“MEMS Qualification: Towards an Approved European Methodology Abstract”

7th ESA Round-Table on MNT for Space Applications/6th CANEUS Workshops
International Week on Micro and Nano Technologies for Space 2010
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MEMS Qualification: A standard approach

MEMS Procurement

- What’s the manufacturer qualificaiton approach to “ready for release”? (Package/Sensor related, Reliability,...)
- Which evaluation conditions were applied by the manufacturer?
- Device details: materials, manufacturing processes,

MEMS Classification

- What the information available on the device type?
- What evaluation methods was used? What conditions were applied?
- Are there any reliability data available that can be used?

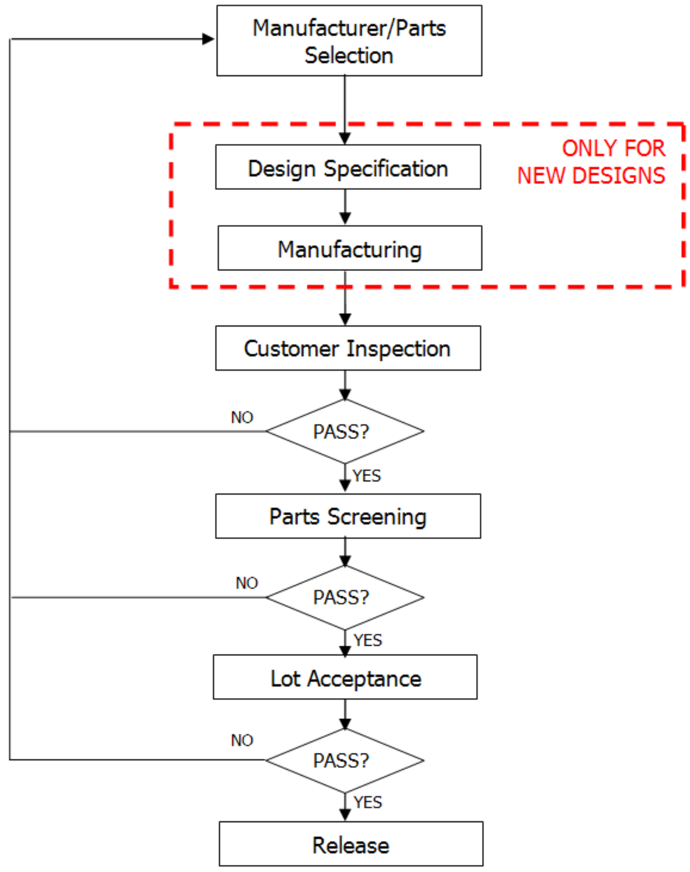
MEMS Evaluation

- Select appropriate standards according to the different requirements;
- Define testing conditions for the methods selected in the evaluation flow;

MEMS Failure Analysis

- Characterize failures and detect root cause.
- Select the appropriate analysis techniques for the failures.

MEMS Procurement - *Flow*



Procurement Plan

Item	Key Information
Payment	Overall Cost Advance Payment
Timelines	Order date Delivery date
Supplier	Main Suppliers Additional Suppliers (if any)
Hardware	Number of devices Manufacturing completion phase

Procurement Criteria:

- Production quality system and assurance level;
- Product specification;
- Product workmanship assessments:
  - Destructive Physical Analysis results;
  - Failure history;
  - Reliability trends;
  - Qualification and screening test results;
- Product availability;
- Manufacturer audit and survey results;
- Manufacturer delivery history.

MEMS Devices Classification – *Challenges*

- Propose a stable but open classification system;
- Integrated standard system with focus in Evaluation and Assessment;
- Set-up of a coherent structure;

Mammals Classification		**MEMS Classification**
Majority already known	**Number of items**	Likely to increase
Relevant throughout	**Classification Criteria**	Some criteria are more suitable to some devices that others
Well-defined system and straight forward definitions	**Definitions**	Unclear definitions
All mammals share some common features	**Similarities**	Only the scale is common to every device
Natural evolution from older species	**Heritage**	Devices created separately with different degrees of maturity. Recent technology.
Classification order based on a “natural” order	**Order**	Classification greatly depends on the approach and target field.

MEMS Devices Classification – *Challenges*

Section of Mammals Classification Matrix(1)

Order	Family Name	Common Name/ Examples	No. of Species	Distribution of Order	General Characteristics of Order
Monotremes	Ornithorhynchidae	Platypus	1	Australia	Lay eggs from which youngs are hatched.
	Tachyglossidae	Echidna	2		
Marsupialia	Didelphidae	Opossums	65	Australia, S and C America	Premature birth of young and continued development outside the womb.
	Thylacinidae	Tasmanian wolf	1		
	Dasyuridae	Native cats, marsupial mice	48		
	Myrmecobiidae	Numbat	1		
	Notoryctidae	Marsupial moles	2		
	Peramelidae	Bandicoots	22		
	Thylacomyidae	Burrowing bandicoots	20		
	Caenolestidae	rat opossums	7		
	Phalangeridae	Phalangers, cuscuses	15		
	Burramyidae	pigmy possums	6		
	Petauridae	Gliding phalangers	25		
	Macropodidae	Kangaroos, wallabies	47		
	Phascolarctidae	Koala	1		
	Vombatidae	Wombat	4		
	Tarsipedidae	Honey possum	1		
Primates	Lemuridae	Lemurs	14	Asia, Africa, S America (humans distributed worldwide)	Omnivorous, multi-purpose dentition, large brain, body position upright, five-digit hands and feet, stereoscopic vision.
	Cheirogaleidae	Dwarf lemurs, mouse lemurs	4		
	Indriidae	Indrii, sifaka, avali	4		
	Daubentoniidae	Aye aye (lemur)	1		
	Lepilmuridae	Sportive lemurs	2		
	Galagidae	Galagos	7		
	Lorisidae	Lorises, pottos, bushbabies	12		
	Tupaiidae	Tree shrews	17		
	Tarsiidae	Tarsiers	3		
	Callitrichidae	Tamarins, marmosets	15		
	Cebidae	New World monkeys	30		
	Cercopithecidae	Old World monkeys	72		
	Hylobatidae	Gibbons, siamangs	7		
	Pongidae	Great apes: gorilla, chimpanzee	10		
	Hominids	Humans	1		

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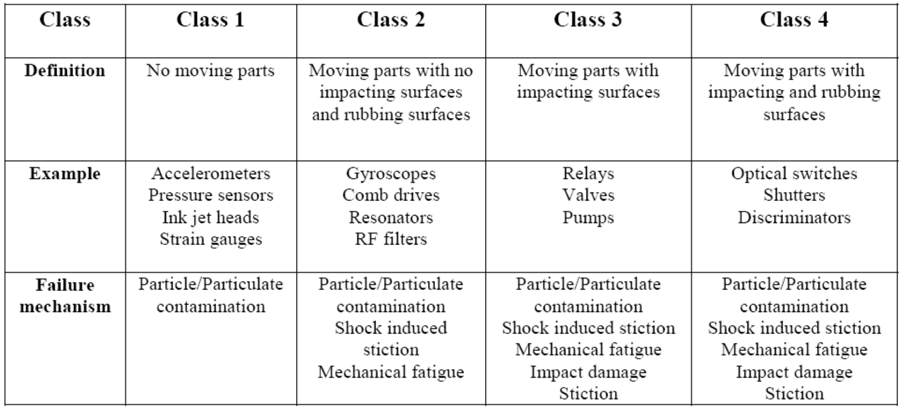
(1) http://www.factophile.com

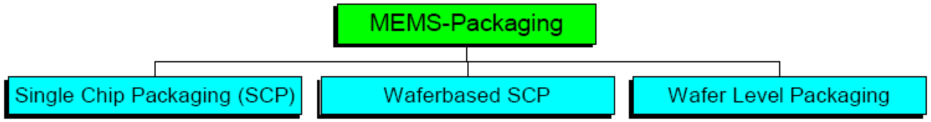
MEMS Classification Matrix – *MEMS Classification Examples*

Example 1



Class	Class 1	Class 2	Class 3	Class 4
Definition	No moving parts	Moving parts with no impacting surfaces and rubbing surfaces	Moving parts with impacting surfaces	Moving parts with impacting and rubbing surfaces
Example	Accelerometers Pressure sensors Ink jet heads Strain gauges	Gyroscopes Comb drives Resonators RF filters	Relays Valves Pumps	Optical switches Shutters Discriminators
Failure mechanism	Particle/Particulate contamination	Particle/Particulate contamination Shock induced stiction Mechanical fatigue	Particle/Particulate contamination Shock induced stiction Mechanical fatigue Impact damage Stiction	Particle/Particulate contamination Shock induced stiction Mechanical fatigue Impact damage Stiction

Example 2



MEMS-Packaging

Single Chip Packaging (SCP)

Waferbased SCP

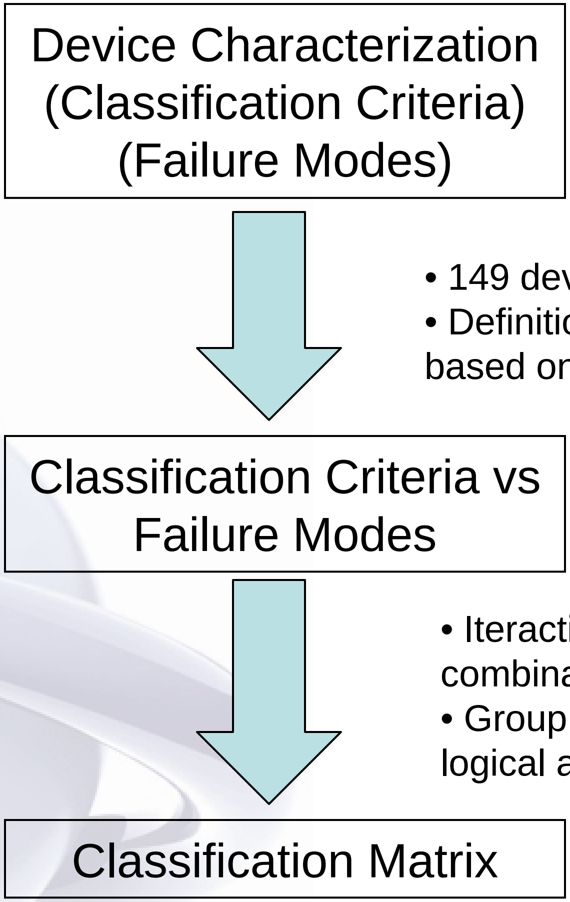
Wafer Level Packaging

Example 3

	MEMS Classification		
Groups	**RF extrinsic**	**RF intrinsic**	**RF reactive**
Details	The MEMS structure is located outside the RF circuit but actuates or controls other devices in the circuit; RF MEMS does not necessarily imply that the system is operating at RF frequencies.	The MEMS structure is located inside the RF circuit and it has the dual but decoupled roles of actuation and RF circuit function.	The MEMS structure is located inside the RF circuit where it has a RF function that is coupled to the actuation.

These examples address the needs of specific MEMS areas but fail to provide an open approach to all type of MEMS!

MEMS Classification Matrix – *Development*



Device Characterization (Classification Criteria) (Failure Modes)

- 149 devices evaluated and characterized;
- Definition of the most relevant classification criteria based on devices main features;

Classification Criteria vs Failure Modes

- Iteractive arrangements for different classification criteria combinations;
- Group validation based on number of covered devices, order and logical arrangement;

Classification Matrix

MEMS Classification Matrix – *Final Version*

Moving	Functional	Working Principle	Suspending Element	Impact Motion	Group
Yes	Optical	Electrostatic	Yes	Yes	**1**
				No	**2**
			No	Yes	**3**
				No	**4**
		Others	Yes	Yes	**5**
				No	**6**
			No	Yes	**7**
				No	**8**
	Non-Optical	Electrostatic	Yes	Yes	**9**
				No	**10**
			No	Yes	**11**
				No	**12**
		Others	Yes	Yes	**13**
				No	**14**
			No	Yes	**15**
				No	**16**

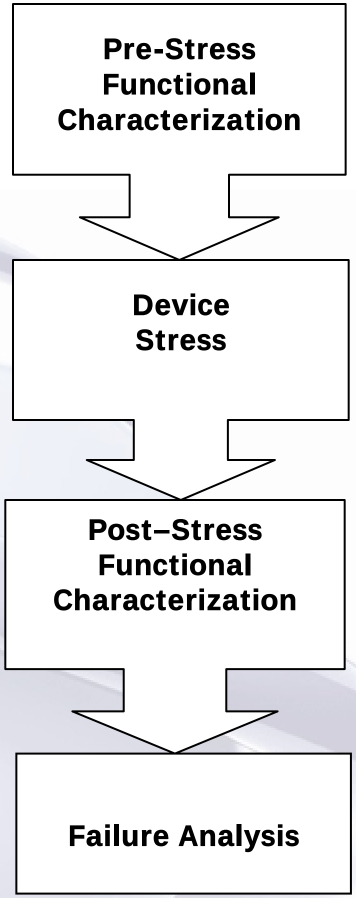
Moving	Functional	Working Principle	Suspending Element	Impact Motion	Group
No	Optical	Electrostatic	Yes	-	**17**
				-	
			No	-	**18**
				-	
		Others	Yes	-	**19**
				-	
			No	-	**20**
				-	
	Non-Optical	Electrostatic	Yes	-	**21**
				-	
			No	-	**22**
				-	
		Others	Yes	-	**23**
				-	
			No	-	**24**
				-	

MEMS Classification Matrix - *Highlights*

- ➢24 groups; 6 levels of classification (3 criteria based on the device functionality + 3 on physical features);
- ➢12 classification criteria considered
(Fabrication Method ,Working Principle (Sensing), Working Principle (Actuation) , Active Element Movement stop/ Material one side/ Material other side/Coating, Encapsulation/Internal Environment Limit, Visual Access, Moving, Impact Motion, Friction Motion, Suspended Element, Suspending Element)
- ➢ Proposed criteria and order minimizes the number of groups and maximizes the number of covered failure modes;
- ➢Open system to new devices and failure mode entries.

- ➢Limited knowledge of failure modes and information on MEMS;
- ➢ Likely failure modes can change along with technological development;
- ➢ MEMS without clear micro-mechanical features don't have a straight forward classification;
- ➢ No natural order. Compromise between grouping factor and devices with similar failure mode, i.e. devices failing into the same group share some failure modes but have others that can distinguish them;

MEMS Evaluation Flow – *Main Steps*



Pre-Stress Functional Characterization

Device Stress

Post–Stress Functional Characterization

Failure Analysis

<u>Pre Stress Functional Characterization</u>

During this phase the device undergoes a functional test which determines the acceptance or rejection of the device based on rejection criteria. Additionally, it may also provide an insight on the nature and severity of the fail.

Inputs: Device, test equipment;/ **Outputs**: Pass/Fail, Severity level;

<u>Device Stress</u>

Once the fail has been determined it may be necessary to access the device for further investigation. Thus, for those devices fully encapsulated and without any access path to the inner areas, opening is necessary. Those with are open may not require access, depending on the failure location.

Inputs: Device, Failure area / **Ou/tputs**: Access to failure area;

<u>Post Stress Functional Characterization</u>

The functional characterization of the fail device is a necessary step in order to get the likely failure location and behaviour of the device. Every relevant parameter should be measured providing insight onto the likely root cause and failure mode.

Inputs: Access to failure area/ **Outputs**: Location of the failure area, Root cause, Failure type;

<u>Failure Analysis</u>

The physical analysis phase comprises the technical methods which provide details and evidence of the details put forward during the previous phase. Inspection methods shall be used to guide the technician to the failure area.

Inputs: Address of the failure area, Root cause, Failure type/ **Outputs**: Evidence of the failure type, Failure mechanism confirmation;

MEMS Evaluation Flow – *Combined Result*

Pre-Stress Inspection

- Product Information
- Component Information
- Technical Key Features
- Main Manufacturing Processes
- Photographs (Sensor, Main Structures)
- Material List
- Assembly/Mounting Properties

- Functional Test
- Hermeticity
- Preconditioning
- ESD
- DDB
- PPIT
- PERA

Construction Analysis:
- Bond Strength Test
- Die Shear test
- Micro Sectioning
- Internal Water Vapour Content
- External VI
- Internal VI (SEM, X-Ray)

Stress Phase

Space Environmental

Thermal Vacuum
Depressurization
Out-gassing
Fine/Gross Leak

TID
Neutrons
Alpha
Protons
Flash X
Heavy Ions

Non-Space Environmental

HAST
PCT
THB

Mechanical Vibration
Mechanical Shock
Acoustic Vibration
Constant Acceleration

Extreme Condition Operation Life

HPOL/LPOL

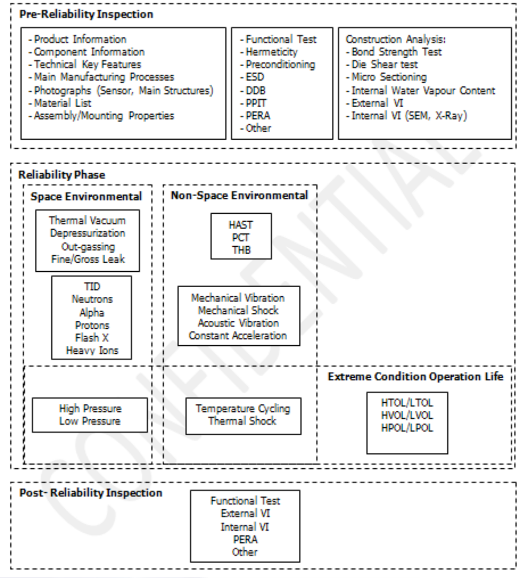
Temperature Cycling
Thermal Shock

HTOL/LTOL
HVOL/LVOL

Post-Stress Inspection

Functional Test
External VI
Internal VI
PERA
Other

MEMS Evaluation Flow – *Outputs*



Evaluation Flows

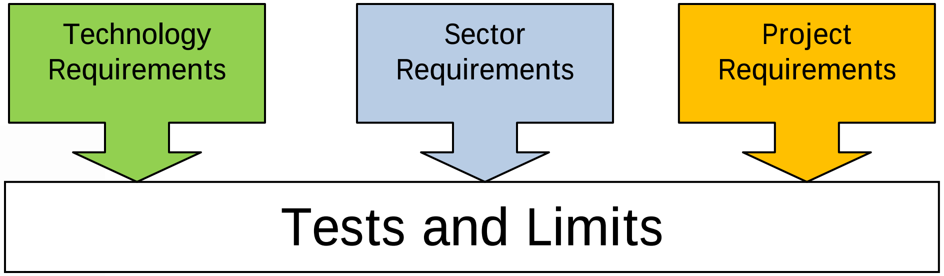
(Evaluation Flow1| EvalMethod_1| EvalMethod_2 |...|...|)
(Evaluation Flow2| EvalMethod_1| EvalMethod_3 |...|...|)
(Evaluation Flow3| EvalMethod_1| EvalMethod_4 |...|...|)
(Evaluation Flow4| EvalMethod_1| EvalMethod_4 |...|...|)
...

Standards&Conditions

(Type1| Standard_1|...|...|)
(Type2| Standard_2|...|...|)
(Type3| Standard_3|...|...|)
...

The final flow and applied standards are a derivation of a broader evaluation flow where parameters like complexity and usefullness are assessed.

11. MEMS Evaluation Flow - *Test/Test Conditions*



Technology Requirements

➢Address the stresses type required to segregate fails closely related with the device operation and design features.

➢Provide evidence about the device performance throughout its lifetime by accelerating environmental and operational parameters such as temperature, pressure or voltage.

Sector Requirements

➢ Environment needs where the device is expected to operate. Therefore, the space conditions dictate that issues such as hermeticity, thermal connectivity should be evaluated with appropriate tests and limits, e.g. out-gassing and depressurization.

Project Requirements

➢ Project special needs. Each mission has its own targeted application and although the operational environment is virtually common to every mission, specific project needs may require specific limits and tests, e.g. the shielding against radiation or the external temperature protection are simples examples may that led to additional tests with mission driven limits.

MEMS Classification Matrix and Evaluation Procedures

Moving	Functional	Working Principle	Suspending Element	Impact Motion	Group	Eval. Flow
Yes	Optical	Electrostatic	Yes	Yes	**1**	**1**
				No	**2**	**2**
			No	Yes	**3**	**3**
				No	**4**	**4**
		Others	Yes	Yes	**5**	**1**
				No	**6**	**2**
			No	Yes	**7**	**3**
				No	**8**	**4**
	Non-Optical	Electrostatic	Yes	Yes	**9**	**1**
				No	**10**	**2**
			No	Yes	**11**	**3**
				No	**12**	**4**
		Others	Yes	Yes	**13**	**1**
				No	**14**	**2**
			No	Yes	**15**	**3**
				No	**16**	**4**

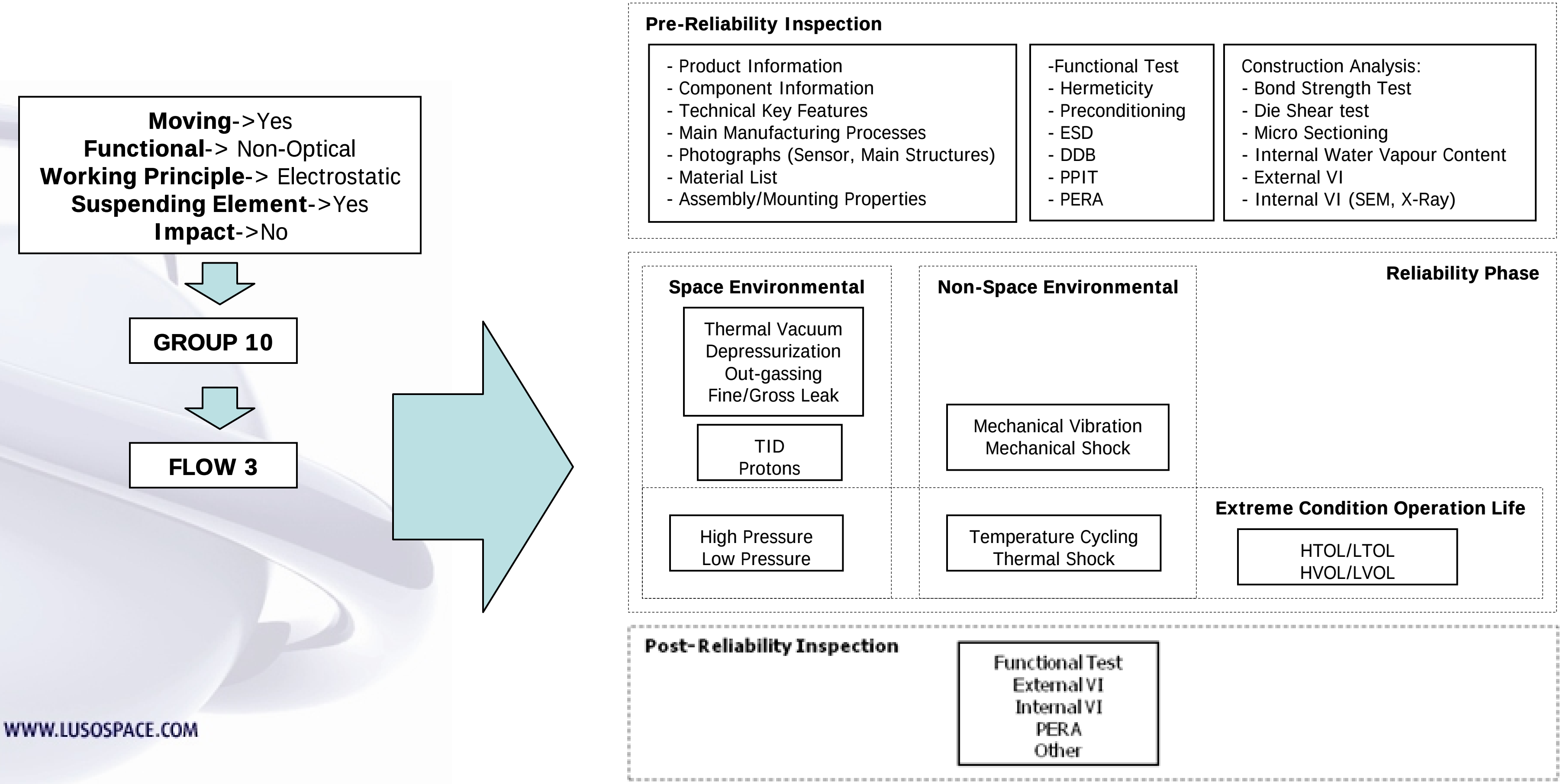
Moving	Functional	Working Principle	Suspending Element	Impact Motion	Group	Eval. Flow
No	Optical	Electrostatic	Yes	-	**17**	**4**
				-		
			No	-	**18**	**4**
				-		
		Others	Yes	-	**19**	**4**
				-		
			No	-	**20**	**4**
				-		
	Non-Optical	Electrostatic	Yes	-	**21**	**4**
				-		
			No	-	**22**	**4**
				-		
		Others	Yes	-	**23**	**4**
				-		
			No	-	**24**	**4**
				-		

MEMS Classification and Evaluation Procedures

Example (Colibrys MS9010 accelerometer)

Classification

Evaluation Flow 3



Moving->Yes
Functional-> Non-Optical
Working Principle-> Electrostatic
Suspending Element->Yes
Impact->No

GROUP 10

FLOW 3

Pre-Reliability Inspection

- Product Information
- Component Information
- Technical Key Features
- Main Manufacturing Processes
- Photographs (Sensor, Main Structures)
- Material List
- Assembly/Mounting Properties

-Functional Test
- Hermeticity
- Preconditioning
- ESD
- DDB
- PPIT
- PERA

Construction Analysis:
- Bond Strength Test
- Die Shear test
- Micro Sectioning
- Internal Water Vapour Content
- External VI
- Internal VI (SEM, X-Ray)

Reliability Phase

Space Environmental

Thermal Vacuum
Depressurization
Out-gassing
Fine/Gross Leak

TID
Protons

High Pressure
Low Pressure

Non-Space Environmental

Mechanical Vibration
Mechanical Shock

Temperature Cycling
Thermal Shock

Extreme Condition Operation Life

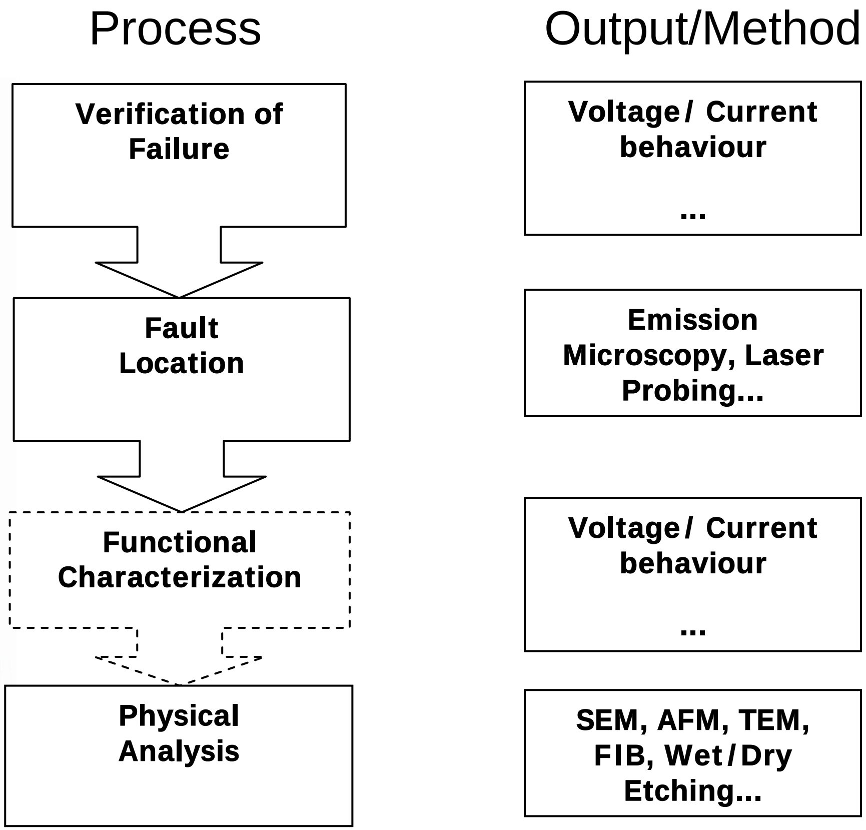
HTOL/LTOL
HVOL/LVOL

Post-Reliability Inspection

Functional Test
External VI
Internal VI
PERA
Other

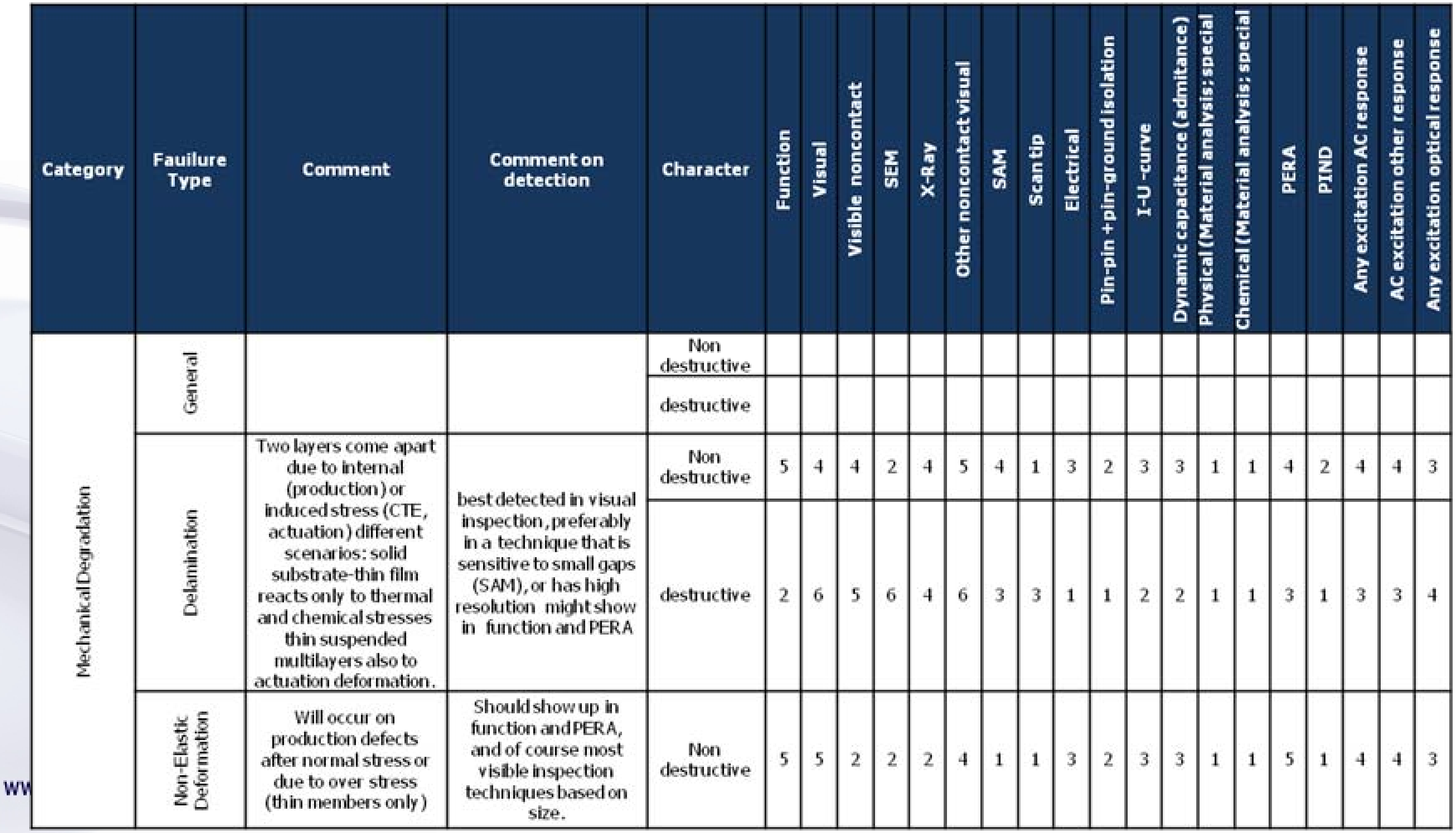
13. MEMS Failure Analysis Flow – *Methodology*

Analysis Flow



Process	Output/Method
Verification of Failure	**Voltage / Current behaviour ...**
Fault Location	**Emission Microscopy, Laser Probing...**
Functional Characterization	**Voltage / Current behaviour ...**
Physical Analysis	**SEM, AFM, TEM, FIB, Wet / Dry Etching...**

MEMS Failure Analysis Flow - *Correlating Failure and Analysis Techniques* (Section)



Category	Fauilure Type	Comment	Comment on detection	Character	Function	Visual	Visible noncontact	SEM	X-Ray	Other noncontact visual	SAM	Scan tip	Electrical	Pin-pin + pin-ground isolation	I-U -curve	Dynamic capacitance (admitance)	Physical (Material analysis; special	Chemical (Material analysis; special	PERA	PIND	Any excitation AC response	AC excitation other response	Any excitation optical response
Mechanical Degradation	General			Non destructive																			
				destructive																			
	Delamination	Two layers come apart due to internal (production) or induced stress (CTE, actuation) different scenarios: solid substrate-thin film reacts only to thermal and chemical stresses thin suspended multilayers also to actuation deformation.	best detected in visual inspection, preferably in a technique that is sensitive to small gaps (SAM), or has high resolution might show in function and PERA	Non destructive	5	4	4	2	4	5	4	1	3	2	3	3	1	1	4	2	4	4	3
				destructive	2	6	5	6	4	6	3	3	1	1	2	2	1	1	3	1	3	3	4
	Non-Elastic Deformation	Will occur on production defects after normal stress or due to over stress (thin members only)	Should show up in function and PERA, and of course most visible inspection techniques based on size.	Non destructive	5	5	2	2	2	4	1	1	3	2	3	3	1	1	5	1	4	4	3

6 – High;1- Low

MEMS Failure Analysis Flow – *Highlights*

- 23 failure types listed and analysed

(Function, Delamination, Elastic Deformation, Non Elastic Deformation, Crack, Fracture, Fatigue, Creep, Hermeticity, Rupture, Particles, Freeze, Stiction, Latch-up, Wear, Contact Damage, Conductor/ Isolator Void, Charging, Inter-Material Diffusion, Electro-Migration, Segregation, Micro Re-crystallization, Macro Re-crystallization, Corrosion)

- 19 groups of analysis techniques considered for the analysis flow, >45 techniques groups evaluated

(Function, Visual, Visible noncontact, SEM, X-Ray, Other noncontact visual, SAM, can tip, Electrical, Pin-pin +pin-ground isolation, I-U –curve, Dynamic capacitance (admittance), Physical (Material analysis; special test), Chemical (Material analysis; special test), PERA, PIND, Any excitation AC response, AC excitation other response, Any excitation optical response)

- 33 evaluation methods analysed

*(Function, Stabilization Bake, Resistance to Soldering Heat, Solderability, Preconditioning, Burn-In, Temperature Cycling, Thermal Shock, High Temperature Operation Life, Low Temperature Operation Life, Temperature Humidity Bias,
Highly Accelerated Stress Test, Pressure Cooker Test, Thermal Vacuum, Rapid Depressurization, Pin to Pin Isolation Test,
Out-gassing, Fine and Gross Leak Test (Seal), Internal Water Vapour Content, Mechanical Shock, Mechanical Vibration,
Acoustic Vibration, Constant Acceleration, Total Ionizing Dose, Neutron, Alpha, Protons Test, Flash X Test, Heavy Ions, Electrostatic Sensitivity Discharge, Dependent Dielectric Breakdown, Non Destructive Magnetic Test, Voltage Endurance Test, Residual Gas Analysis)*

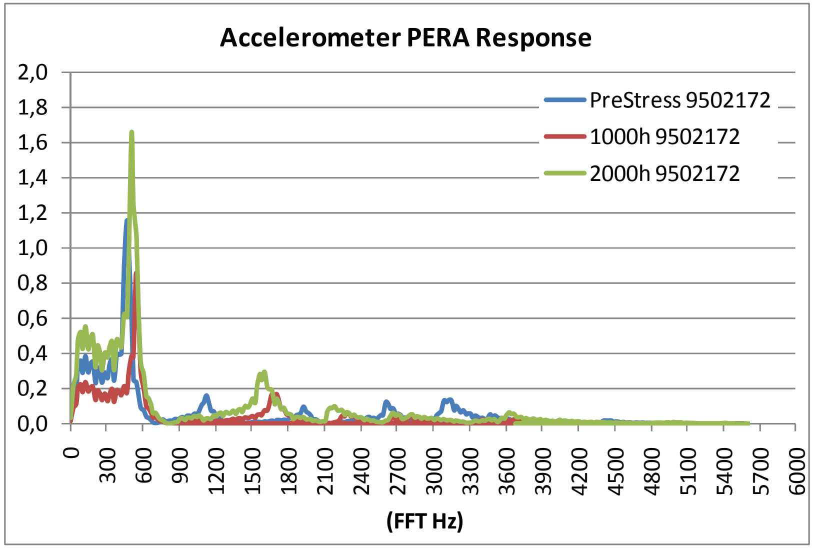
MEMS Qualification: A standard approach

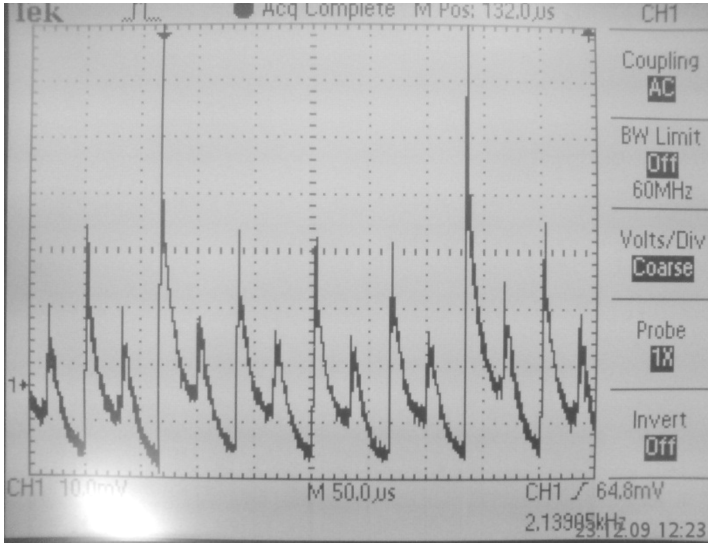
How to improve?

- *Use the a common Classification, Evaluation, Analysis platform;*
- *Be pro-active, criticize, submit comments and suggestions;*
- *Propose updates and changes, if necessary;*
- *Develop test methods in the MEMS area;*
- *Share test results, applied test limits, sample sizes...;*

Example: New test methodology (PERA – “Periodic Excitation Response Analysis”)

Accelerometer PERA results:





Results:

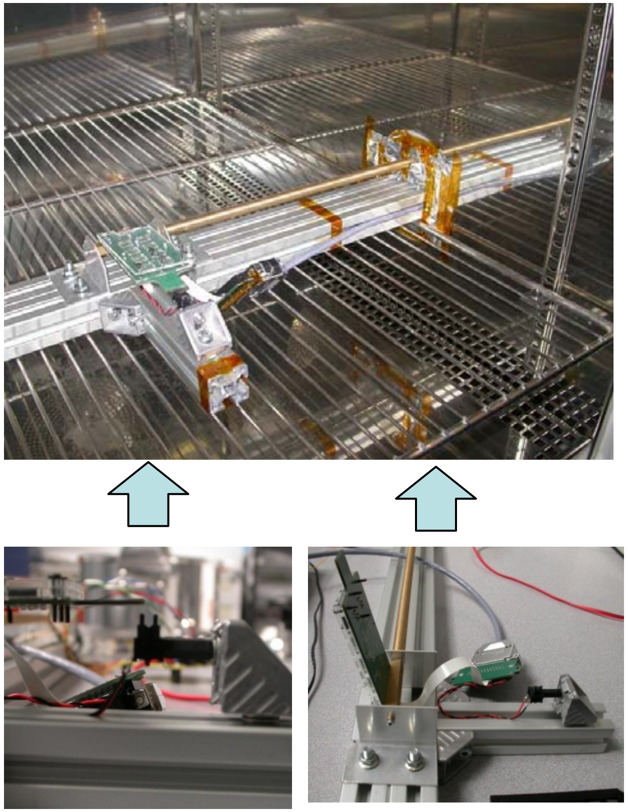
- Complex frequency response, heavily influenced by mount properties -> only coarse infromation about device health.

- No resnoance at 3.7kHz, probably supressed by electronics -> More suplier input and more analysis/test necessary

Example: Test Set-up details

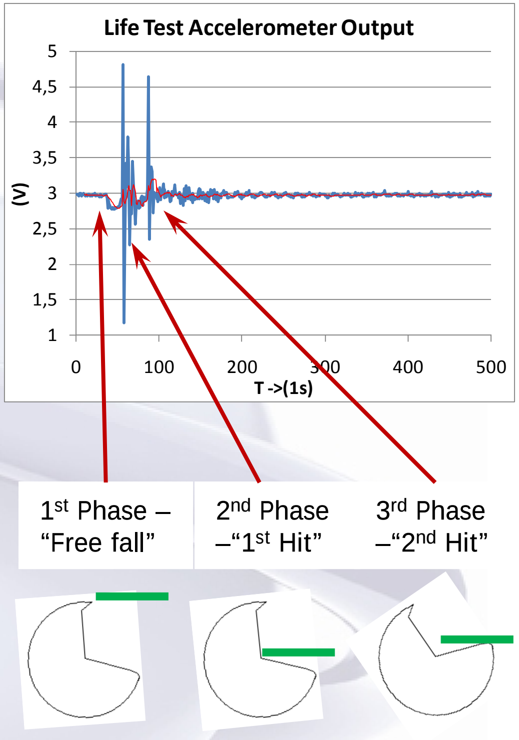
Frequency Analysis Set-up

Angle Analysis Set-up



Example:Test Set-up details

Pulse Shape



1st Phase – "Free fall"

2nd Phase –"1st Hit"

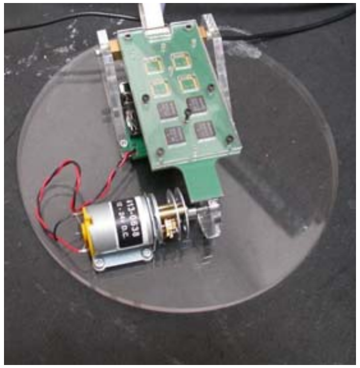
3rd Phase –"2nd Hit"

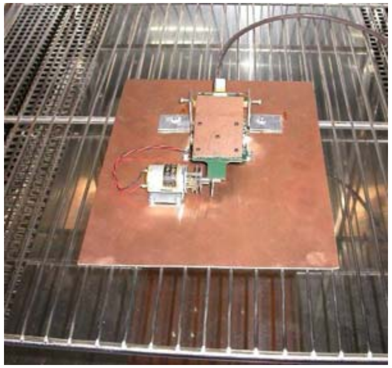
Operational Life Test Set-up

HVOL
LVOL
LTOL

HTOL

HPOL
LPOL





Example: Test Plan and Test Limits

Test	Standard Name	Parameters/Conditions
Total Ionizing Dose	ESCC 22900	Co-60,: 82rad/min, TID: 30kRad (Si)
Preconditioning*	JESD22-A113; JEDEC J-STD-020	24h Bake, 125ºC, 3x IR reflow
Temperature Cycling	MIL-STD-883E Method 1010	500cycles -55<T(ºC) <+125
Thermal Shock	MIL-STD-883E Method 1011.9	-55<T(ºC) <+125 100cycles
Thermal Vacuum	ECSS-E-10-03A Parag 5.1.15 ESA PSS-01-702	10cycl,-55ºC<T(ºC) <+80ºC , 10^-8<P(bar) <1
Depressurization		100KPa (1 Bar) to 5KPa (5x10-2 Bar) at a rate of 3.2 KPa/sec (3.2x10-2 bar/sec)
Pin to Pin Isolation Test*	MIL-STD-883, Method 1003	Cond_A: 10 volts ±10%
Out-gassing	ECSS-Q-ST-70-02C	125ºC, 24h, 10^-3Pa
Fine and Gross Leak Testing (Seal)*	Mil- Std-883E Method 1014.9	Cond_A:5x10^-8 atm.cm^3/sec
Mechanical Shock	MIL-STD 883E Method 2002	5400g
Mechanical Vibration	MIL-STD 883 Method 2007 Mil-Std-883 Method 2005	10g, FFR
Internal Water Vapour Content	MIL-STD 883 Method 1018.2	
Electrostatic Sensitivity Discharge*	MIL-STD-883 Method 3015 (HBM)	HBM (~2000V)
Time Dependent Dielectric Breakdown*	IEC 62374	-
High Temp Operational Life	Mil Std 883, Method 1005	1000h, T=120ºC
Low Temp Operational Life	Mil Std 883, Method 1005	1000h,T=-50ºC
High Voltage Operational Life	-	1000h, V=5.5V
Low Voltage Operational Life	-	1000h, V=2.5V
High Pressure Operational Life	-	1000h, P=2atm
Low Pressure Operational Life	-	1000h, P~10^-3atm

Conclusions

- The presented classification matrix is driven by the need to have a standard approach in the MEMS space sector;
- The proposed procedures form an open classification, evaluation and analysis system;
- As an pure theoretical methodology it requires experimental support to validate flows and parameters;
    - Information about testing parameters are vital to reach meaningful values on test levels/limits;
- The presented results should be discussed and criticized in the current MNT space strategy set out by ESA.

...information collected from the ESA sponsored project **“ Procedures for MEMS Qualification”**

Project Consortium:

Lusosapce

(Rodrigues, Bruno)

(Fettig, Rainer)

EADS Astrium

(Oudea, Coumar)

Thales Alenia Space

(Vendier, Olivier)

Alter Tecnologica

(Gutierrez, Francisco)

BACK- UP

Periodic Excitation Response Analysis

Common techniques coupling to (the mass) of electrons, molecules and lattices by means of electro(magnitic) forces.

- IR-Spectroscopy
- Admittance test (I(V,f) for network analysis
- Admittance test (I(V,f) for analysis of composit materials

Common techniques coupling to mass of bulk materials:

- Ultrasound analysis techniques

13. MEMS Failure Analysis: PERA

In MEMS there are several emerging techniques coupling to the mass of elastically suspended Members

•Tip excitaton at wafer level and laser readout (Laser Vibrometer) (mech in, opt out)
•Generallized Admittance Test (electric in, electric out)

Because of the nature of the resonances various methods of excitation and readout are possible depending on access levels:

•Force input: Electrical, mechanical (tip, shaker, acoustic, gas pressure), magnetic, thermal..
•Response output: electrical, optical, mechanical, ...

13. MEMS Failure Analysis: PERA

Advantages:

- Nondestructive
- Several access options
- Potentially simple
- many results (Amplitudes, resonances, damping, stops...)

Dissadvantages:

- Limited heritage
- Complex results

13. MEMS Failure Analysis: PERA

Accelerometers are perfect candidates for PERA:

- Built in frequency response readout
- Simple mechanical structure

Accelerometer PERA test condition:

Mechanical excitation on shaker
Read out of Signal through readout electronics