25 cm, hight 30 cm | Dose rate available: 10 kGy/h to 30 kGy/h |
| **FACILITY: RITA** | Institute: CEN-SCK |
| Contact:<br>Benoit BRICHARD, ☎ +32 (0)14 33 26 40<br>Bbrichar@sckcen.be | Address:<br>Boeretang 200,<br>B-2400 Mol<br>Belgium |
| Source: $^{60}$Co | Activity: |
| Volume available: diameter 35 cm, height 45 cm | Dose rate available: 1 kGy/h to 5 kGy/h |

## GAMMA IRRADIATIONS FACILITIES , cont.

| | |
|---|---|
| **FACILITY: GEUSE** | Institute: CEN-SCK |
| Contact:<br>Benoit BRICHARD, ☎ +32 (0)14 33 26 40<br>Bbrichar@sckcen.be | Address:<br>Boeretang 200,<br>B-2400 Mol<br>Belgium |
| Source: irradiated fuel | Activity: |
| Volume available: diameter 9 cm, height 60 cm | Dose rate available: 100 Gy/h to 500 Gy/h |
| **FACILITY: CAL (Calibration cell)** | Institute: CEN-SCK |
| Contact:<br>Benoit BRICHARD, ☎ +32 (0)14 33 26 40<br>Bbrichar@sckcen.be | Address:<br>Boeretang 200,<br>B-2400 Mol<br>Belgium |
| Source: $^{60}$Co | Activity: |
| Volume available: 1 dm3 | Dose rate available: 10 Gy/h |
| **FACILITY: GAMMACELL 220** | Institute: Instituto Superior di Sanita |
| Contact:<br>Riccardo VARI<br>☎ +39 (0)64 991 42 43<br>Riccardo.Vari@roma1.infn.it | Address:<br>P. le Aldo Moro 2,<br>00185 Roma,<br>Italy |
| Source: $^{60}$Co | Activity: |
| Volume available: 15.2 cm diameter x 20.6 cm high | Dose rate available: 240 Gy / hour |
| **FACILITY: industrial gamma source** | Institute: Instituto Technologico e Nuclear |
| Contact:<br>Jose MARQUES<br>☎ +351 1 955 00 21<br>jmarques@alf1.cii.fc.ul.pt | Address:<br>P-2685 Sacavem (near Lisbon)<br>Portugal |
| Source: $^{60}$Co | Activity: |
| Volume available: > 1 m3 | Dose rate available: ~ 1 kGy / hour |
| **FACILITY: experimental gamma source** | Institute: Instituto Tecnologico e Nuclear |
| Contact:<br>Jose MARQUES<br>☎ +351 1 955 00 21<br>jmarques@alf1.cii.fc.ul.pt | Address:<br>P-2685 Sacavem (near Lisbon)<br>Portugal |
| Source: $^{60}$Co | Activity: |
| Volume available: > 1 dm3 | Dose rate available: ~ 0.1 - 10 kGy / hour |
| **FACILITY: Conservatome** | Institute: Conservatome |
| Contact:<br>M. GOMINET<br>☎ +33 04 78 06 41 14 | Address:<br>F-01120 Dagneux<br>France |
| Source: $^{60}$Co | Activity: |
| Volume available: | Dose rate available: 2 kGy / hour |
| **FACILITY: Joint research Center** | Institute: Joint research Center |
| Contact:<br>G.P. TARTAGLIA<br>☎ +31 22 46 53 34 | Address:<br>Petten<br>The Netherland |
| Source: $^{60}$Co, spent-fuel elements | Activity: |
| Volume available: | Dose rate available: adjustable |

## GAMMA IRRADIATIONS FACILITIES , cont.

| | |
|---|---|
| **FACILITY: CARIS** | Institute: CARIS-Mediris |
| Contact:<br>P. DARDENNE<br>☎ +32 71 81 00 84 | Address:<br>B-6220 Fleurus<br>Belgium |
| Source: $^{60}$Co | Activity: |
| Volume available: | Dose rate available: 4 kGy / hour |
| **FACILITY: RISO** | Institute: RISO Nat. Lab. |
| Contact:<br>A. MILLER<br>☎ +45 42 37 41 43 | Address:<br>DK-4000 Roskilde<br>Denmark |
| Source: $^{60}$Co | Activity: |
| Volume available: | Dose rate available: 2 kGy / hour |
| **FACILITY: (Garching)** | Institute: Garching |
| Contact:<br>H. HEUSINGER<br>☎ +49 89 32 09 22 08 | Address:<br>D-8046 Garching<br>Deutschland |
| Source: $^{60}$Co | Activity: |
| Volume available: | Dose rate available: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Source: | Activity: |
| Volume available: | Dose rate available: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Source: | Activity: |
| Volume available: | Dose rate available: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Source: | Activity: |
| Volume available: | Dose rate available: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Source: | Activity: |
| Volume available: | Dose rate available: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Source: | Activity: |
| Volume available: | Dose rate available: |

## X-RAYS IRRADIATIONS FACILITIES

| | |
|---|---|
| **FACILITY: SEIFERT RP149** | Institute: CERN |
| Contact:<br>Federico FACCIO,<br>☎ +41 (0)22 767 20 65<br>Email: Federico.Faccio@cern.ch | Address:<br>CERN / EP<br>CH-1211 Geneve 23<br>Switzerland |
| Beam diameter: 1 cm maxi | Dose rate available: 600 rad / mn to 48 krad / mn |
| **FACILITY: ARACOR** | Institute: TRAD Tests et Radiations |
| Contact: http: / / www.trad-int.com /<br>Christian CHATRY, ☎ +33 (0)5 61 00 95 60<br>Fax. +33 (0)5 61 00 95 61<br>Email: atrad@ibm.net | Address:<br>La pointe bleue, Voie l’Occitane, BP 698<br>31319 Labege Cedex<br>France |
| Beam diameter: | Dose rate available: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Volume available: | Dose rate available: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Volume available: | Dose rate available: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Volume available: | Dose rate available: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Volume available: | Dose rate available: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Volume available: | Dose rate available: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Volume available: | Dose rate available: |

## NEUTRON IRRADIATIONS FACILITIES

| | |
|---|---|
| **FACILITY: PROSPERO** | Institute: CEA-DAM |
| Contact:<br>Philippe ZYROMSKI<br>☎ +33 (0)3 80 23 51 60<br>Fax +33 (0)3 80 23 52 16 | Address:<br>CEA Valduc<br>F-21120 Is-sur-Tille<br>France |
| Source: reactor | Mean energy: 0.75 MeV |
| Room: 80 m2 x 6.5 m high | Maximum flux: 0.8E14 n.cm$^{-2}$.h$^{-1}$ (1MeV eq.) |
| **FACILITY: Ljubljana Neutron Irradiation Facility** | Institute: Jozef Stefan Institute |
| Contact: Igor MANDIC<br>http://www-f9.ijs.si/~mandic/Reactor.html<br>☎ +386 61 177-3900<br>Fax: +386 61 219-385<br>Email: Igor.Mandic@ijs.si | Address:<br>Jamova 39,<br>1000 Ljubljana,<br>Slovenija |
| Source: reactor | Energy: |
| Volume available: | Maximum flux: |
| **FACILITY: CERI** | Institute: CNRS CERI |
| CERI Contact: G. BLONDIAUX<br>http://rosalie.cnrs-orleans.fr/~ceri/ceriuk.html<br>☎ (33) 2.38.25.54.26<br>Fax : (33) 2.38.63.02.71<br>Email : blondiau@cnrs-orleans.fr<br>HEP contact: Marie-Laure ANDRIEUX<br>ISN Grenoble, France<br>☎ +33 (0)4 76 28 41 28<br>Email: Andrieux@isn.in2p3.fr | Address:<br>3A rue de la Ferollerie<br>45071 Orléans cedex 2<br>France |
| Neutron source: thick beryllium target bombarded by protons or deuterons | Energy: tuneable from 5 to 34 MeV |
| Volume available: | Maximum flux: |
| **FACILITY: CRC** | Institute: CRC Louvain la Neuve |
| HEP Contact: Federico FACCIO<br>☎ +41 (0)22 767 20 65<br>Email: Federico.Faccio@cern.ch | Address: |
| Source: mono-energetic neutrons | Energy: 25 - 70 MeV |
| Volume available: | Fluence available: 1E6 cm$^{-2}$.s$^{-1}$ (30 mm diameter) |
| **FACILITY: ITN** | Institute: Instituto Tecnologico e Nuclear |
| Contact:<br>Jose MARQUES<br>☎ +351 1 955 00 21<br>jmarques@alf1.cii.fc.ul.pt | Address:<br>P-2685 Sacavem (near Lisbon)<br>Portugal |
| Source: reactor | Energy: |
| Volume available: | Maximum flux: |
| **FACILITY: CERN-PS / IRRAD 2** | Institute: CERN |
| Contact: Maurice GLASER<br>☎ +41 (0)22 767 20 58<br>Email: Maurice.Glaser@cern.ch<br>http://irradiation.web.cern.ch/irradiation/ | Address:<br>CH-1211 Geneve 23<br>Switzerland |
| Source: synchrotron | Energy: 50 keV - 1 MeV |
| Volume available: | Maximum flux: 3-10E12 n.cm-2.s-1 |

## NEUTRON IRRADIATIONS FACILITIES, Cont.

| | |
|---|---|
| **FACILITY: ISIS** | Institute: Rutherford Appleton Laboratory |
| Contact:<br>M. EDWARDS<br>☎ +44 235 821 900<br>ME@IBM-2.Rutherford.ac.uk | Address:<br>Chilto Didcot<br>Oxfordshire OX11 0QX<br>United Kingdom |
| Source: spallation neutrons | Mean energy: |
| Room: | Maximum flux: |
| **FACILITY: GELINA** | Institute: Central Bureau for Nuclear Measurements |
| Contact:<br>J-M SALOME<br>☎ +32 14 57 15 03 | Address:<br>B-2440 Geel<br>Belgium |
| Source: | Mean energy: |
| Room: | Maximum flux: |
| **FACILITY: FRM** | Institute: FRM |
| Contact:<br>H. GERSTENBERG<br>☎ +49 89 32 09 21 60 | Address:<br>D-8046 Garshing<br>Deutschland |
| Source: | Mean energy: (low temperature) |
| Room: | Maximum flux: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Source: | Mean energy: |
| Room: | Maximum flux: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Source: | Mean energy: |
| Room: | Maximum flux: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Source: | Mean energy: |
| Room: | Maximum flux: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Source: | Mean energy: |
| Room: | Maximum flux: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Source: | Mean energy: |
| Room: | Maximum flux: |

## PROTON AND PION IRRADIATIONS FACILITIES

| | |
|---|---|
| **FACILITY: PSI Philips Cyclotron** | Institute: PSI |
| Contact: Stefan ADAM<br>http://www1.psi.ch/www_gfa_hn/abe/Philwelc.html<br>☎ +41 (0)56 310 33 93<br>Fax: +41 (0)56 310 33 83<br>Email: Stefan.Adam@psi.ch | Address:<br>ABE division<br>CH-5232 Villigen PSI<br>Switzerland |
| Source: Cyclotron | Proton energy: ≤ 72 MeV |
| Volume available: | Flux available: |
| **FACILITY: CERN-PS / IRRAD 1 & IRRAD 3** | Institute: CERN |
| Contact: Maurice GLASER<br>☎ +41 (0)22 767 20 58<br>Email: Maurice.Glaser@cern.ch<br>http://irradiation.web.cern.ch/irradiation/ | Address:<br>CH-1211 Geneve 23<br>Switzerland |
| Source: accelerator | Proton energy: 24 GeV |
| Volume available: | Flux available: 1-3E13 p.cm-2.s-1 |
| **FACILITY: PSI Pion and Muon Beam Lines** | Institute: PSI |
| Contact: C. PETITJEAN<br>http://www.psi.ch/ltp/ltpprop.html<br>☎ +41 (0)56 310 32 60<br>Fax: +41 (0)56 310 31 91<br>Email: claude.petitjean@psi.ch | Address:<br>Paul Scherrer Institut<br>WLGA / D15<br>CH-5232 Villigen PSI<br>Switzerland |
| Source: accelerator | Pions energy: 100 MeV to 500 MeV |
| Volume available: | Flux available: |
| **FACILITY: CRC** | Institute: CRC Louvain la Neuve |
| HEP Contact: Federico FACCIO<br>☎ +41 (0)22 767 20 65<br>Email: Federico.Faccio@cern.ch | Address: |
| Source: protons | Energy: 10 - 70 MeV |
| Volume available: | Flux available: 5E8 $cm^{-2}.s^{-1}$ maxi |
| **FACILITY: IUCF Cyclotron** | Institute: Indiana University Cyclotron Facility |
| Contact:<br>Charles FOSTER<br>Email: foster@iucf.indiana.edu<br>☎ +1 (812) 855-9365<br>Fax: +1 (812) 855-6645<br>http://www.iucf.indiana.edu/MPRI/RADhmpg.htm | Address:<br>2401 Milo B, Sampson Ln<br>Bloomington, IN 47408<br>USA |
| Source: cyclotron | Energy: 30 – 200 MeV |
| Volume available: | Flux available: 1E2 - >1E11 p.cm2.s-1 |
| **FACILITY: TRIUMF Cyclotron** | Institute: |
| Contact:<br>Ewart BLACKMORE,<br>E-mail: ewb@triumf.ca<br>☎ +1 (604) 222-7461<br>Fax: (604) 222-7309<br>http://www.triumf.ca/pif/ | Address:<br>4004 Wesbrook Mall,<br>Vancouver, B.C.,<br>Canada |
| Source: cyclotron | Energy: 65 – 120 MeV; 180 – 500 MeV |
| Volume available: | Flux available: |

## HEAVY IONS IRRADIATIONS FACILITIES

| | |
|---|---|
| **FACILITY: CYCLONE** | Institute: UCL |
| Contact: http://www.cyc.ucl.ac.be/<br>Guy BERGER,<br>☎ +32 (0)10 47 32 25<br>Fax: +32 (0)10 45 21 83<br>Email: berger@cyc.ucl.ac.be | Address:<br>Bâtiment Marc de Hemptinne<br>Chemin du cyclotron, 2<br>B-1348 Louvain-la-Neuve<br>Belgium |
| Source: Cyclotron | Energy: p ≤ 90 MeV, d ≤ 55 MeV, • ≤ 110 MeV, heavy ions 0.6 to 27.5 MeV/AMU |
| Volume available: | Dose rate available: |
| **FACILITY: TVDG** | Institute: BNL |
| Contact: http://www.tvdg.bnl.gov/tvdg.html<br>☎ to Sandy, +1 516 344 45 81<br>Fax to Chuck CARLSON, +1 516 344 4583<br>E-Mail to Peter THIEBERGER, pt@bnl.gov | Address:<br>Building 901A<br>Upton, N.Y. 11973-5000<br>USA |
| Source: Tandem Van de Graaf | Max. energy: H: 29 MeV, … , U: 385 MeV. |
| Volume available: | Dose rate available: |
| **FACILITY: PSI Philips Cyclotron** | Institute: PSI |
| Contact: Stefan ADAM<br>http://www1.psi.ch/www_gfa_hn/abe/Philwelc.html<br>☎ +41 (0)56 310 33 82<br>Fax: +41 (0)56 310 33 83<br>Email: Stefan.Adam@psi.ch | Address:<br>ABE division<br>CH-5232 Villigen PSI<br>Switzerland |
| Source: Cyclotron | Energy: 120 MeV Z2/A (charge Z, mass number A) |
| Volume available: | Dose rate available: |
| **FACILITY: GANIL** | Institute: GANIL |
| Contact:<br>Daniel GUERREAU<br>☎ +33 (0) 2 31 45 46 47<br>http://ganinfo.in2p3.fr/ | Address:<br>Boulevard Henri Becquerel<br>B.P. 5027<br>14076 Caen Cedex 5<br>FRANCE |
| Source: accelerator | Energy: 24 MeV/A => 95 MeV/A |
| Volume available: | Dose rate available: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Source: | Energy: |
| Volume available: | Dose rate available: |
| **FACILITY:** | Institute: |
| Contact: | Address: |
| Source: | Energy: |
| Volume available: | Dose rate available: |

# Appendix 5: References

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