Astrium Space Transportation
Competence Centre

TE612 n° 153 069
Ed.- 19 November 2009
Page 1

MEMSRAD

Technical Note – TN6

WP n°: 6000.1

FINAL VERSION OF RADIATION REQUIREMENTS GUIDELINES

ESA_QEC1014TS_C

DIFFUSION

- Du document :

ESA/ESTEC (2)	M. POIVEY
INFODUC (2)	M. GAILLARD, POIROT
TE612	M. FORMOND
TE612	M. OUDEA
TE612	M. CARRIERE
TAS	M. VENDIER

TA413

- De la page documentaire, du résumé de synthèse et de la présente liste de diffusion :

TE6	M. ABOUT
TS11	M. MACRET
TE61	M. COPPOLA
TS1	M. LEVEUGLE

Internal reference : TE612 n° 153 069	**Issue**	**Rev.**	**Date :** 19/11/09
Structured reference :	1		**Page**

CLASSIFICATION	**COMPANY**	**MILITARY**	**PROGRAMME**
	EADS-ST unprotected ☒	Unclassified (NP) ☐	General Public (1) ☐
	EADS-ST Reserved ☐	Confidential (CD) ☐	Industry (2) ☐
	EADS-ST Confidential ☐	Secret (SD) ☐	Restricted (3) ☐
	EADS-ST Secret ☐	Top Secret N/A	Confidential (4) ☐
	Restricted (DR) ☐	French National (SF) ☐	

CONTRACT	**Customer**	**Contract number** 20293/06/NL/CP			**Programme** MEMSRAD
	Contractual doc^t yes ☒ no ☐ as requested ☒ as per CWS ☐	C.Work Unit	Item	Sub-item	**CWS** **WP** WP n° : 6000.1

TITLE MEMSRAD: MEMS Sensitivity to Space Radiation

Final version of Radiation Requirements Guidelines for MEMS Devices

ABSTRACT

This document constitutes the updated final version of radiation requirements guidelines. This report is a delta document, contains additional comments to the existing guidelines of TN2 (WP n° 2000.3), after performing radiation tests on MEMS type 1: accelerometer and MEMS type 2 (RF MEMS).

KEYWORDS

MEMS, Sensors, Radiation, Space, Guidelines

File ref. : **Software** : WORD 97		**Configuration management**	**Distribution category**
Language code : ENG **Taking precedence** : FR		None ☐ Internal ☐	**Interest** Short term ☐ Medium or long term ☐
figures	appendices	Customer ☐	**Sup. distribution** Authorized ☐ Checked ☐

VISAS	**Author**	**Controller**	**Quality**	**Section Manager**	**Department Head**
Sigle	Infoduc & TE612			TE612	TE61
Name	R. GAILLARD, C. OUDEA			V. FORMOND	J.F. COPPOLA
Signature					

ISSUE / REVISION STATUS RECORD		
Issue and revision n°	**Date**	**Main reasons for document change (+ paragraphs nb concerned in case of revision) Document validity status (reference and date)**
1 - 0	15-04-07	Original document – First draft version – WP :1000.2
2 - 0	26-06-07	First revised document (ESA comments included) – Second Version – WP:2000.1
3 - 0	09-08-07	Second revised document (Round Table comments included) – Third version – WP:2000.3
4-0	19-11-09	Upgraded guidelines version taking into account Radiations tests performed on MEMS type 1 and Type 2, and evolution of standards
5 - 0	16-12- 2009	Include comments from Ch. Poivey (ESA/ESTEC)

ABSTRACT

SECTION: TE612 **NUMBER**: 153 069 **DATE**: 19/11/2009

AUTHOR(S): C. OUDEA – TE612
R. GAILLARD - INFODUC

TITLE: MEMSRAD
FINAL VERSION OF RADIATION REQUIREMENTS GUIDELINES FOR MEMS DEVICES

This document constitutes the updated final version of radiation requirements guidelines. This report is a delta document, contains additional comments to the existing guidelines of TN2 (WP n° 2000.3), after performing radiation tests on MEMS type 1: accelerometer and MEMS type 2 (RF MEMS).

Section Manager TE612

V. FORMOND

TABLE OF CONTENTS

1 ABBREVIATIONS AND ACRONYMS

ASIC	Application Specific Integrated Circuit	**SEE**	Single Event Effects
BiCMOS	Bipolar CMOS	**SEB**	Single Event Burnout
CMOS	Complementary Metal Oxide Semiconductor	**SEFI**	Single Event Functional Interrupt
COTS	Commercial Off The Shelf	**SEGR**	Single Event Gate Rupture
DD	Displacement Damage	**SEL**	Single Event Latch-up
ELDRS	Enhanced Low Dose Rate Sensitivity	**SEP**	Single Event Phenomena
ESA	European Space Agency	**SET**	Single Event Transient
IMU	Inertial Measurement Unit	**TID**	Total Ionizing Dose
LET	Linear Energy Transfer		
MEMS	Micro Electro Mechanical Systems		
MNT	Micro and Nano Technologies		
MOTS	MEMS Off The Shelf		
NIEL	Non Ionizing Energy Loss		
RF MEMS	Radio Frequency MEMS		

2 APPLICABLE AND REFERENCE DOCUMENTS

2.1 APPLICABLE DOCUMENTS

- ESCC Basic Specification N°22900 Total ionizing dose testing Issue 3 March 2007
- ESCC Basic Specification No. 25100 ISSUE 1 October 2002 :SINGLE EVENT EFFECTS TEST METHOD AND GUIDELINES

2.2 REFERENCE DOCUMENTS

- ASTM F-1192 -Standard Guide for the Measurement of Single-Event Phenomena from Heavy Ion Irradiation of Semiconductor Devices.
- EIA/JESD57 -Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation.
- IEEE Standard 1431 -2004 Specification Format Guide and Test Procedure for Coriolis Vibratory Gyros
- ASTM E 666 - Standard Method for Calculation of Absorbed Dose from Gamma or X Radiation.
- ASTM E 668 - Standard Practice for the Application of Thermo luminescence Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronic Devices.
- ASTM E 1249 - Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices.
- ASTM E 1250 - Standard Method for Application of Ionization Chambers to Assess the Low Energy Gamma Component of Cobalt 60 Irradiators Used in Radiation Hardness Testing of Silicon Electronic Devices.
- ASTM E 1275 - Standard Practice for Use of a Radiochromic Film Dosimetry System.
- ASTM F 1892 - Standard Guide for Ionizing Radiation (Total Dose) Effects Testing of Semiconductor Devices.
- MIL-STD-883 E (MIL-STD-883E NOTICE 5 07 March 2003) METHOD 1019.6 March 2003 is related to total ionizing dose testing (TID test).
- MIL-STD-883, Revision H; 28 Aout 2008 Draft Method 1019.7

- MEMSRAD TN2: WP n° 2000.3, “Radiation Requirements Testing Guidelines for MEMS Devices”, TE624, n°: 148 494 Ed.3 – 09/08/2007.

3 GENERALITIES

This document constitutes the Technical Note TN6 of the MEMSRAD, related to WP 6000.1, « Final version of Radiation Requirements Guidelines for MEMS Devices".

This report is a delta document, contains additional comments to the existing guidelines of TN2 (WP n° 2000.3), after performing radiation tests on MEMS type 1: accelerometer and MEMS type 2 (RF MEMS).

This document aims to propose a first official version for radiation testing methods and procedures applied to MEMS to evaluate or qualify their performance when subjected to radiation existing in a space environment.

An important work has already been performed to develop such guidelines for the evaluation and qualification of microelectronic devices. These methods used by space organisations and industrial companies working for space applications are continuously updated to take into account new phenomenon or effects. These test procedures and methods will be used as a guide and we will focus on particular or specific aspects related to MEMS.
Real space environments consists near the earth in radiation belts (electrons E<7 MeV) and protons (E<500 MeV)) solar flares (protons and heavy ions), galactic and extragalactic heavy ions (HI).
Three main effects are to be studied: total ionizing dose (TID), displacement damage (due to protons), single event effects (destructive or not) related to heavy ions and protons.

This document is divided in 7 separate chapters, the chapters 4 to 9 is the same as TN2, WP n°2000.3, and chapter is exclusively the additional comments to update a Final version:

- Chapter 4: MEMS definition and classification
- Chapter 5: Choosing a radiation environment or facility to simulate space radiation effects, measure the radiation environment (flux, dose rate, energy spectrum)
- Chapter 6: Define parameters to be measured and how to measure them: Define conditions during irradiation (specific environment to simulate sensors inputs, bias voltages,)
- Chapter 7: Define the TID (Total Ionizing Dose) testing guidelines
- Chapter 8: Define the Displacement Damage testing guidelines
- Chapter 9: Define the SEE (Single Event Effects) testing guidelines
- Chapter 10: Additional Comments after radiation testing of MEMS Type 1 (Accelerometer) and MEMS type 2 (RF MEMS)

The application of these guidelines consists in obtaining a better knowledge of the reliability of MEMS in space environment. So it will also probably be necessary to study the possible synergy between radiation effects and other operating conditions (temperature,).

4 MEMS DEFINITIONS AND CLASSIFICATION:

MEMS or Microsystems represents a great variety of devices. It is a new class of systems for which standardization is just beginning.
MEMS can be classified in different categories:

- Sensors (accelerometers, gyrometers, pressure and temperature sensors)
- Actuators and motors (RFMEMS, microengines), Systems (IMU).

They are called Microsystems (Europe), MEMS (North America) or Micromachines (Japan).
These devices are made using basically the same techniques used to make integrated circuits, but modified to have moving parts.
MEMS are often made from Silicon, though now larger choices of materials including polymers are used.

4.1 MEMS CLASSIFICATION

As indicated below MEMS can be separated in four Classes when reliability is studied:

- No moving parts
- Moving Parts
    - No rubbing or impacting surfaces
    - Impacting surfaces
    - Impacting and rubbing surfaces

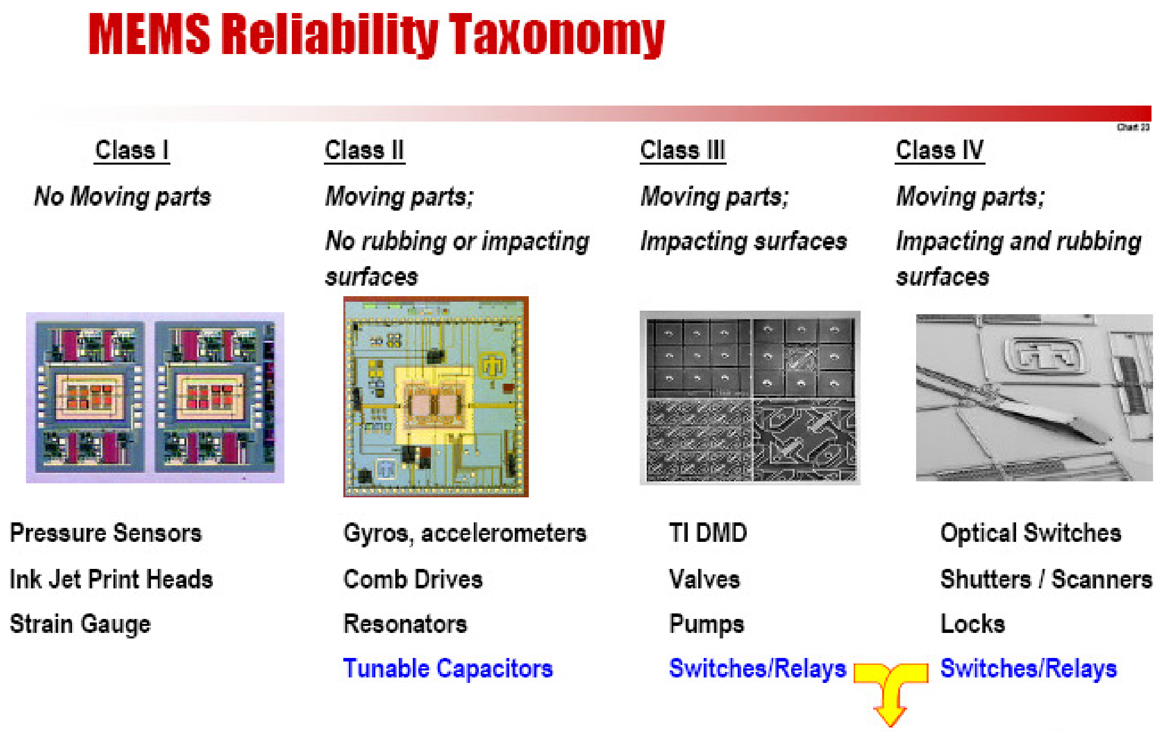
Other classifications consider the presence or not of electronics and its relative importance in the function:

- Pure mechanical: microengines
- Electrical command: RF MEMS
- Electronics in driving and sensing (accelerometers, gyroscopes)

MEMS can also be classified as sensors and actuators

For a given MEMS type (e.g. accelerometer or RF MEMS) different technologies can be used for which very different radiation effects can be expected.

For example RF **MEMS** switches can be divided into electrostatic, magnetic, thermal, and piezoelectric types by the actuation mechanism of cantilever or membrane. Most of studies on RF **MEMS** switches have focused on the electrostatic actuation types.



On this figure the MEMS classification is performed for reliability studies.
In the opinion of this author Reliability aspects are related to the moving parts and the failure mechanisms associated with these moving parts.

4.2 EXISTING STANDARDS:

Many Organizations are involved in MEMS standardization. Some are listed below.

- International organizations:
  - International Organization for Standardization (IOS)
  - International Electro technical Commission (IEC)
  - European Committee for Electro technical Standardization (CENELEC)
- National standards organizations:
  - DIN and DKE from Germany
  - BSI form UK
  - And others.
- Trade associations:
  - Semiconductor Equipment and Material International (SEMI)
- Professional groups:
  Institute of Electrical and Electronics Engineers (IEEE)

International Electro technical Commission (IEC) publications and working documents are listed below

4.2.1 IEC Publications (5)

IEC 62047-1 (2005-09) Ed. 1.0:
Semiconductor devices - Micro-electromechanical devices - Part 1: Terms and definitions

IEC 62047-2 (2006-08) Ed. 1.0:
Semiconductor devices - Micro-electromechanical devices - Part 2: Tensile testing method of thin film materials

IEC 62047-3 (2006-08) Ed. 1.0 Bilingual
Semiconductor devices - Micro-electromechanical devices - Part 3: Thin film standard test piece for tensile testing

IEC 62047-4 (2008-08) Ed. 1.0 Bilingual
Semiconductor devices - Micro-electromechanical devices - Part 4: Generic specification for MEMS

IEC 62047-6 (2009-04) Ed. 1.0 Bilingual
Semiconductor devices - Micro-electromechanical devices - Part 6: Axial fatigue testing methods of thin film materials

4.2.2 IEC Work in progress (3)

IEC 62047-5 Ed. 1.0
Part 5: RF MEMS Switches

PNW 47-1905 Ed. 1.0
Part 7: MEMS FBAR Filter & Duplexer

PNW 47-1907 Ed. 1.0 (Proposed New Work)
Part 9: Bonding strength measurement in MEMS packaging

4.2.3 IEC Work Programme of Group MEMS 47F (10)

(Future IEC 62047-14): Semiconductor devices -Micro-electromechanical devices - Part 14: Forming limit measuring method of metallic film materials

(Future IEC 62047-16): Semiconductor devices -Micro-electromechanical devices - Part 16: Test method for residual stress measurement

(Future IEC 62047-5) Semiconductor devices - Micro-electromechanical devices - Part 5: RF MEMS Switches

(Future IEC 62047-7 Ed. 1.0) Semiconductor devices - Micro-electromechanical devices - Part 7: MEMS BAW Filter & Duplexer for Radio Frequency Control and Selection

(Future IEC 62047-8 Ed. 1.0) Part 8: Strip bending test method for tensile property measurement of thin films

IEC 62047-9 Ed. 1.0) Part 9: Wafer to wafer bonding strength measurement for MEMS

(Future IEC 62047-10 Ed. 1.0) Part 10: Micropillar compression test for MEMS materials

(Future IEC 62047-11 Ed. 1.0) Part 11: Test method for linear thermal expansion coefficients of MEMS materials

(Future IEC 62047-12 Ed. 1.0) Part 12: A method for fatigue testing thin film materials using the resonant vibration of a MEMS structure

-(Future IEC 62047-13 Ed. 1.0) Part 13: Adhesive strength measurement method for MEMS structure

4.3 RADIATION TESTING GUIDELINES

MIL standard, ASTM and JEDEC standards are published and used by the microelectronic testing community. ESA ESCC standards and guidelines are widely used in Europe.

For example in MIL-STD-883 E (MIL-STD-883E NOTICE 5 07 March 2003) METHOD 1019.6 March 2003 is related to total ionizing dose testing (TID test).
ASTM F1192-00, JESD57 are related to Single Event Effects testing.

ESCC main guidelines for radiation testing are:

- ESCC-25100 to Single Event Effects
- ESCC 22900 to total ionizing dose testing

The new testing guidelines for MEMS will be strongly influenced by these testing procedures used for microelectronic devices.

These guidelines have in common all the procedures concerning the radiation environment and dosimetry methods. These dosimetry methods are generally ASTM standards.

Radiation effects on electronic devices and particularly on MEMS are not yet fully understood.
So we must consider these radiation testing guidelines as a first version that will have probably important evolution. The aim of this work is to “open doors” to allow better understanding of radiation effects on MEMS.

5 CHOOSING THE RADIATION FACILITY

5.1 TOTAL IONIZING DOSE:

In space the ionizing dose is due to electrons and protons. We want to reproduce the effects not the environment.
The usual method is to use Co60 gamma rays sources, X-rays radioactive sources or X rays emitted from X Rays generators.
For X rays at low to moderate energies, radiation dose at interfaces can be strongly modified when dissimilar Z materials are used. X rays are very efficient to study radiation effects at the wafer level.
Qualified facilities are used by the space community to study TID in microelectronic devices. These sources can be used to study MEMS.
Radiation equivalence between Co60 and real ionizing radiation environment can be an important question mainly because in insulator the yield value of electron-hole separation is a strong function of the density of carriers generated along an ionizing track.

The important parameters to consider for total ionizing dose testing facility are:

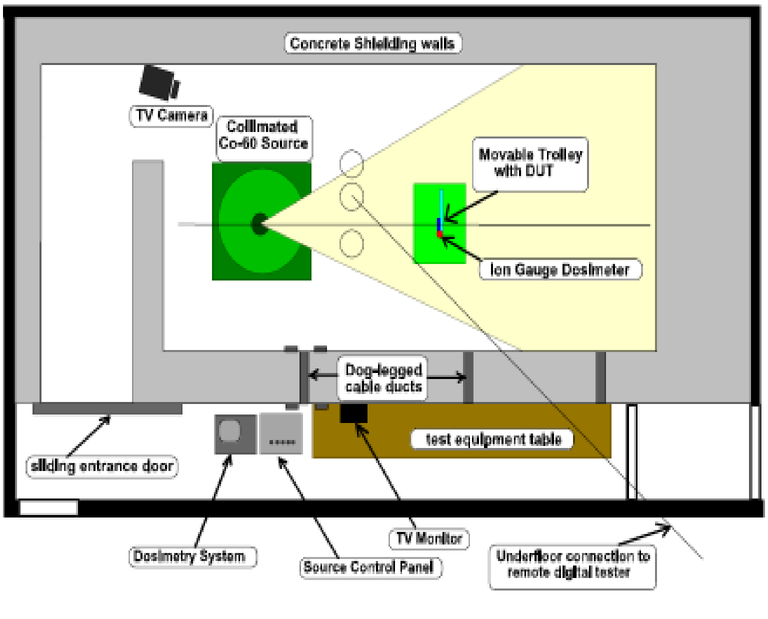
- Dose rate available, law of variation of dose rate with distance
- Variation of energy spectrum with device location (influence of walls or enclosure)
- Uniformity of radiation field
- Dosimetry method and precision obtained.

These points are well described in MIL-STD883H- method 1019.7 and we reproduce the main points below:

2.1 Radiation source. The radiation source used in the test shall be the uniform field of a ^{60}Co gamma ray source. Uniformity of the radiation field in the volume where devices are irradiated shall be within ±10 percent as measured by the dosimetry system, unless otherwise specified. The intensity of the gamma ray field of the ^{60}Co source shall be known with an uncertainty of no more than ±5 percent. Field uniformity and intensity can be affected by changes in the location of the device with respect to the radiation source and the presence of radiation absorption and scattering materials.
2.2 Dosimetry system. An appropriate dosimetry system shall be provided which is capable of carrying out the measurements called for in 3.2. The following American Society for Testing and Materials (ASTM) standards and guidelines or other appropriate standards and guidelines shall be used:
ASTM E 666 - Standard Method for Calculation of Absorbed Dose from Gamma or X Radiation.
ASTM E 668 - Standard Practice for the Application of Thermo luminescence Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronic Devices.
ASTM E 1249 - Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices.
ASTM E 1250 - Standard Method for Application of Ionization Chambers to Assess the Low Energy Gamma Component of Cobalt 60 Irradiators Used in Radiation Hardness Testing of Silicon Electronic Devices.
ASTM E 1275 - Standard Practice for Use of a Radiochromic Film Dosimetry System.
ASTM F 1892 - Standard Guide for Ionizing Radiation (Total Dose) Effects Testing of Semiconductor Devices.
These industry standards address the conversion of absorbed dose from one material to another, and the proper use of various dosimetry systems. 1/

Different Co60 facilities can be found in Europe (ESA supported and others) and in particular ESA manages such a facility at ESTEC, Noordwijk.

ESA –ESTEC Co60 facility:



Estec 2000 Ci Co-60 Facility

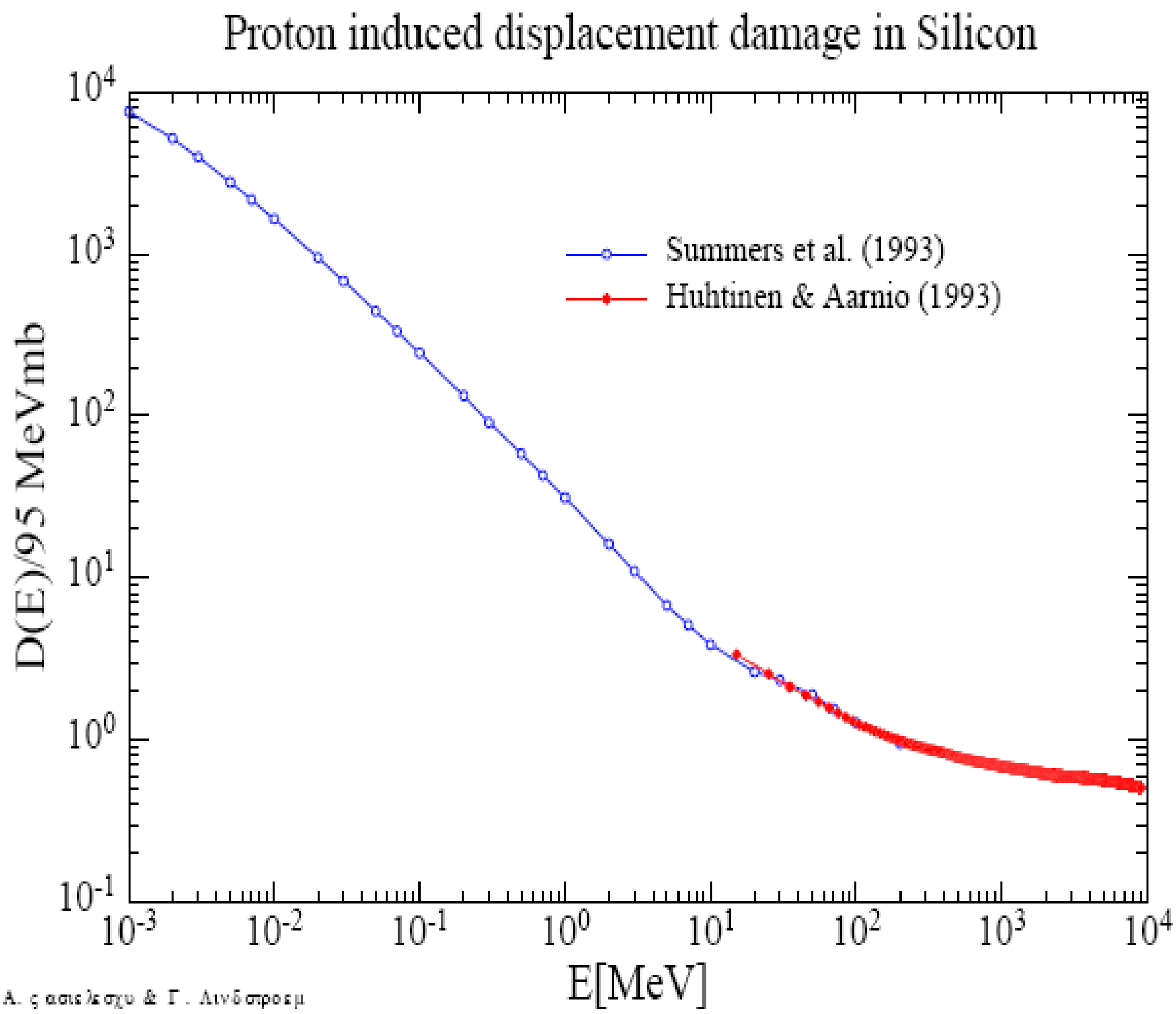
The nominal activity is 2000 Ci for Total Dose Testing but the present activity is around 1465 Ci (Nov 10th 2009) which permits dose rates between 0.7 and 50 Rads/min (0.007 and 0.5 Gy/min). At 1m the dose rate is 28 rads/min
At 50 Rads/min uniform irradiated area approx. 15 x 15 cm and at 0.7 Rads/min uniform irradiated area 240 x 240 cm.
Dynamic setting of dose rate can be performed via computer both before and during radiation runs. Computer controlled Halt of radiation test at required total dose.
During the experiment Logging of radiation and DUT parameters at defined intervals to a pc text file can be done.
Due to the available volume in the experimental room important experimental set-up (rotating tables, power supplies,.) can be used to perform on-line characterization of MEMS.

For MEMS device that present an electronic part separated from the Mechanical sensor or actuator, it is interesting in the evaluation phase to separate the degradation contributions of the mechanical part from the contribution of the electronic part. A low energy X-Rays source allows the use of masks in high Z materials with a low thickness to obtain a good resolution of the shallowed part.

5.2 DISPLACEMENT DAMAGE

Radiation induced Displacement damage in materials in space is mainly related to proton environment. Displacement damage is the result of atoms displaced from a stable position. When this displacement occurs the atom leaves a void named a vacancy that can form structural defects (vacancy, divacancy, vacancy-impurity association). These defects behave in semiconductor materials as recombination centre, trapping center, doping compensation center. These centers affect semiconductor parameters such as minority carrier lifetimes, carrier density, and carrier mobility.
One generally considers that mechanical properties of silicon and metals are mostly unchanged (Young's modulus, yield strength not significantly affected) at levels met in space for a typical mission duration of 15 Years..
The important parameter to consider is the NIEL (Non Ionizing Energy Loss) coefficient.. The NIEL coefficient is related to the energy of the particle and the nature of the material.

The NIEL curve obtained for protons in silicon is given below as a normalized curve relative to 95MeVmb which corresponds to the 1MeVeq neutron damage in silicon.



- 95 MeV.mb is equal to 2,144 keV.cm2/g in silicon.

So the proton energy spectrum met in radiation belts or coming from solar flares can be simulated by single proton energy. The choice of this proton energy is often related to available facilities.
In Europe proton facilities are sponsored by ESA:

- UCL Louvain (Be)
- PSI Villingen (Ch)

At PSI the high energy proton line can deliver initial proton energies: of 254, 102 and 60 MeV. These energies can be reduced with an energy degrader. The energies available using the PIF degrader vary quasi continuously from 35 (6) MeV up to 254 (60) MeV. The energy straggling for the 300 MeV initial beam are

- FWHM=7.2 MeV at 200.0 MeV,
- FWHM=15.4 MeV at 50.0 MeV..

The maximum beam intensity at 254 MeV is about 1 nA.

The maximum flux at 254 MeV with 10 mA split beam (focused beam): $2.5*10^8$ protons/sec/cm2. Beam profiles are either flat or Gaussian-form with minimum FWHM=6 cm. The irradiations take place in air and the maximum diameter of the irradiated area is 9 cm. The accuracy of the flux/dose determination is about 5%. The neutron background is less than 10^{-4} neutrons/proton/cm2. During irradiations, devices and sample positioning are supervised by the computer. Sample mounting frame is 25 x 25 cm2 (SEU and HIF facilities compatible) is attached to the XY table Data acquisition system allows automatic runs with user pre-defined irradiation criteria

At PSI the low energy beam proton line main characteristics are given below.

- Energy range: 6 to 63 MeV
- Proton flux: <$5\cdot 10^8$ p/cm2/sec
- Beam spot: circle, up to 9 cm diameter
- Beam uniformity: > 90% over 5 cm diameter
- Flux/Dosimetry: about 5% absolute accuracy
- Irradiation take places in air
- Sample frame Brookhaven and HIF compatible is fixed on the XY table

Protons induce both displacement damage and total ionizing dose damage. When we want to separate these two effects a usual approach is to use neutrons to evaluate displacement damage and to use gamma rays to evaluate total ionizing dose. This point is important to allow the identification of the degradation mechanism in the mechanical part of MEMS.

Neutron reactors can be found in particular in France (CEA-Valduc), in Belgium (Moll). The neutron flux is given in 1MeV-eq displacement damage. The associated gamma dose varies strongly between installations.

5.3 SINGLE EVENT EFFECTS

Single event effects are defined as the effects obtained by the interaction of a single particle in the Microsystems. These effects are widely studied in microelectronics. Both Destructive (SEL Single Event Latch-up, Single Event Burnout (SEB), Single Event Gate Rupture (SEGR)) and non destructive (SEU Single Event Upset, SET Single Event Transient SEFI Single Event Functional Interrupt) are observed.

Non destructive effects can modify the content of registers, memory cells or the output state of a circuit. SEU is of concern for digital circuits such as memory or microprocessor and also for mixed circuits such as Digital Analog, Analog Digital converters, Pulse-width modulators used in DC/DC converters in power supplies. SET can be found in analog circuits and in particular in regulators, operational amplifiers and comparators. A transient modification of the output voltage is observed.

In case of regulators, if this transient is not filtered, the over voltage can destroy other circuits fed by this regulator.

SEL is generally related to the switching in the low impedance state of a parasitic thyristor found in bulk CMOS technology or in some BiCMOS or Bipolar technologies. The important current can destroy power supply metallization in an integrated circuits and the dissipated power can give a localised fusion.

Destructive effects such as SEB are related to the activity of parasitic NPN bipolar transistor found in the structure of Power MOS devices.

SEGR and dielectric damage are related to the effect of an important ionization along the track of a heavy ion. It is believed that a pre-existing field must exist to observe damage. The radiation effects community agrees that more investigations are needed.

The MEMS is by definition a microsystem that may contain both electronic and mechanical parts. Even if Single Event Effects concern only electronics the global response of the system will include the mechanical part response to the stimulus or perturbation generated in the electronic part.
Dielectric rupture or dielectric damage is of concern for sensor and microengines or actuator.

In space the single event effects are due to heavy ions and protons. In Atmosphere SEE are due to high energy neutrons generated by the interaction of cosmic rays (mainly protons) with nitrogen and oxygen.

In Europe Heavy ions facilities are sponsored by ESA to test microelectronics (UCL Louvain, RADEF Jyvaskyla Finland).
One of the limitations of these facilities is the ion range.
The heavy ion range obtained in Louvain and Rader, are given below:
Louvain

Ion	Energy MeV	Range µm	LET	Ion	Energy MeV	Range µm	LET
10B2+	41	80	1.7	13C4+	131	266	1.2
15N2+	62	64	2.97	22Ne7+	235	199	3.3
20Ne4+	78	45	5.85	28Si8+	236	106	6.8
40Ar8+	150	42	14.1	40Ar12+	372	119	10.1
84Ar17+	316	43	34.0	58Ni18+	567	98	20.6
132Xe26+	459	43	55.9	83Kr25+	756	92	32.4

←------------------Coktail1-------------------------→←------Cocktail2-----------------------------------→

RADEF

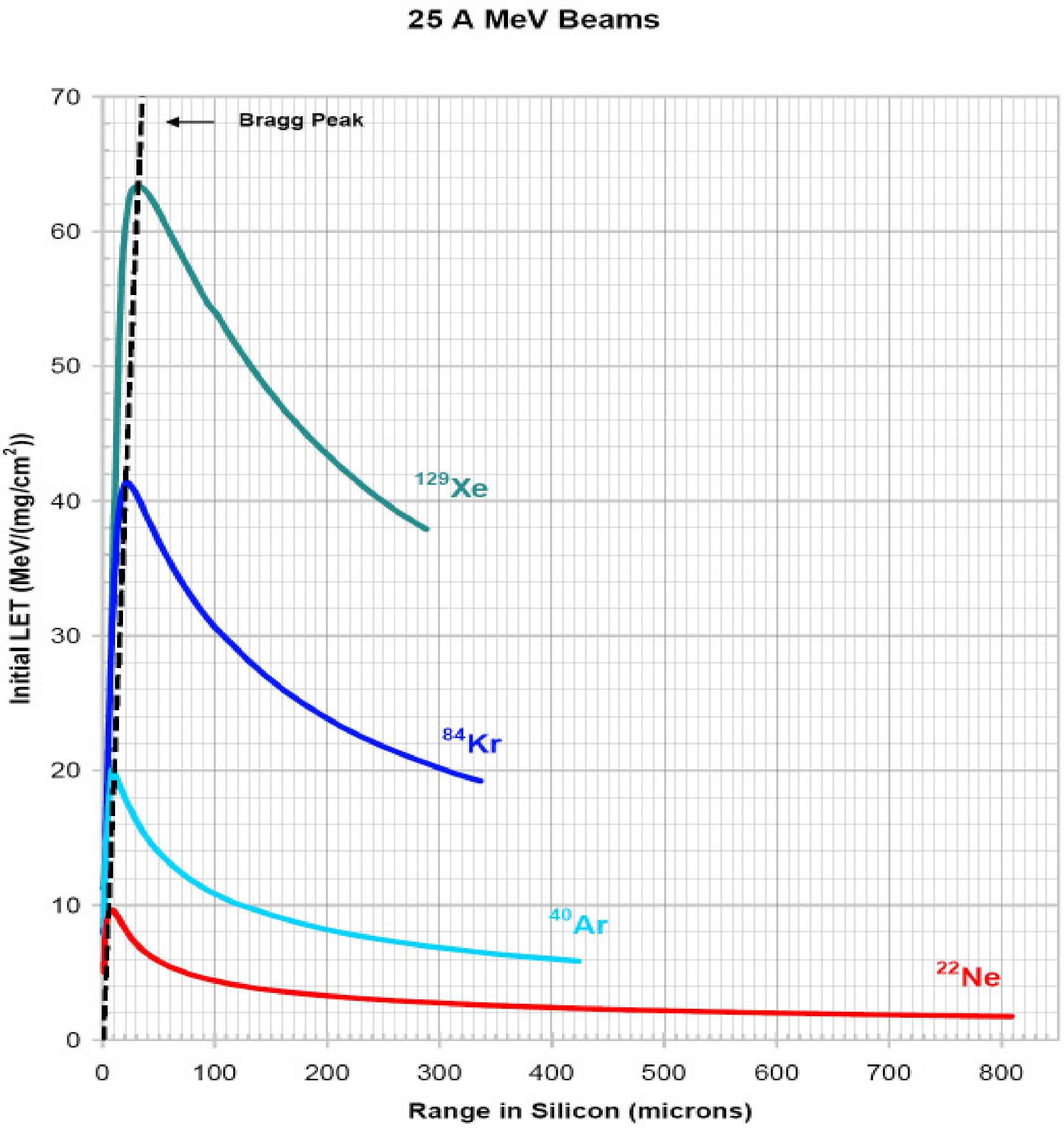
Ion	Energy MeV	Range µm	LET	Ion	Energy MeV	Range µm	LET
14N3+	86	108	2	15N4+	139	218	1.7
28Si6+	172	74	8	20Né6+	186	149	3.5
56Fe12+	345	64	22	30Si8+	278	132	6.0
84Kr18+	517	66	35	40Ar12+	372	117	10.0
136Xe29+	830	68	64	56Fe15+	523	99	18.0
				82Kr22+	768	96	30
				131Xe36+	1217	97	53

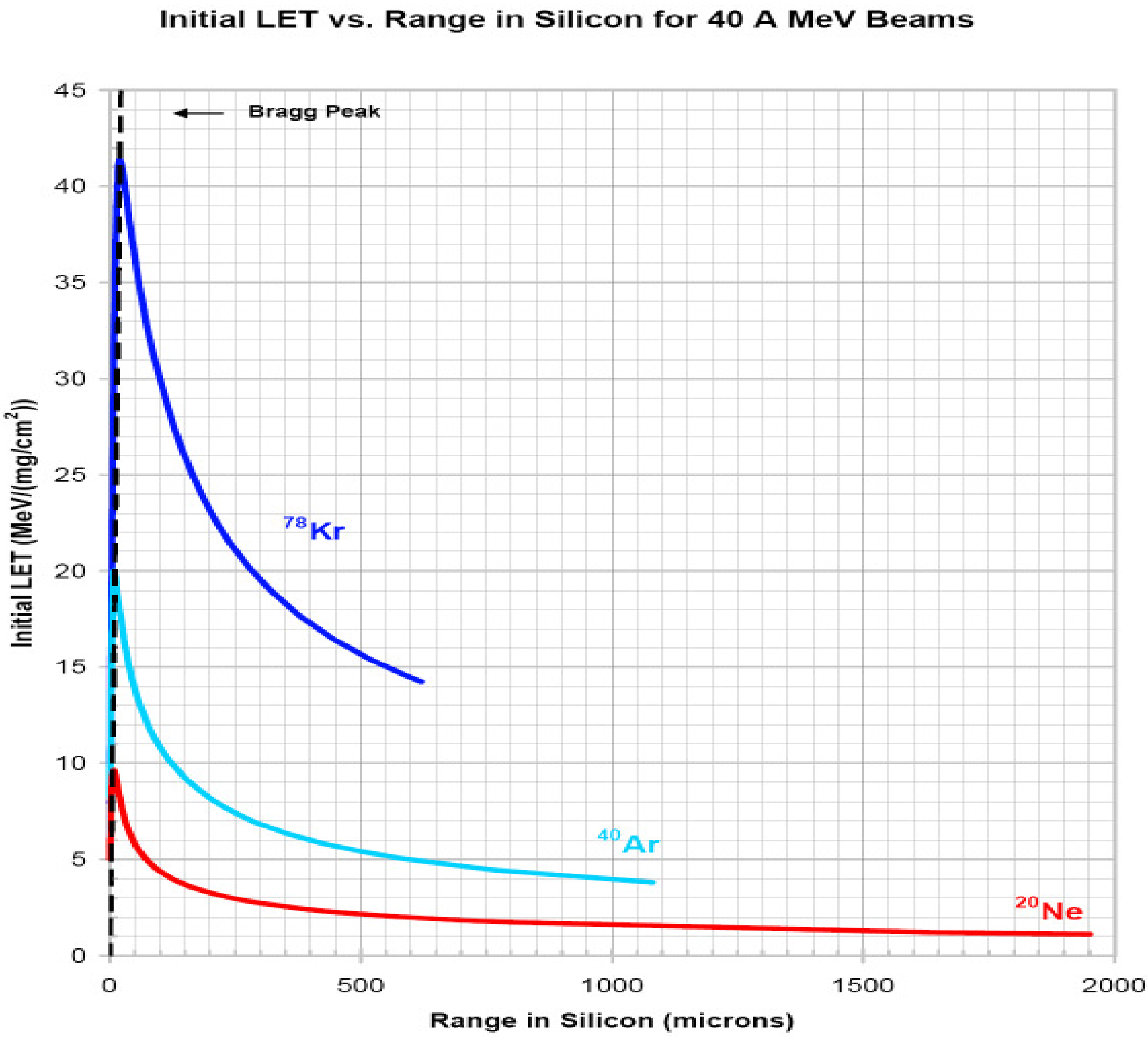
←------------------Coktail1-------------------------→←------Cocktail2-----------------------------------→

Usually for microelectronic testing the package is opened (delided) to allow to the heavy ions to reach the sensitive zone.
Front irradiation is preferred when it is possible. But for new generation devices (Flip-Chip, BGA,..) a back irradiation is often used. The silicon substrate is thinned in order to obtain a final thickness lower than the heavy ion range. This procedure used for electronic devices can be a real limitation for MEMS when the package can't be removed (working under vacuum for example).
Only a few facilities in the world deliver heavy ions with important ranges (TAMU at Texas University and GANIL (Grand Accelerateur National d'Ions Lourds).

At Ganil Ions species from C (96MeV/A) to U (24MeV/A) are available on the high energy line. But only one ion specie can be used during a test campaign. The ion energy can be reduced by using absorbers.

For TAMU, heavy ions cocktails giving 15, 25, 40 MeV/A are available. The LET is not constant when the ion penetrates in the material. This is illustrated below for two 25MeV/A and 40 MeV/A cocktails.




Initial LET vs. Range in Silicon for 40 A MeV Beams
Bragg Peak
78Kr
40Ar
20Ne
Initial LET (MeV/(mg/cm2))
Range in Silicon (microns)
0
5
10
15
20
25
30
35
40
45
0
500
1000
1500
2000

6 DEFINING THE PARAMETERS TO BE MEASURED AND HOW TO MEASURE THEM

This is the main point of the testing method and procedure. As already pointed out many times MEMS can have both electronic and mechanical parts.
Measuring techniques of electrical parameters (voltage, current, frequency, power, charge,..) are well documented but mechanical parameters measurements are least evident.
We need to separate here sensors and actuators.
For sensors reproducing the input sensor range can be an important and difficult challenge.
Here, we first recall the general requirements for electrical measurements (from Method 1019.6 and then we will illustrate the discussion by considering successively two sensors namely an accelerometer and a gyroscope and one actuator family namely RF MEMS.

6.1 GENERAL ASPECTS: METHOD 1019.6

General aspects of measurement apparatus are given below. These rules apply also for MEMS testing. Some qualities of mechanical or other methods used to measure MEMS (rotation tables, vibration, and pressure) must be properly defined in accordance with the precision required by the MEMS devices selected for testing.

.Method 019.6 content is recalled below:

2.3 Electrical test instruments. All instrumentation used for electrical measurements shall have the stability, accuracy, and resolution required for accurate measurement of the electrical parameters. Any instrumentation required to operate in a radiation environment shall be appropriately shielded.

2.4 Test circuit board(s). Devices to be irradiated shall either be mounted on or connected to circuit boards together with any associated circuitry necessary for device biasing during irradiation or for in-situ measurements. Unless otherwise specified, all device input terminals and any others which may affect the radiation response shall be electrically connected during irradiation, i.e., not left floating. The geometry and materials of the completed board shall allow uniform irradiation of the devices under test. Good design and construction practices shall be used to prevent oscillations, minimize leakage currents, prevent electrical damage, and obtain accurate measurements. Only sockets which are radiation resistant and do not exhibit significant leakages (relative to the devices under test) shall be used to mount devices and associated circuitry to the test board(s). All apparatus used repeatedly in radiation fields shall be checked periodically for physical or electrical degradation. Components which are placed on the test circuit board, other than devices under test, shall be insensitive to the accumulated radiation or they shall be shielded from the radiation. Test fixtures shall be made such that materials will not perturb the uniformity of the radiation field intensity at the devices under test. Leakage current shall be measured out of the radiation field. With no devices installed in the sockets, the test circuit board shall be connected to the test system such that all expected sources of noise and interference are operative. With the maximum specified bias for the test device applied, the leakage current between any two terminals shall not exceed ten percent of the lowest current limit value in the pre-irradiation device specification. Test circuit boards used to bias devices during accelerated annealing must be capable of withstanding the temperature requirements of the accelerated annealing test and shall be checked before and after testing for physical and electrical degradation.

2.5 Cabling. Cables connecting the test circuit boards in the radiation field to the test instrumentation shall be as short as possible. If long cables are necessary, line drivers may be required. The cables shall have low capacitance and low leakage to ground, and low leakage between wires.

2.6 Interconnect or switching system. This system shall be located external to the radiation environment location, and provides the interface between the test instrumentation and the devices under test. It is part of the entire test system and subject to the limitation specified in 2.4 for leakage between terminals.

6.2 FUNCTIONAL AND PARAMETER TESTING OF AN ACCELEROMETER

MEMS present a broad range of functionalities and working principle. To establish our guidelines we will focus on several examples that will help us in establishing the generic specification. When microelectronic devices are tested, measurements and stimulis are performed in the word of electrical values (voltages, currents, frequencies). With MEMS inputs can come from different domains (temperature, pressure, acceleration, rotation,…) and outputs can be electrical but also mechanical (rotation, micro-displacement).

So methods of measurement and needed apparatus will strongly differ from one MEMS type to an other one..

For an accelerometer, the main parameters to be accurately monitored are:

- Zero offset
- Linearity
- Maximum range
- Dynamic response as a function of frequency
- Out of axis sensitivity

6.2.1 Static sensitivity:

The objectives of this series of tests are to characterize the accelerometer under static conditions for
1) Stability of bias (zero offset) and scale factor over temperature and time
2) Linearity over the range of one g acceleration

The test procedure consist of observing the output of the test device to input accelerations using the Earth's gravitation field as the excitation source
The static sensitivity of an accelerometer is determined by changing the angle between one of the sensor's sensitive axes and the earth's gravitational field from 0° to 90° or from 0° to 180°. Assuming zero offset, the corresponding output voltage equals once or twice the static sensitivity [V/g], respectively. The second method is preferred, because this way a lower inaccuracy in the measured output voltage is obtained, due to the fact that the sensitive axis is less sensitive to variations in angles around 0° or 180° than it is to variations in angles around 90°.

An accelerometer can also be tested using a procedure and data reduction method similar to the procedures specified in IEEE STD 337-19722 and IEEE STD 530-19783. These documents describe in detail a model for the accelerometer that defines an input/output function with associated error terms.. Data is collected for different orientations of the devices input axis relative to the local gravity vector. The coefficients of the model terms are determined by regression analysis (least squares fit) of the test data. The magnitude of the coefficients provides insight into the error sources present in the design. Stability of the coefficients over time and temperature provides a measure of device stability.

When the dynamic range far exceeds ± 1 g, the linearity of the devices is measured using a centrifuge machine (such as Ideal Aerosmith Inc Model 1068).The units must be mounted on the horizontal centrifuge rotary table, with their sensitive axe lying along the radius of the centrifuge The output of each unit is then recorded for gradually increasing angular velocity, which is converted into the applied effective centrifugal acceleration, using the precise distance of the accelerometer center of mass from the centrifuge center. The same test must be repeated for negative accelerations, by mounting the unit with the sensitive axis pointing the opposite direction.

6.2.2 Dynamic sensitivity

The dynamic sensitivity or frequency response of an accelerometer is determined by putting the sensor on a precision linear shaker unit (Ex Gearing and Watson GWV20), and applying accelerations to it with an amplitude of 1 g at several frequencies, and by comparing the output voltage of the sensor with the output voltage of a reference accelerometer (Piezotronics ICP 301A10). The response of the accelerometer is measured with a Dynamic Signal Analyzer. The sensitivity measurements can be performed using an automated accelerometer calibration system at various dynamic input frequencies (such as Endevco Model 28952).

Sometimes two different shakers are needed for low (1–200 Hz) and high (20–10,000 Hz) frequency band characterization. The amplitude and phase plots are measured as a function of frequency

6.2.3 Off-axis sensitivity

The off-axis sensitivity of an accelerometer can be determined by measuring its output voltage while applying acceleration in a perpendicular direction. The acceleration is applied by a shaker unit and controlled by a reference accelerometer (EG the computerized Klinger transverse sensitivity test machine).

6.2.4 Temperature response

The sensitivity of the sensors to temperature variations can be characterized in an automated temperature-controlled chamber with computer-controlled 2g turnover stages
The temperature of the chamber is stabilized and the units are soaked for 30 min at each programmed temperature from Tmin to Tmax before a 2g turnover test (+1g, 0g, −1g reading) is performed. The maximum sensitivity deviation and maximum zero-measured-output (ZMO) deviation values in the full temperature range were calculated from the 2g turnover test results at each temperature step.

6.2.5 Noise measurement output

The noise level of the units can be measured using analog noise meter (Eg: Bruel&Kjoer type 2425).
The noise level of each unit is measured for different frequency bands (DC-100 Hz, DC-300 Hz and DC-1000 Hz). The tests can be performed after connecting the devices to a battery instead of a DC power source, in order to eliminate the added noise due AC-DC conversion in the power source.

6.3 FUNCTIONAL AND PARAMETRIC TESTING OF GYROS

Coriolis vibrating gyros can use vibrating beams (prismatic or triangular), single, dual or multi-tine tuning forks, hemispherical, ring or cylindrical vibrating shells, vibrating plates**...** Tuning fork gyros contain a pair of masses that are driven to oscillate with equal amplitude but in opposite directions. When rotated, the Coriolis force creates an orthogonal vibration that can be sensed by a variety of mechanisms. Some uses comb-type structures to drive the tuning fork into resonance. Rotation causes the proof masses to vibrate out of plane, and this motion is sensed capacitively with a custom CMOS ASIC. The resonant modes of a MEMS inertial sensor are extremely important. In a gyro, there is typically a vibration mode that is driven and a second mode for output sensing.
A recent IEEE standard 1431 IEEE Standard Specification Format Guide and Test Procedure for Coriolis Vibratory Gyros gives the details of the measurement to be performed. In particular the main purpose of this test series is to measure gyro scale factor, gyro scale factor errors and gyro scale factor sensitivities.
Some Parameters (such as noise measurement at zero rate output) were discussed above for accelerometers.

6.3.1 Resonance modes

To study mechanical resonance as a function of exciting frequency optical techniques can be used. A laser vibrometers (such as Polytech OFV501) can be used to measure the resonance frequencies, Q-factors, mode shapes, hysteresis, snap-down voltage, symmetry (by exciting different electrodes), operational voltage, and survivability (by driving it with a very large amplitude signal) of the microgyroscope.

6.3.2 Rotation rate measurement

The rotation testing of the microgyroscope uses a high precision rate table (or rotating table). This rate table must have a high rate resolution (about 0.01 degrees per second). A vacuum chamber can be used if necessary depending upon the MEMS package.

6.4 FUNCTIONAL AND PARAMETER TESTING OF RF MEMS

RF MEMS measurements include the actuation characteristics and the RF characteristics of the switch in On and Off States. Specific high frequency apparatus and good RF practices are needed.

6.4.1 RF CHARACTERIZATION of Switches

The RF performance of RF MEMS switches are measured from zero to the maximum frequency using a vector network analyzer. The switch is probed in the up state and down state to obtain the insertion loss:

- In the up state this parameter must be very low— less than 0.1 dB across the frequency band— because the switch in this condition is a continuous length of transmission line.
- In the down state, the isolation must be as high as possible (> 20 dB for all frequencies), which indicates that a good electrical short exists between signal and ground.

6.4.2 Command levels

Command levels, (actuation level and hysteresis) are fundamental parameters for RF MEMS, because they are found to be very sensitive to electrostatic charging. The actuation level is obtained by first slowing increasing the command voltage till a switching is obtained and then slowly decreasing the command voltage till the reverse switching is obtained.

6.4.3 Dynamic testing:

In order to obtain information about the dynamic behaviour of the switch a dynamic test setup must be utilized. The dynamic test setup consists of a function generator that supplies a dc control signal to the actuation pad and an oscilloscope to measure the output signal. A square wave is used for the actuation signal and an amplifier can be used to increase the actuation signal to the required potential. A close examination of the transition from up state to down state allows measurement of the switching speed and transition time. The switching speed is the time between the application of the actuation signal and the modulation of the output signal, and the transition time is the time required for the output signal to change from on to off.

A laser Doppler vibrometer can also be used to study the switching behaviour of the MEMS.

6.4.4 Self Actuation

Self actuation is a measurement of the RF level that can modify the state of the switch.
When RF is applied the RF level and the frequency must be specified and recorded.

7 TID TESTING PROCEDURE:

Method 1019.6 is followed and some comments are given when needed.
In the following paragraphs of the method (3.1 to 3.5), general recommendations are given concerning sample selection and handling, burn-in, dosimetry, Pb/Al shields to avoid dose enhancement, radiation levels.

3. PROCEDURE. The test devices shall be irradiated and subjected to accelerated annealing testing (if required for time-dependent effects testing) as specified by a test plan. This plan shall specify the device description, irradiation conditions, device bias conditions, dosimetry system, operating conditions, measurement parameters and conditions, and accelerated annealing test conditions (if required).

3.1 Sample selection and handling. Only devices which have passed the electrical specifications as defined in the test plan shall be submitted to radiation testing. Unless otherwise specified, the test samples shall be randomly selected from the parent population and identically packaged. Each part shall be individually identifiable to enable pre- and post-irradiation comparison. For device types which are ESD-sensitive, proper handling techniques shall be used to prevent damage to the devices.

3.2 Burn-in. For some devices, there are differences in the total dose radiation response before and after burnin. Unless it has been shown by prior characterization or by design that burn-in has negligible effect (parameters remain within post-irradiation specified electrical limits) on the total dose radiation response, then one of the following must be done:
3.2.1 The manufacturer shall subject the radiation samples to the specified burn-in conditions prior to conducting total dose radiation testing or
3.2.2 The manufacturer shall develop a correction factor, (which is acceptable to the parties to the test) taking into account the changes in total dose response resulting from subjecting product to burn-in. The correction factor shall then be used to accept product for total dose response without subjecting the test samples to burn-in.

3.3 Dosimetry measurements. The radiation field intensity at the location of the device under test shall be determined prior to testing by dosimetry or by source decay correction calculations, as appropriate, to assure conformance to test level and uniformity requirements. The dose to the device under test shall be determined one of two ways:
(1) by measurement during the irradiation with an appropriate dosimeter, or (2) by correcting a previous dosimetry value for the decay of the $_{60}$Co source intensity in the intervening time. Appropriate correction shall be made to convert from the measured or calculated dose in the dosimeter material to the dose in the device under test.

3.4 Lead/Aluminum (Pb/Al) container. Test specimens shall be enclosed in a Pb/Al container to minimize dose enhancement effects caused by low-energy, scattered radiation. A minimum of 1.5 mm Pb, surrounding an inner shield of at least 0.7 mm Al, is required. This Pb/Al container produces approximate charged particle equilibrium for Si and for TLDs such as CaF_2. The radiation field intensity shall be measured inside the Pb/Al container (1) initially, (2) when the source is changed, or (3) when the orientation or configuration of the source, container, or test-fixture is changed. This measurement shall be performed by placing a dosimeter (e.g., a TLD) in the device-irradiation container at the approximate test-device position. If it can be demonstrated that low energy scattered radiation is small enough that it will not cause dosimetry errors due to dose enhancement, the Pb/Al container may be omitted.

3.5 Radiation level(s). The test devices shall be irradiated to the dose level(s) specified in the test plan within ±10 percent. If multiple irradiations are required for a set of test devices, then the post-irradiation electrical parameter measurements shall be performed after each irradiation.

The method clearly indicates the influence of the test plan. This test plan must be carefully prepared before the experiment.

7.1 DOSE RATE

The dose rate chosen during the experiment is a very complicated issue. Generally higher degradation is obtained at high dose rate. So high dose rate is a worst case and a low dose rate (value closer to the real application) must be chosen when total dose degradation is critical. ELDRS (Enhanced Low Dose Rate Sensitivity) is a particular effect found to be important in some bipolar or BiCMOS technologies. For these technologies, the degradation increases when the dose rate is reduced so high dose rate is no longer a worst case and the extrapolation to the real application is more difficult. In MEMS dielectric charging value and sign has been observed to be a function of dose rate. So choosing dose rate will be an important and difficult issue.

For microelectronic devices, ELDRS effect is taken into account in Method 1019.6 in paragraph 3.6

3.6 Radiation dose rate. The radiation dose rate for bipolar and BiCMOS linear or mixed-signal parts used in applications where the maximum dose rate is below 50 rad(Si)/s shall be determined as described in paragraph 3.13 below. Parts used in low dose

rate applications, unless they have been demonstrated to not exhibit an ELDRS response shall use Condition C, Condition D, or Condition E.
Note: Devices that contain both MOS and bipolar devices may require qualification to multiple subconditions to ensure that both ELDRS and traditional MOS effects are evaluated.
3.6.1 Condition A. For condition A (standard condition) the dose rate shall be between 50 and 300 rad(Si)/s [0.5 and 3 Gy(Si)/s] ^{60}Co 2/ The dose rates may be different for each radiation dose level in a series; however, the dose rate shall not vary by more than ±10 percent during each irradiation.
2/ The SI unit for the quantity absorbed dose is the gray, symbol GY. 100 rad = 1 Gy.
3.6.2 Condition B. For condition B, for MOS devices only, if the maximum dose rate is < 50 rad(Si)/s in the intended application, the parties to the test may agree to perform the test at a dose rate ≥ the maximum dose rate of the intended application. Unless the exclusions in 3.12.1b are met, the accelerated annealing test of 3.12.2 shall be performed.
3.6.3 Condition C. For condition C, (as an alternative) the test may be performed at the dose rate agreed to by the parties to the test.
3.6.4 Condition D. For condition D, for bipolar or BiCMOS linear or mixed-signal circuits only, the parts shall be irradiated at <10 mrad(Si)/s unless the specification dose is greater than 25 krad(Si). For radiation levels greater than 25 krad(Si) the total irradiation time shall be > 1000 hours and the dose rate shall be determined from the total dose (including any overtest factors) and the irradiation time.
3.6.5 Condition E. For condition E, for bipolar or BiCMOS linear or mixed-signal circuits only, the parts shall be irradiated at between 0.5 and 5 rad(Si)/s if the specification dose is < 50 krad(Si). Condition E applies to elevated temperature irradiation at 100°C }5°C and does not apply for devices with specification doses >50 krad(Si) unless it can be demonstrated that the elevated temperature irradiation test provides a conservative bound for low dose rate response at a radiation specification level that is above 50 krad(Si).

The particular behaviour of MEMS devices is not presently known (at least for the mechanical part) and the rather complex procedure given above will not be followed in a first time. First the sensitivity as a function of dose rate need to be established, particularly if dielectric charging mechanisms are the main source of degradation.

At least 2 different dose rates will be chosen in the range available at the facility. For example if we use the ESA Gamma Irradiation Facility, we can choose: 3krad/h, 300 rad/h. For a total dose of 50 krad this will need respectively 16.6h, 7days. Special irradiations under very low dose rate must be considered if the sign of the output variation change for the 2 first dose rate values.

Temperature:
Irradiation can be performed either at room temperature or at elevated temperature (for bipolar and BiCMOS) to study ELDR effects

3.7 Temperature requirements. The following requirements shall apply for room temperature and elevated temperature irradiation.
3.7.1 Room temperature irradiation. Since radiation effects are temperature dependent, devices under test shall be irradiated in an ambient temperature of 24°C ±6°C as measured at a point in the test chamber in close proximity to the test fixture. The electrical measurements shall be performed in an ambient temperature of 24°C ±6°C. If devices are transported to and from a remote electrical measurement site, the temperature of the test devices shall not be allowed to increase by more than 10°C from the irradiation environment. If any other temperature range is required, it shall be specified.
3.7.2 Elevated temperature irradiation. For bipolar or BiCMOS linear or mixed-signal circuits irradiated using Condition E dose rate, devices under test shall be irradiated in an ambient temperature of 100°C +–5°C as measured at a point in the test chamber in close proximity to the test fixture.

High temperature irradiation is to be performed only if needed (if an ELDRS is observed of MEMS devices).

7.2 ELECTRICAL MEASUREMENTS

3.8 Electrical performance measurements. The electrical parameters to be measured and functional tests to be performed shall be specified in the test plan. As a check on the validity of the measurement system and pre- and post-irradiation data, at least one control sample shall be measured using the operating conditions provided in the governing device specifications. For automatic test equipment, there is no restriction on the test sequence provided that the rise in the device junction temperature is minimized. For manual measurements, the sequence of parameter measurements shall be chosen to allow the shortest possible measurement period. When a series of measurements is made, the tests shall be arranged so that the lowest power dissipation in the device occurs in the earliest measurements and the power dissipation increases with subsequent measurements in the sequence.
The pre- and post-irradiation electrical measurements shall be done on the same measurement system and the same sequence of measurements shall be maintained for each series of electrical measurements of devices in a test sample. Pulse-type measurements of electrical parameters should be used as appropriate to minimize heating and subsequent annealing effects. Devices which will be subjected to the accelerated annealing testing (see 3.12) may be given a pre-irradiation burn-in to eliminate burn-in related failures.

This paragraph gives general recommendations concerning the sequence and rapidity of measurement. The idea is to avoid annealing as much as possible.
The choice of parameters to be measured is defined in the test plan. Generally, when possible, the data sheet is used as a guide but this is not a strict obligation. The test plan definition results of a trade-off between needs from the customer and possibilities of measurements (apparatus, radiation facility environment, cost,..)

The other important point is to keep a device non-irradiated as a reference to check the stability of the devices and the stability of the measurement apparatus. *This device must have stable parameters and a sufficient reliability, in order to allow checking apparatus during the full duration of the test. In some MEMS self-charging can be an important effect that complicates the separation from true radiation effects from natural aging shift of some parameters.*

7.3 TEST CONDITIONS

This paragraph is very important as it describes the two possible irradiation scenarios:
In flux testing or remote testing:

3.9 Test conditions. The use of in-flux or not in-flux testing shall be specified in the test plan. (This may depend on the intended application for which the data are being obtained.) The use of in-flux testing may help to avoid variations introduced by post-irradiation time dependent effects. However, errors may be incurred for the situation where a device is irradiated in-flux with static bias, but where the electrical testing conditions require the use of dynamic bias for a significant fraction of the total irradiation period. Not-in-flux testing generally allows for more comprehensive electrical testing, but can be misleading if significant post-irradiation time dependent effects occur.
3.9.1 In-flux testing. Each test device shall be checked for operation within specifications prior to being irradiated. After the entire system is in place for the in-flux radiation test, it shall be checked for proper interconnections, leakage (see 2.4), and noise level. To assure the proper operation and stability of the test setup, a control device with known parameter values shall be measured at all operational conditions called for in the test plan. This measurement shall be done either before the insertion of test devices or upon completion of the irradiation after removal of the test devices or both.
3.9.2 Remote testing. Unless otherwise specified, the bias shall be removed and the device leads placed in conductive foam (or similarly shorted) during transfer from the irradiation source to a remote tester and back again for further irradiation. This minimizes post-irradiation time dependent effects.
3.9.3 Bias and loading conditions. Bias conditions for test devices during irradiation or accelerated annealing shall be within ±10 percent of those specified by the test plan. The bias applied to the test devices shall be selected to produce the greatest radiation induced damage or the worst-case damage for the intended application, if known. While maximum voltage is often worst case some bipolar linear device parameters (e.g. input bias current or maximum output load current) exhibit more degradation with 0 V bias. The specified bias shall be maintained on each device in accordance with the test plan. Bias shall be checked immediately before and after irradiation. Care shall be taken in selecting the loading such that the rise in the junction temperature is minimized.

When “In Flux testing” is chosen, it is generally possible for electronic devices to apply correct stimulis (voltage or currents) to the devices. For sensors, this is generally mostly impossible, because it is very difficult to simulate the inputs. For example for accelerometer testing the acceleration will be limited to ± 1g (gravity) and for pressure sensor the pressure will be limited to the atmospheric pressure.

So in flux testing will be limited to available conditions of gravity or atmospheric pressure, and remote testing will be mandatory to simulate the full scale domain of accelerations or pressure.
Even with remote testing it will be not so easy to group on the irradiation site the full testing apparatus (detailed for accelerometers in the preceding chapter).
Electrical conditions applied during irradiation are a very important point to consider because it can strongly influence the results.

Post irradiation procedure:
This defines the timing intervals that should be observed at each radiation step and after the end of the irradiation.
3.10 Post-irradiation procedure. Unless otherwise specified, the following time intervals shall be observed:
a. The time from the end of an irradiation to the start of electrical measurements shall be a maximum of 1 hour unless Condition D is used, in which case the maximum time shall be 72 hours.
b. The time to perform the electrical measurements and to return the device for a subsequent irradiation, if any, shall be within two hours of the end of the prior irradiation unless Condition D is used, in which case the maximum time shall be 120 hours.
To minimize time dependent effects, these intervals shall be as short as possible. The sequence of parameter measurements shall be maintained constant throughout the tests series.

In method 1019.6 the following paragraphs 3.11 and 3.12 give details of procedures concerning ELDRS. This approach will not be detailed in this guideline because we do not know if these effects will be met in MEMS. As indicated above this point can be investigated by using at least 3 different dose rates during irradiation.

At least 2 methods can be used:
- Change the dose rate during a test: this procedure was used by Knudson for accelerometers showing that the sign of variation was changing.
- Irradiate 3 lots of devices at 3 different dose rates

7.4 TEST REPORT

This paragraph is a guideline to prepare the radiation test report.
It lists the **minimum information** that must be present in the report. This is fully applicable to MEMS devices at the exception of the reference to MIL-PRF-38535 and MIL-PRF-38534 qualification.

3.14 Test report. As a minimum, the report shall include the device type number, serial number, the manufacturer, package type, controlling specification, date code, and any other identifying numbers given by the manufacturer. The bias circuit, parameter measurement circuits, the layout of the test apparatus with details of distances and materials used, and electrical noise and current leakage of the electrical measurement system for in-flux testing shall be reported using drawings or diagrams as appropriate. Each data sheet shall include the test date, the radiation source used, the bias conditions during irradiation, the ambient temperature around the devices during irradiation and electrical testing, the duration of each irradiation, the time between irradiation and the start of the electrical measurements, the duration of the electrical measurements and the time to the next irradiation when step irradiations are used, the irradiation dose rate, electrical test conditions, dosimetry system and procedures and the radiation test levels. The pre- and post-irradiation data shall be recorded for each part and retained with the parent population data in accordance with the requirements of MIL-PRF-38535 or MIL-PRF-38534. Any anomalous incidents during the test shall be fully documented and reported. The accelerated aging annealing procedure, if used, shall be described. Any other radiation test procedures or test data required for the delivery shall be specified in the device specification, drawing or purchase order.

The contents of test report that are detailed above can be completed by other informations. The idea is to put all the useful informations on what was tested (detailed identification of the DUT (Device Under Test)) how it was tested (temperature, timing, dose rate, bias conditions, inputs). Also specific apparatus used for test must be detailed.
The particular events that occurred during the experiment must be recorded.

7.5 TEST PLAN

The summary given in method 1019.6 groups the main points that must be given in the test plan.

4. SUMMARY. The following details shall be specified in the applicable acquisition document as required:
a. Device-type number(s), quantity, and governing specifications (see 3.1).
b. Radiation dosimetry requirements (see 3.3).
c. Radiation test levels including dose and dose rate (see 3.5 and 3.6).
d. Irradiation, electrical test and transport temperatures if other than as specified in 3.7.
e. Electrical parameters to be measured and device operating conditions during measurement (see 3.8).
f. Test conditions, i.e., in-flux or not-in-flux type tests (see 3.9).
g. Bias conditions for devices during irradiation (see 3.9.3).
h. Time intervals of the post-irradiation measurements (see 3.10).
i. Requirement for extended room temperature anneal test, if required (see 3.11).
j. Requirement for accelerated annealing test, if required (see 3.12).
k. Documentation required to be delivered with devices (see 3.14). *

This test plan is very important. It must be established with in mind the possibility to realise all the different points of the experiment without any derogation. This test plan must be accepted by both parts (customer and testing team).

8 DISPLACEMENT DAMAGE TESTING

Displacement damage in space is mainly due to protons. Displacement damage can also be induced by energetic electrons but to a much lower extent. As indicated previously the normalisation procedure uses the NIEL concept. The NIEL is the quantity of energy per unit mass (keV/g) delivered as atomic displacement damage by a particle of given energy.
The NIEL dose is obtained by multiplying the NIEL coefficient by the fluence of particles. In electronic devices the observed degradation was found to be proportional to NIEL. This is surprising because the damage volume is related to the energy of the recoils. But after annealing it seems that the number of residual defects is proportional to the energy deposited.
In electronic devices, the residual defects modify the carrier lifetime, carrier density and carrier mobility. These parameters affect some electrical parameters (gain of bipolar transistors, direct voltage of diodes). CMOS technology is not sensitive to displacement damage at fluence levels met in space applications.
In MEMS displacement damage degradation at low fluence has not been studied. In particular the possibility to create microcracks in strain dielectric beams has not been studied.

8.1 DISPLACEMENT DAMAGE TESTING WITH PROTONS

Protons induced both ionizing effects and displacement damage. In case of testing with protons, the total ionizing dose procedure should be applied. The interpretation of results will be more complex because the observed degradation will be the combined result of total ionizing dose degradation which is function of time and of displacement damage which is stable in time. So in an evaluation test where the main objective is to evaluate the degradation mechanisms, it would be better to test ionizing effects by highly ionizing and low displacement damaging coefficient radiation (photons or electrons) and to test displacement damage by particles with low ionizing and high displacement damage coefficient.

8.2 DISPLACEMENT DAMAGE TESTING WITH NEUTRONS

In place of protons, rapid neutrons obtained either with a fission reactor or a 14 MeV –D-T generator can be used. The neutron fluence of these facilities is given in 1MeV-eq neutron damage. This factor can be compared to the Proton NIEL curve to define the fluence level of the test.
In electronic devices, displacement damage in steady state condition does not depend on the electrical bias of the devices during irradiation.
Displacement damage is stable at room temperature so annealing effects can be neglected and there is not any timing requirement to perform the tests.
This simplifies strongly the testing procedure.
Detailed testing can be performed outside the irradiation room. In these experiments some radioactivity can be induced in the samples and measurements can be performed only after several days. This allows in house testing with the dedicated apparatus that can't be used outside the laboratory.
When we consider displacement damage in MEMS we must first verify that the previous hypothesis (damage independent of electrical and mechanical state) is still correct. A first experiment will be needed to verify that the mechanical state of sensors or actuators does not modify the sensitivity to displacement damage.

9 SINGLE EVENT EFFECTS TESTING

The purpose of these testing guidelines is to establish a procedure to study single event effects in MEMS. By definition a MEMS is a system and we want to establish a procedure to understand the response mechanisms of this system (in order to eventually improve the device or to use it in a better way). We want also to be able to predict the occurrence of events in particular space missions.

In the analysis of the response mechanisms, the heavy ions beam can be used as a probe

We will use both the ESCC basic specification ESCC N°25100: "SINGLE EVENT EFFECTS TEST METHOD AND GUIDELINES" and ASTM F1192-00(2006) Standard Guide for the Measurement of Single Event Phenomena (SEP) Induced by Heavy Ion Irradiation of Semiconductor Devices as guides for this chapter.

A great part of these documents can be used as the basis to establish the guidelines for single event effects on MEMS because SEE are expected only in the electronic part of the MEMS. This assertion should be verified by experimental testing.

The Summary of ASTM F1192-00 standard is given below:

"1. Scope

1.1 This guide defines the requirements and procedures for testing integrated circuits and other devices for the effects of single event phenomena (SEP) induced by irradiation with heavy ions having an atomic number Z 2. This description specifically excludes the effects of neutrons, protons, and other lighter particles that may induce SEP via another mechanism. SEP includes any manifestation of upset induced by a single ion strike, including soft errors (one or more simultaneous reversible bit flips), hard errors (irreversible bit flips), latchup (permanent high conducting state), transients induced in combinatorial devices which may introduce a soft error in nearby circuits, power field effect transistor (FET) burn-out and gate rupture. This test may be considered to be destructive because it often involves the removal of device lids prior to irradiation. Bit flips are usually associated with digital devices and latch up is usually confined to bulk complementary metal oxide semiconductor, (CMOS) devices, but heavy ion induced SEP is also observed in combinatorial logic programmable read only memory, (PROMs), and certain linear devices that may respond to a heavy ion induced charge transient. Power transistors may be tested by the procedure called out in Method 1080 of MIL STD 750.

1.2 The procedures described here can be used to simulate and predict SEP arising from the natural space environment, including galactic cosmic rays, planetary trapped ions and solar flares. The techniques do not, however, simulate heavy ion beam effects proposed for military programs. The end product of the test is a plot of the SEP cross section (the number of upsets per unit fluence) as a function of ion LET (linear energy transfer, or ionization deposited along the ion's path through the semiconductor). This data can be combined with the system's heavy ion environment to estimate a system upset rate.

1.3 Although protons can cause SEP, they are not included in this guide. A separate guide addressing proton induced SEP is being considered.

1.4 The values stated in International System of Units (SI) are to be regarded as standard. No other units of measurement are included in this guide.

This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use."

As indicated in the above short presentation of ASTM F1192-00, the scope of this standard is “for testing integrated circuits and other devices”. Other devices means probably discrete electronic devices such as power MOS, IGBT.
We recall below the titles of the different paragraphs of ESCC N°25100: “SINGLE EVENT EFFECTS TEST METHOD AND GUIDELINES” Issue 1 October 2002

1. Scope
1.1 general
1.2 purpose
1.3 Applicable documents

2 Terms Definition, Abbreviations, Symbols and Units
(LET, Effective LET, Charge Transfer and Deposition, Flux, Fluence, Cross-section, Ion Specie, Range, Energy, SEU or Soft Error, Latch-Up, Soft Latch, SHE, MBU, SEB, Threshold LET, Saturated Cross-section)

3. Equipment and general procedures
3.1 Radiation Source and Dosimetry
3.1.1 Source general
3.1.2 Source Heavy Ions
3.1.3 Source Protons
3.1.4 Dosimetry
3.1.5 Temperature
3.2 Test System
3.2.1 Test board and cabling
3.2.2 Device Test System

4 Test Planning and procedures
4.1 Sample Size Selection Preparation
4.2 Electrical measurement
4.2.1 SEU
4.2.2 Latch-Up
4.2.3 Unit of Measure
4.3 Test Plan

5. Documentation

In these new guidelines we will follow the same plan. Most of the chapters can be directly incorporated in the new guidelines.

Here we focus of what should be added or be substracted to this document.

1 Purpose:

If this guideline is specific for MEMS, the purpose of this specification is to define the requirements for the ***testing of MEMS or Microsystems*** for SEE arising from irradiation by energetic heavy ions or protons..

2 Definitions:

MEMS or Microsystems should be added and defined
SET (Single Event Transient) should be added and defined

3 Equipment and General Procedures

3.1 Radiation sources and dosimetry
3.1.2 Source Heavy ions.

One important point to consider is the heavy ion range. In the present specification, “The accelerator shall be capable of delivering ions with a range of at least 30 µm in silicon”, the range must be at least 30 µm. In some power devices this range is considered as insufficient.
In MEMS built with a 3D structure, this minimum can be too much low. In particular in some MEMS package can’t be removed.
It could be better to say “the accelerator shall be capable of delivering ions with a range sufficient to reach the sensitive volume of the device with a residual range of at least 30µm

3.2.1 About positioning the device:
Generally the heavy ions irradiation is performed under vacuum and due to the limited range of the ions only perpendicular or low angle tilting is performed.
For some sensors such as accelerometers, the irradiation with a horizontal beam perpendicular to the die can correspond to a zero input or ± 1g input. Tilting will modify both the ion angle incidence and also the input to the sensor.

4.2.1 Single Event Upset.
For some MEMS that do not contain any microelectronic or active discrete device, single event effects will probably not be observed. But microdose effects remain to be studied.
For sensors, the main response will probably be due to an impact in the electronic part. A global response will be observed at the output. As usually observed in analog circuits response, a SET (Single Event Transient) will be observed. The amplitude and shape of this transient is a function of the LET, the position of the impact but also of the input of the sensor.
As we previously said during the test, only limited input conditions can be obtained (limited accelerations, pressure,..) so it will be necessary to be able to extrapolate experimental results to other operating conditions.

For a given LET the output SET must be fully recorded. A graph giving Amplitude versus Duration can be given as a synthesis of the result. These different amplitudes and durations are related to the position of the impact of the heavy ions in different elementary devices of the electronic circuit in the MEMS.

4.2.2 Unit of measure
The sensitivity of a device is expressed by the cross-section whose unit is an area unit, defined as the number of SET divided by the fluence.
To consider that a SET exists, the amplitude of the event must be greater than noise. A particular amplitude and/or duration threshold can be chosen to record only SET with sufficient amplitude or duration.
In our opinion the use of effective LET is no more a useful approach and at least this notion must be used carefully.

4.3 Test Plan
The main problem to consider is the flux when long duration transient are expected. The flux must be reduced enough to be sure that the transient observed is really due to only one particle. The flux should be selected to obtain a period between two events at least ten times greater than the SET duration.
To anticipate these effects a pre-screening of the devices is suggested. A pulsed laser facility can be used. Most Laser facilities can test silicon devices and obtain a mapping of the sensitive zones. Laser pre-screening has many limitations but it can be also a useful tool to understand the upset mechanism..

5 Documentation
Two sets of documents are required
a) test plan
b) test report
All the points given in ESCC 25100 should be entered in the test Plan.

10 ADDITIONAL COMMENTS AFTER RADIATION TESTING OF MEMS TYPE I (ACCELEROMETER) AND MEMS TYPE II (RF MEMS).

This chapter contains additional comments to the existing guidelines after performing radiation tests on type I (accelerometer) and type II (RF-MEMS).

Comments are given on the main preceding chapters of the previous guidelines when needed.

10.1 STANDARDS EVOLUTION (CHAPTER 4)

Following standards evolution is an absolute necessity. These standards are related to definitions and measurement principles and methods. In Chapter 4, recent and future IEC standards and methods were presented.

Radiation testing methods and guidelines up to date versions must also be considered. If the modifications may concern MEMS testing, the modification must be taken into account in the guidelines.

10.2 NUMBER OF SAMPLES

The number of samples that are necessary to obtain and characterize is a function of the maturity of the technology and of the sensitivity of devices to a given effect.
The number of devices indicated below is for the initial characterization phase.
For Hardness Assurance, this number should be much less because experiments are only performed on devices in the worst case.

10.2.1 SEE testing

If SEL or destructive effects can exist (MEMS with an electronic circuit or for thin dielectrics) the minimum number of devices tested should be 5. 5 spare devices should be ready to complete the experiments if necessary.
If no SEL is possible, and if the lot is homogeneous, at least 3 devices should be tested.

10.2.2 TID testing:

At least 10 devices per dose rate and 2 Ref. are necessary.
In the characterisation phase at least two dose rates should be studied. These dose rates must differ by at least two decades. The actual separation between low value of the HDR and high value of the LDR window in ESA total dose guidelines for electronics should be increased.
So at least 24 “good” components are needed for TID. If we add spares in case of initial damage or maverick devices, a number of 30 devices seems accurate

10.2.3 Displacement damage:

At least 5 devices per level of fluence and 1 Ref are needed for specific displacement damage test with neutrons. Generally 3 fluences separated by a decade are used.
So a total of 16 components should be needed.

Because proton test potentially induces all the effects (DD, SEE, TID) a number of 10 devices with 3 devices in 3 different electrical configurations and 1 spare is required. The electrical configuration should be identical to those used in TID.

10.2.4 Recommendations

Today, we can consider there are two categories of MEMS devices:

- Industrialized
- Pre-Industrialized.

Industrialized MEMS (MOTS –MEMS COTS):

total: about 40-50 samples
Reference sample can be limited to 1 sample

Pre-industrialized MEMS:

One should be able to screen the most stable components from the other, so that a larger population is needed.
Total: about 80-100 samples (this is what we have used for MEMS type 2: RF)

Other important point is the number of reference sample to be biased in worst condition.
This will be used to decorrelate natural device aging vs. pure radiation effects.

Lastly: 'follower' sample (min 2) to be used as a follower to environment that has been seen by components outside the test campaign (travel, storage etc). They shall be tested prior to each (off line) test sequence.

For measurements, when they do not correspond to written standard, one should use a golden sample to prove the test set-up has not evolved from previous test run.

The following table gives the summary of the number of devices needed:

Effect	TID	SEE	DD (neutrons)	Protons
Characterization	30	10	15	10
Hardness Assurance	10	5	5	5

10.3 CHOOSING THE RADIATION FACILITY (CHAPTER 5)

10.3.1 Total ionizing dose

Low dose rate testing: A specific low activity facility should be used to meet more easily low dose rate levels of 1 to 10mrad/s (3.6 rad/h to 36 rad/h) where true low dose rate effects have been found on some electronic devices. The actual low dose rate window of ESA (<360 rad/h) is often used at the highest limit of 360 rad/h in order to limit the test duration and the same irradiation facility is used to perform both HDR and LDR tests.

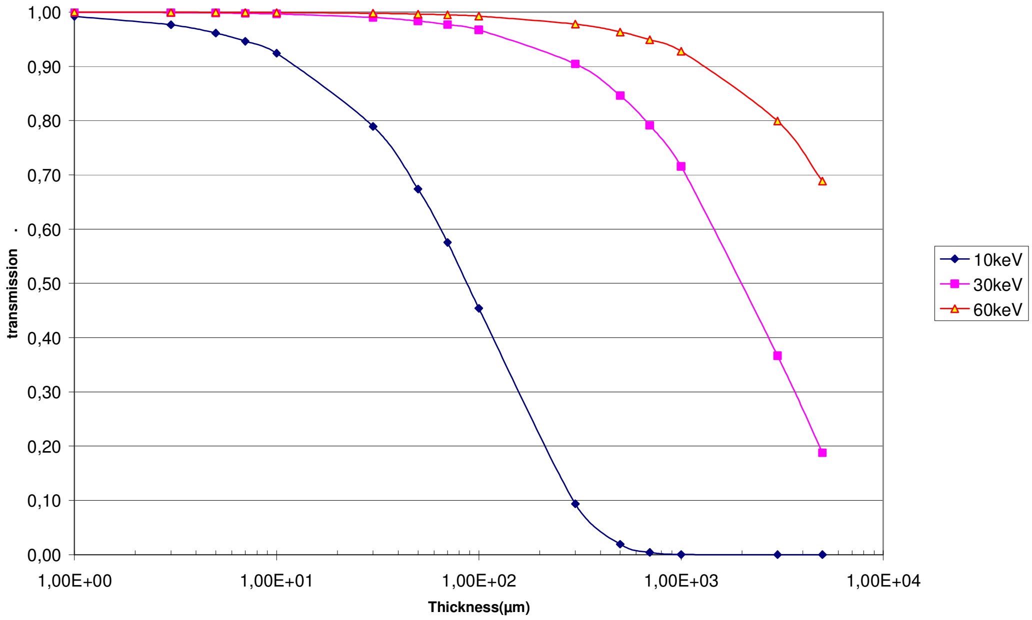
Use of X-Rays source: It is useful to separate the ionizing damage contribution from the sensor and the electronics in the evaluation phase. For monolithic devices, separate irradiation can be performed by using low energy X-Rays (10 keV) from a low energy X-Rays Tube. Thin masks of high Z materials (Ta, W) that can protect different parts of the device with an excellent geometry accuracy are used. This procedure allows to develop fast mitigation techniques by locating the sensitive parts.

In hybrid devices (such as MEMS type 1 tested), the sensor is much thicker and higher energy X-rays are required. The attenuation coefficient of X-rays in silicon obtained from http://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html, are given below for energy E comprised between 5 keV and 100 keV.

Energy (MeV)	μ/ρ cm^2/g
5.00000E-03	2.450E+02
6.00000E-03	1.470E+02
8.00000E-03	6.468E+01
1.00000E-02	**3.389E+01**
1.50000E-02	1.034E+01
2.00000E-02	4.464E+00
3.00000E-02	**1.436E+00**
4.00000E-02	7.012E-01
5.00000E-02	4.385E-01
6.00000E-02	**3.207E-01**
8.00000E-02	2.228E-01
1.00000E-01	1.835E-01

The transmission factor for X-rays energies of 10keV, 30keV and 60keV as a function of the silicon thickness is given below.

To irradiate sensors with thickness >100µm up to 5mm, X-Rays with 60keV energy is needed. A mask of Tantalum (Ta, Z=73) can be used to protect the other zones. At E=60keV, the transmission behind 1mm of Ta is less than 1%.



10.3.2 Displacement damage

The separation of Displacement Damage from Total Ionizing Dose Damage is difficult or even impossible when a proton beam is used.

So neutron irradiation should be preferred at least in the evaluation phase of a new device. A fission reactor can be used. High fluence levels can be reached in order to obtain displacement damage threshold fluence. In that way displacement damage mechanisms can be studied and compared to total ionizing dose sensitivity.

10.3.3 Single Event Effects

The package of MEMS devices is an important part of the device. So, removing it may modify the MEMS properties and parameters.

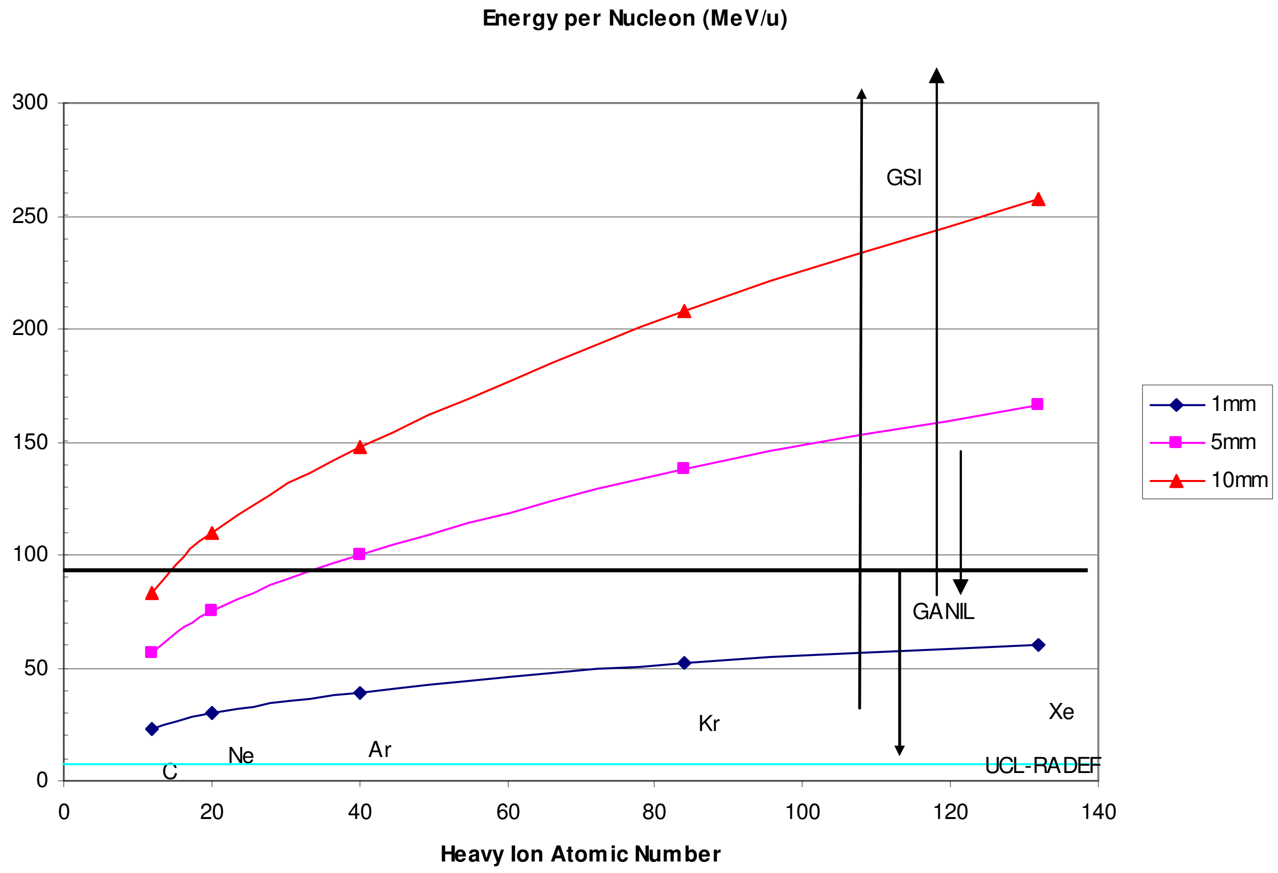
Calculation of ion penetration in the structure by using a precise technology model of the device (materials definition and thickness) must be performed prior to the choice of the heavy ion irradiation facility

When the MEMS is a hybrid device (such as MEMS type I tested) a good approach to prepare the Heavy Ions experiment is to use a focused laser with a short duration pulse. The photon wavelength is chosen to obtain a sufficient penetration in the electronic device (1.06µm for silicon devices). A crude estimation of the threshold LET and of the cross-section is obtained. The main advantage is to locate the precise origin of the perturbation when several dies are used in the device. An other interest is to check the measurement apparatus and to obtain the shape, the amplitude and the duration of the transients. Finally the Laser facility can be used as a fast Latch-up screening facility. If SEL is detected, proper SEL protection and detection methods must be developed before the heavy ion testing. Laser test is limited to electronic parts and particularly well adapted to test silicon devices. For other electronic devices with greater bandgap, shorter wavelengths are needed.

To test sensors with thickness of the order of 300µm to 1mm, high energy heavy ions facilities must be used. Such facilities are GANIL and GSI. To compare the different facilities one criteria is the energy in MeV per nucleon.

Facility	UCL Low	UCL high	RADEF	GANIL	GSI
Energy per nucleon	3.5 to 4.1	8.4 to 10.1	6.1 (Low) to 9.3 (High)	35 to 95 (see below)	5-1000

The energy per nucleon necessary to cross 1mm, 5mm and 10mm of silicon as a function of Ion Type are given below. The range calculation is performed by SRIM08.



UCL and RADEF can't be used even for low A ions such as Carbon. GANIL covers the need for 1mm thickness for most of the ions with its maximum 95 MeV/nucleon. For greater thickness GSI-SIS must be used.

GSI allows irradiation of MEMS devices without opening the package.

10.4 DEFINING THE PARAMETERS TO BE MEASURED AND HOW TO MEASURE THEM (CHAPTER 6)

As already said this part is one most important part of the guidelines.

10.4.1 Knowledge of the DUT

Before any test, a precise knowledge of the functionality of the devices to be tested is needed. The more important parameters must be identified and test. A reference to standards to identify the best measurement methods is first needed.

A literature survey of related publications and analysis of sensitive parameters and methods to measure them must be done prior to establish the test plan.

10.4.2 Measurement methods

When a particular measuring method is chosen, the precision must be evaluated and the different parameters that may influence the measurement results must be identified to be fixed at a given value and recorded. The experiment must be easily reproduced by other people and for that purpose enough details must be given.

This is illustrated below on the example of RF-MEMS:

The switching threshold for positive voltage and negative voltage is an important parameter used to define the command level in practical applications. A simple way to measure it is to use a saw tooth generator with a range greater than these levels. So generally only the amplitude of this saw tooth will be specified. But other parameters that will affect the precision are needed:

The voltage increment between time samples: this is the voltage resolution of the measurement

The frequency of the saw tooth (or the saw tooth duration). The frequency must be low enough so that the measurement is considered as a quasi-static one. A Maximum voltage variation rate in Volt/ms must be specified in order that the used value during the test does not influence the actuation level and the hysteresis.

The precision of the digital oscilloscope used (generally 8 bits but 10 bits and 12 bits should be much better.

More generally as said in Chapter 6: the precision of the apparatus should be evaluated and compared to the requirements.

10.4.3 Protection of the measurement electronics

As indicated in paragraph 6.1 Method 1019.6 specifies that *Electrical test instruments. All instrumentation used for electrical measurements shall have the stability, accuracy, and resolution required for accurate measurement of the electrical parameters. Any instrumentation required to operate in a radiation environment shall be appropriately shielded.*

This statement is very important but it is too succinct. It must be detailed in particular concerning “appropriately shielded”. During TID tests the shielding of the direct radiation is generally correct but diffused radiation and reflected radiation by the walls must also be taken into account. The vulnerability of the measuring electronics must be also established in order to know the minimum level of shielding needed.

During Single Event Effects testing the risk of upset and SEFI (Single Event Functional Interrupt) must be also considered to avoid any interruption of acquisition or control.

10.4.4 Data extraction tools and In line testing

Generally an important quantity of data is expected when in-line measurements are performed. Particular tools dedicated to the extraction of useful parameters must be developed and checked before the experiments. These tools must be specified in the test procedure.
If in-line experiment is performed, the in-line extraction and following of main parameters evolution is needed in order to avoid performing a “blind experiment”. This point is fundamental to verify that the experiment is correct.

10.4.5 In-line testing reliability of the experiment

Total dose testing may last a week or more. If automatic measurement is performed, the electronic system must be robust enough to work properly without any interrupt, drift or failure.

The reliability of the devices tested must be previously checked to verify that they may resist to such a long experiment without failure or drift. This is particularly the case for actuators with a limited number of functioning cycles. Generally a screen is performed to avoid early failures but the end of life is not evaluated and can’t be compared to the irradiation tests requirements.

Automatic measurement techniques are absolutely required to avoid human errors but the procedure used must be tested in detail and verified before the experiment is performed (dry run).

10.5 INPUTS TO SENSORS

Sensors input value may influence the importance and the mechanisms of degradation or perturbation during radiation tests. It may be complex to simulate the input range of the sensors.

For accelerometers with +- 2g range, the earth gravitation field can be used to simulate continuously the domain +1g to -1g with a sufficient accuracy by modifying the angle between the g vector and the sensitive axis of the accelerometer. Such a tool should be previously tested before irradiation and if electronic circuits are used to drive this tool, they should be “properly shielded” or situated outside of the radiation field.

For accelerometers with higher range, this approach may be insufficient. Specific simulation devices must be used. Again the reliability of this apparatus must be evaluated and the apparatus must be properly shielded.

In case of impossibility to simulate the correct input, the existing input must be recorded and its stability checked by an independent tool.

10.6 IMPORTANCE OF PRE, ON-LINE AND POSTRADIATION MEASUREMENTS

Pre-irradiation:
Pre-irradiation precise characterization of devices is an important issue because the values obtained for the different parameters are reference values.
Several characterizations must be performed and in particular the sensitivity to temperature, humidity, or other environmental parameters that may affect the behaviour of the devices must be known.

On-line characterisation:
On-line characterization is often a complicated issue that needs an important development of measuring tools. On line characterization is useful when nothing is known concerning the behaviour of the devices.
This method allows a quick determination of the failure level. In line measurement allows real-time understanding of what happens to the devices. But for that purpose tools must be developed to extract in line the parameters and display the results.
On line characterization is not required for displacement damage study with neutrons.
On line characterization is useful for TID because degradation laws can be highly non linear with saturation or even inversion of the slope of degradation.

Post irradiation:
Post irradiation measurements are required when the damage is time-dependent such as TID effects. The idea is to simulate what should happen for longer times in a real environment.
A relation between temperature and acceleration factor is generally applied but this law must be established first. The high temperature of the annealing must not induce a specific degradation effect related to this temperature.
It would be good also to test the devices during this annealing test (with periodic testing at room temperature) in order to follow the post-irradiation behaviour...

11 CONCLUSION

The document is a final version related to WP 6000.1, “Radiation testing guidelines for MEMS devices”, is a delta document, contains additional comments to the existing guidelines of TN2 (WP n° 2000.3), after performing radiation tests on MEMS type 1: accelerometer and MEMS type 2 (RF MEMS).

The package of MEMS devices is an important part of the device. So removing the lid could modify the MEMS intrinsic properties and parameters.

For establishing this version of testing guidelines of MEMS, we have taken into account with already established standards dedicated to electronic devices testing.

The existing guidelines separate TID, displacement damage and single event effects.

On the other hand some MEMS standards begin to be published. They are incorporated in reference documents in this specification. Standards for testing particular systems (previously obtained with discrete devices or with other technologies) is also considered and taken into account.

This document presents some comments on the usual radiation testing guidelines and indicates topics of improvement after performing radiation tests on Industrialized MEMS (Accelerometers) and Pre-Industrialized MEMS (RF).

This MEMS radiation testing guidelines is incorporated all best of these techniques and procedures.