Quantitative Accelerated Life Testing of MEMS

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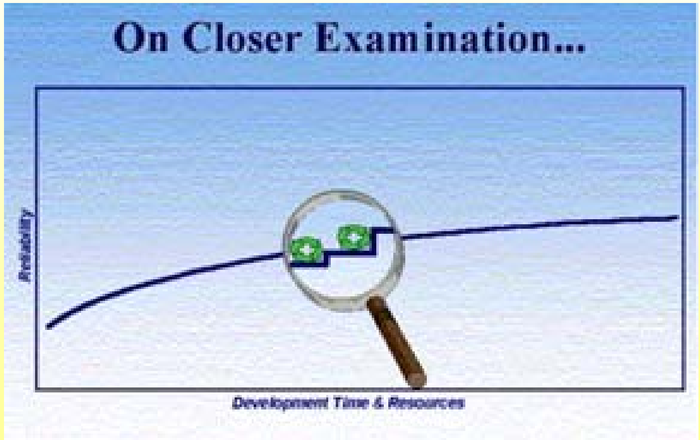

On Closer Examination...
Reliability
Development Time & Resources

1. Quantitative Life Testing

Quantitative / Qualitative Life Testing

- **Quantitative Life Testing**: Reliability tests for calculating reliability parameters (failure rate, MTBF, etc.):
  - Large samples – in order to have enough data (failures) from the tests;
  - The operational conditions must be carefully simulated (the same stress factors and stress levels, etc.).

- **Qualitative Life Testing** :
  - Reliability tests for identifying design weaknesses (Accelerated Stress Testing) or for studying the behaviour of a product in various operational conditions;
  - Large variety of stress (also other than the operational ones) and stress levels;
  - Attempt to find out the limits of the product.

1. Quantitative Life Testing

Laboratory / Operational Reliability

- **Operational reliability**: Field data (cheap, many errors, various failure criteria, various applications) – ***low accuracy***

- **Laboratory reliability**: Field conditions are simulated by life testing at various stress levels – ***good accuracy***
  - *Simulating the application(s),*
  - *Significant electrical parameters for reliability characterisation,*
  - *Failure criteria (depending on application)*
  - *Long tests (> 1 year) for accurate results*
  - *Need to obtain the results more quickly!*

1. Quantitative Life Testing

Laboratory Reliability
Quantitative Life Testing

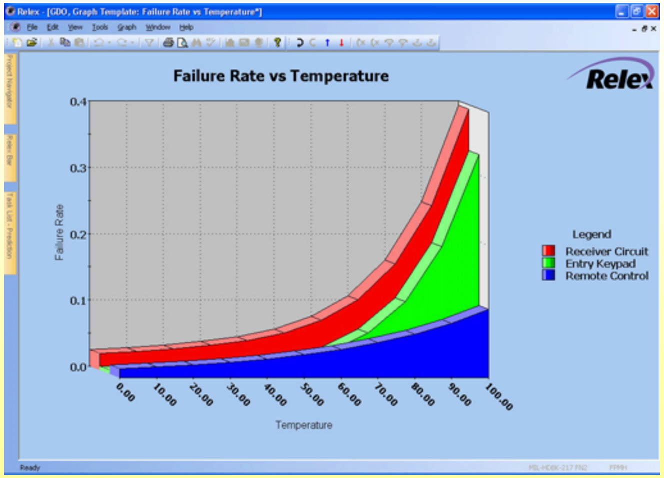
Reliability analysis

- **Laboratory tests** (normal / accelerated)
Normal: big samples (e.g. 200), 5000 hours (one year)

- **Failure analysis**

- **Statistical processing of data**

- **Corrective actions**



1. Quantitative Life Testing

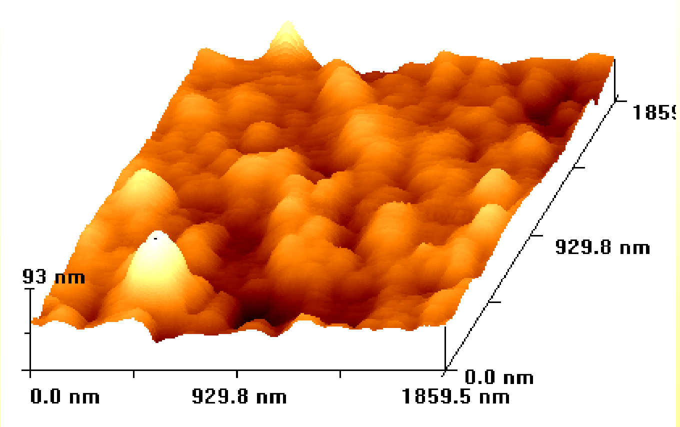
Reliability analysis

Failure analysis

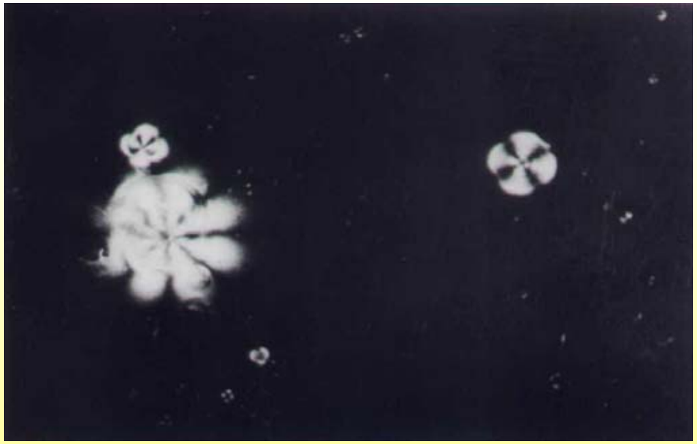
- Defect / Failure, Failure mode / Failure mechanism (FM)

- Identifying FM and separating the statistical populations damaged by each FM

- Methods for failure analyses: electrical, pyhsical, chemical, spectroscopical, etc.



AFM analysis. The surface of Cr layer



Oxide analysis with nematic liquid crystals. Pinholes in oxide layer

Reliability analysis

Statistical processing of data

If there are failures:

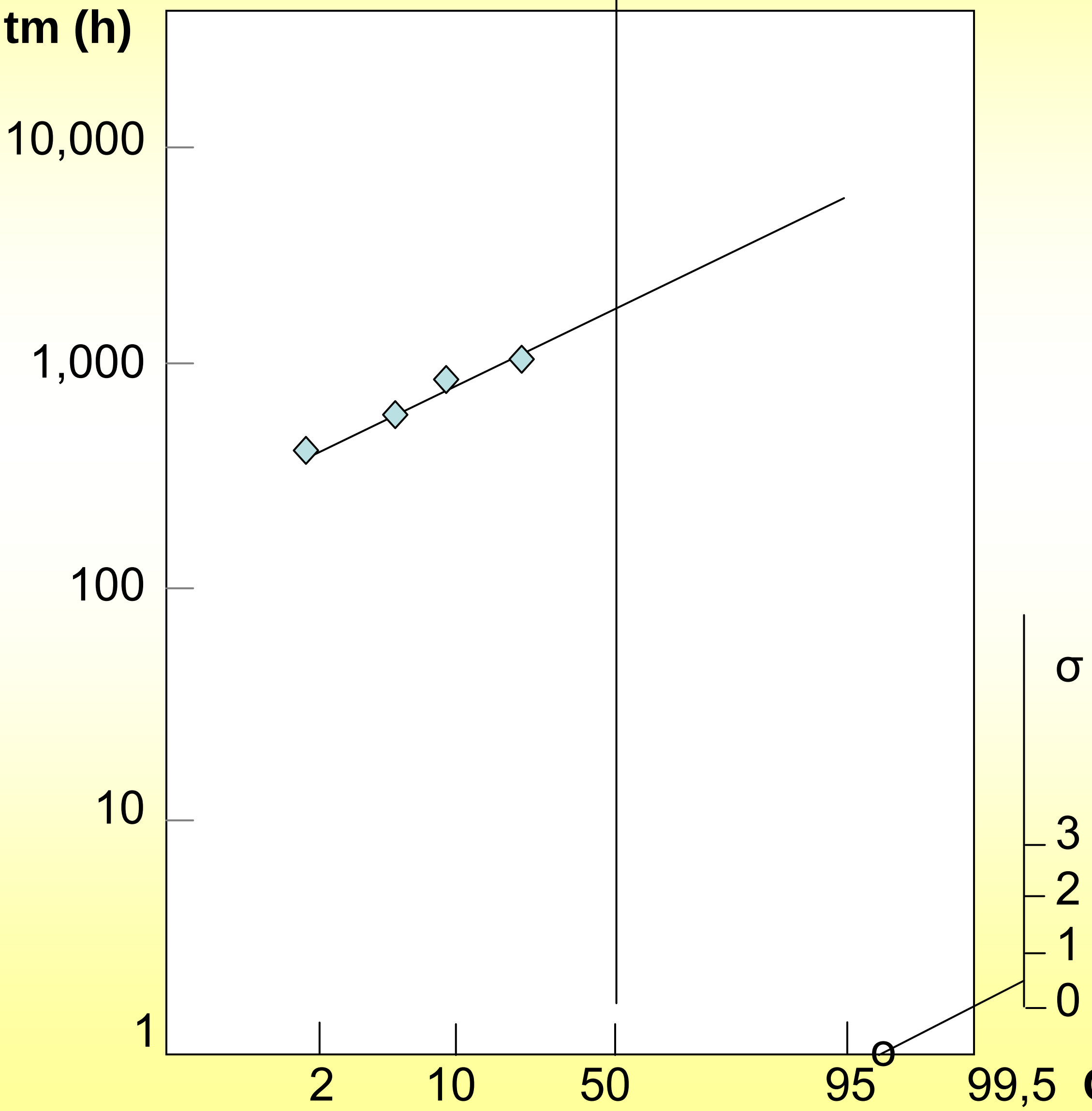
- Separate processing for each failure mechanism
- Distribution laws: exponential, Weibull, lognormal, etc. **which allow extrapolation**
- Estimation methos (grafical, analitical – MLE, etc.), concordance tests (K-S, etc.)
- Characteristic parameters: failure rate, MTBF

No failures:

- Drift of the electrical parameters
- Normal law (Gauss) – estimation methods, concordance tests
- One may predict the failure moment (if the electrical parameters are the significant ones)

1. Quantitative Life Testing

Lognormal Distribution



100 devices in Life Test

tm (h)	400	600	900	1000
F-M1	2	4	4	30
CF-M1	2	6	10	40
%-M1	2%	6%	10%	40%

RESULT: tm = 1,800h, σ = 0.4

1. Quantitative Life Testing

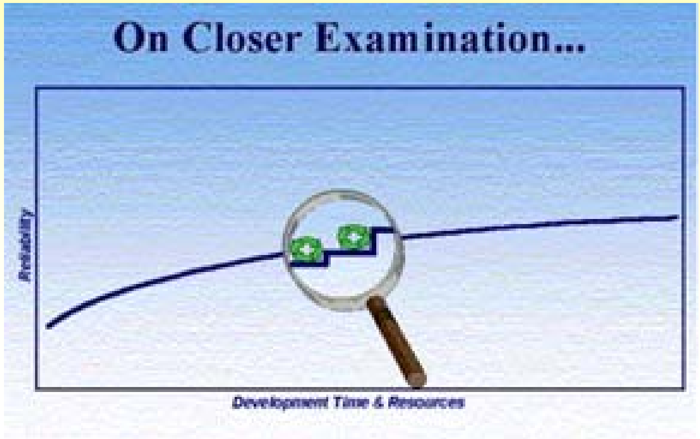
Reliability analysis

Corrective actions

Changes in manufacturing and control technology:

- procedures,
- parameters,
- control and / or monitoring points

- **By "Building-in reliability" and "Concurrent engineering", the focus is shifted from "correction", to "prevention".**



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1. Quantitative Life Testing
2. Accelerated Testing in Reliability
3. Accelerated Life Testing of MEMS
4. Case study and conclusions

2. Accelerated Testing in Reliability

- Why Accelerated Life Testing? For shortening the duration of the reliability testing.

- Accelerated test: an aging deterioration of an item to induce normal failures by operating at stress levels much higher than would be expected in normal use.

- Effect: The testing time is compressed and fruitful results are obtained much more quickly than in normal tests (at operational conditions)

- Purpose:
    - To identify design weaknesses (Accelerated Stress Testing – AST)
    - To quantify reliability parameters (Accelerated Life Testing – ALT)

- Accelerating factors: more frequent power cycling, higher vibration levels, high humidity, more severe temperature cycling, higher temperatures

2. Accelerated Testing in Reliability

	Product Development Tests (PDT)	**Qualification Tests (QT)**	**Accelerated Life Tests (ALT)**
Objective	Technical information	Proof that the product is qualified to serve in the given capacity	To quantify the reliability parameters
End point	Type (nature), time, level, number of failures, stress and strain at failure, etc.	Predetermined time (or number of cycles), number of failures for the specified test and pass/ fail conditions	Time / stress variation of the reliability parameters (failure rate, MTBF)
Follow up activity	Failure analysis, material selection and/or design decision	Pass/fail decision, decision of conducting ALTs and/or additional PDTs	Physics and statistics of failure analysis, revisiting material selection and/or design decision, prediction of the probability of failure
Ideal test	Depends on test objective	No failure in a long time	Numerous failure in a short time

2. Accelerated Testing in Reliability

Laboratory Reliability
Quantitative Accelerated Life Testing

Reliability analysis

- **Laboratory tests** (normal / accelerated):
  - **normal**: one big sample (e.g. 200), 5000 hours (1 year)
  - **accelerated**: many small samples (20-50 items), shorter times (3-4 days… 1 month)
- **Failure analysis**
- **Statistical processing of data** (Arrhenius law, others)
- **Corrective actions**

Reliability analysis

Laboratory tests (Accelerated Life Testing - ALT):

- **Constant-stress tests** – (most accurate):
  - 4 samples of 50 items, 1000 hours , 4 stress levels, bias + temperature
- **Step-stress tests** – (less accurate):
  - 4 samples of 25 items, 4 steps, 1…180 h at each step, bias + temperature
- **"Fingerprint test"** – (indicative only):
  - 1 sample of 25…50 items, 10 steps,
  - 4 hours at each step,
  - bias + temperature

Reliability analysis

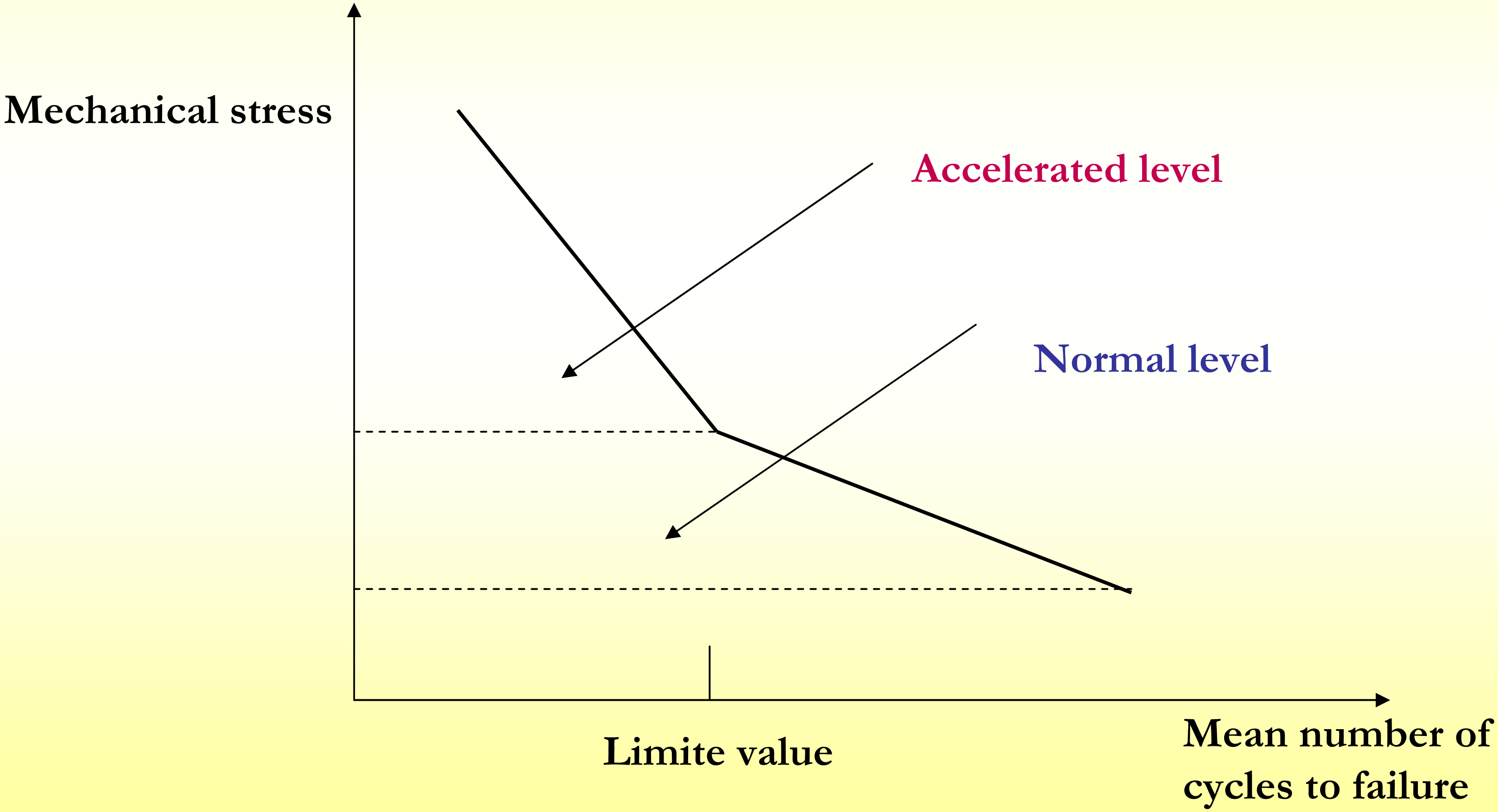
Failure analysis

- The failure modes / mechanisms at high stress must be **the same as at normal stress**!
- ALT is useful only if, under the accelerated conditions, the item passes through ALL the same states, in the approximately SAME order, as may expected in normal use, but in a much SHORTER period of time.

Failure analysis is essential for ALT:

- An understanding of the anticipated failure mode(s) / mechanism(s)
- A knowledge of the magnitutde of the acceleration of each failure mechanism, as a function of the accelerating stress (ALT models)

Necesarry caution at the acceleration of tests



2. Accelerated Testing in Reliability

Failure analysis is used in….

Accelerated Life Testing – ALT	→	To quantify reliability parameters (failure rate, MTTF)
Extrapolation	→	Accelerating law (different for each failure mechanism)
Distribution law for each failure mechanism	→	To identify the failure mechanism for each failed device
Accelerated aging tests (screening the reliable devices)	→	Different acceleration of aging for different failure mechanism
Designing the optimum screening test mechanism	→	To know the acceleration factors and statistics for all failures

2. Accelerated Testing in Reliability

Reliability analysis

Statistical processing of data

- Separate processing for each failure mechanism
- Distribution laws: exponential, Weibull, lognormal, etc.

- Models for accelerated life:

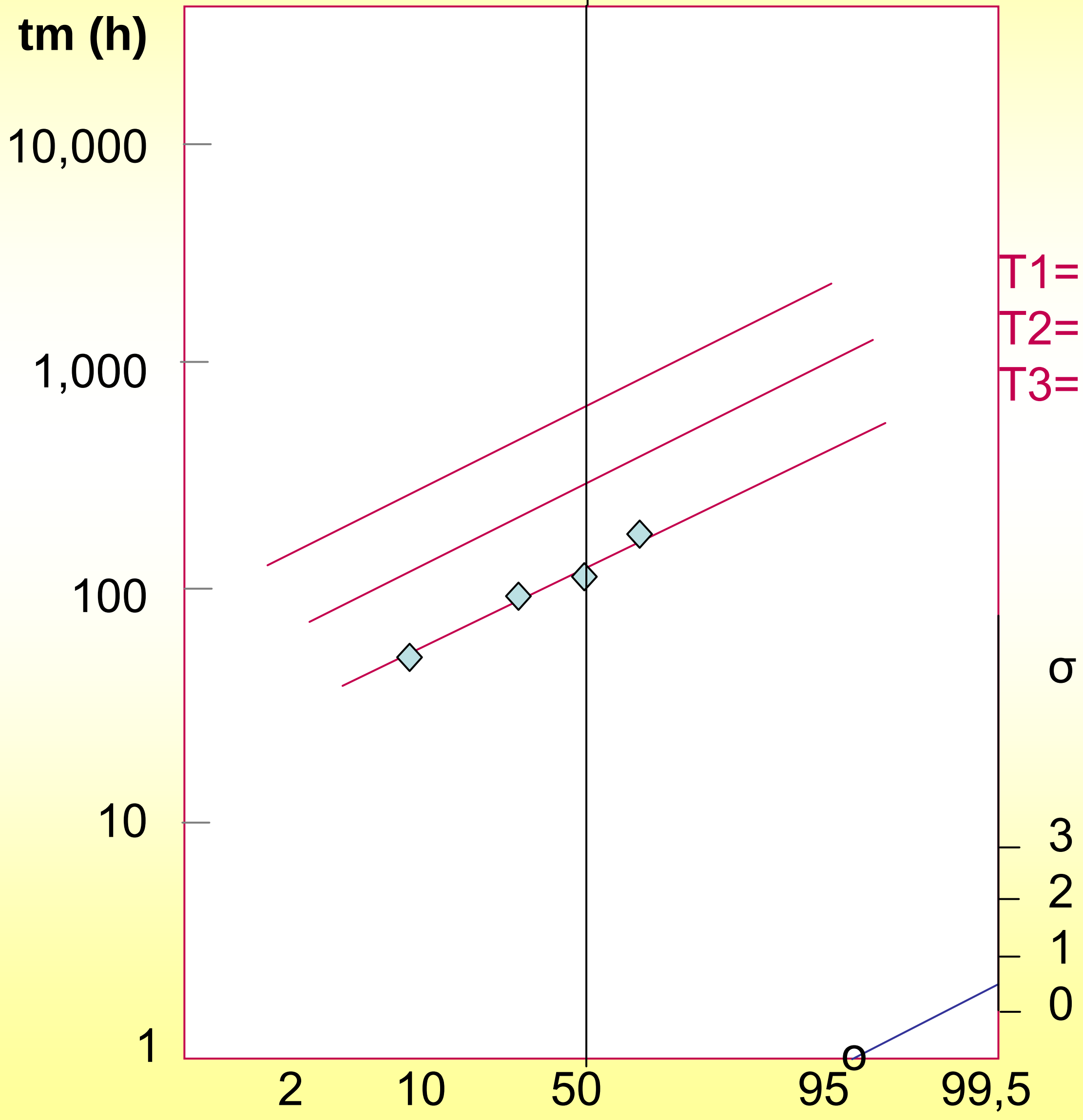
  - **Inverse Power Law:**

Life (normal) / Life (acc) = (Acc stress / Normal stress)^n

  - **Arrhenius Acceleration Model:**

Life = A exp (Ea / kT)

2. Accelerated Testing in Reliability



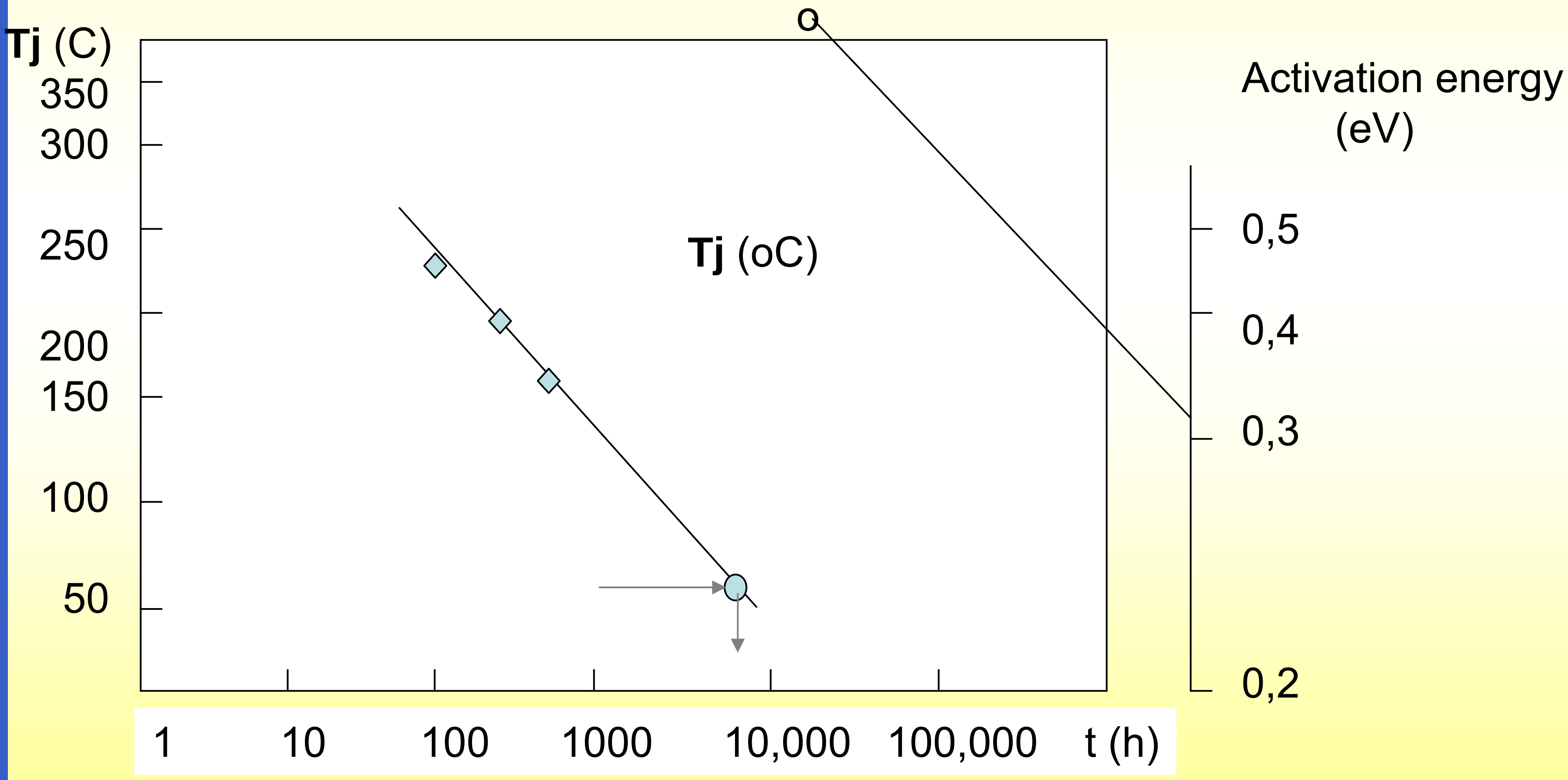
Lognormal distribution

For each FM

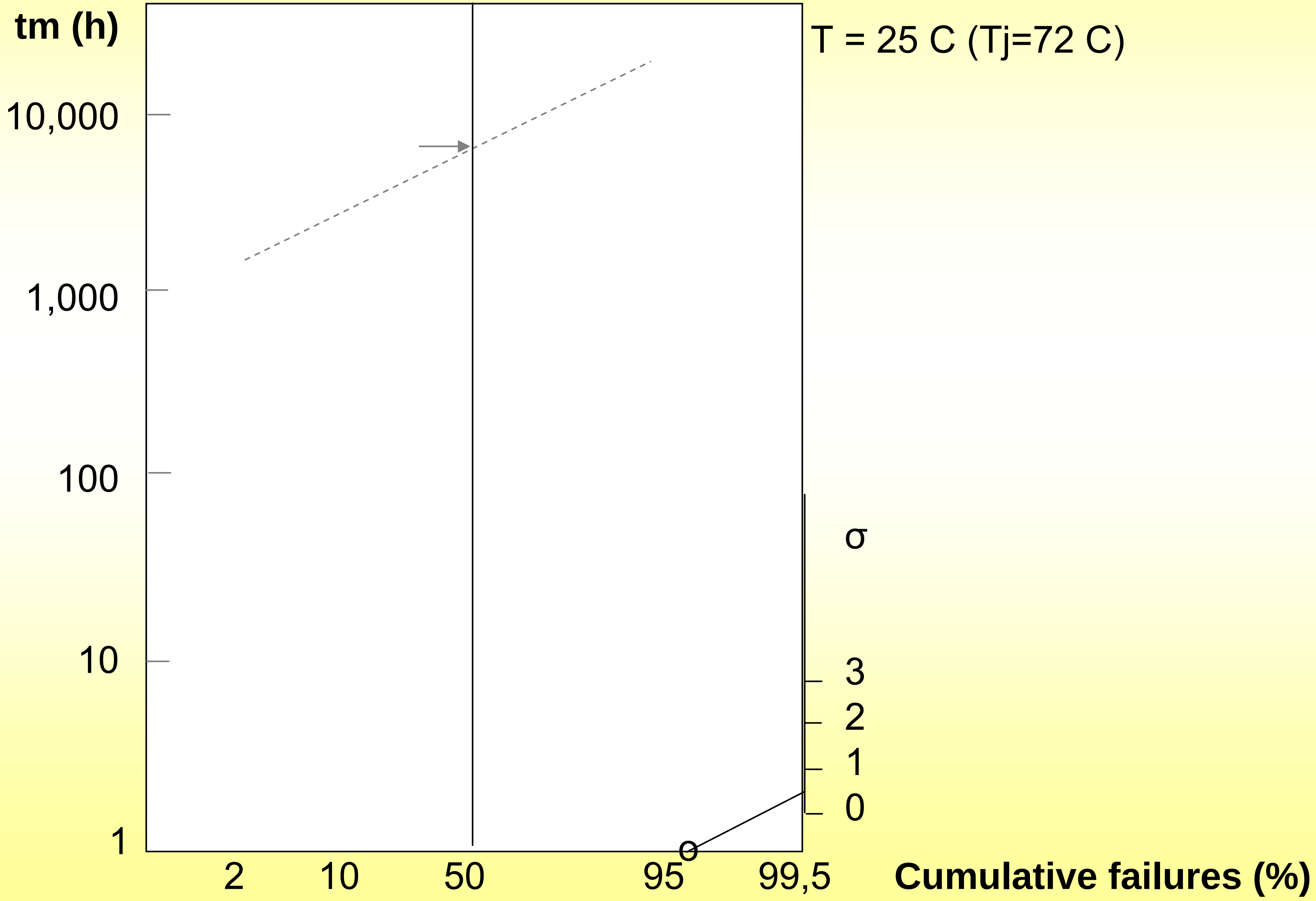
tm = 600h (T1)
tm = 200h (T2)
tm = 100h (T3)

2. Accelerated Testing in Reliability

Arrhenius law for accelerating with T and S



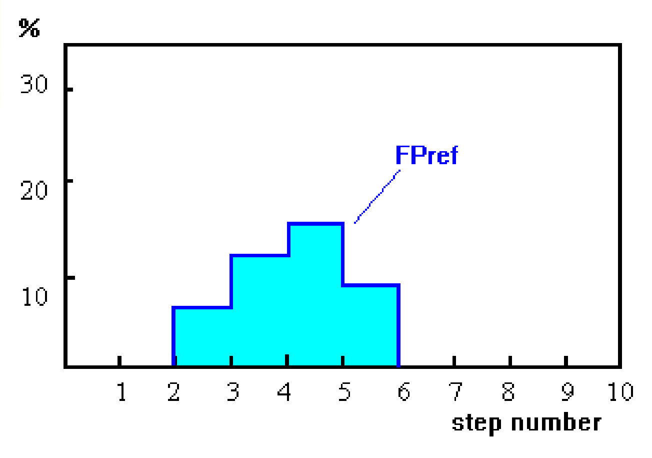
2. Accelerated Testing in Reliability

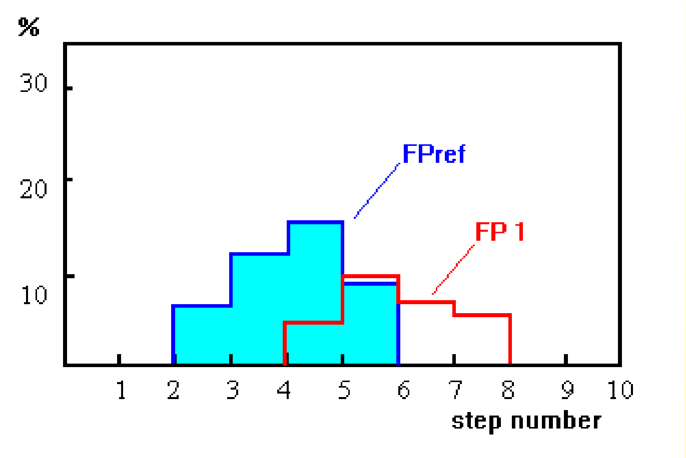


2. Accelerated Testing in Reliability

"Fingerprint" test:

- 1 sample (25…50 items)
- 10 steps (bias + temperature)
- The failures at each stress step are identified
- % at each step vs. step number = batch "fingerprint" (FP)
- Initially, FP for a reference batch (FPref), where λ (t), calculated by using constant-stress tests, is lower than a limiting value after a given time period.
- Then, for any subsequent batches, only FP is used, with a short and cheap test (FP1 in figure).
- By comparing FP1 with FPref, one may say if λ of this batch is below the limit.





Accelerated Life Testing – When?

Position of the reliability engineer	**Product reliability**	**A priori known information**	**Comments**
Member of the development team	Low reliability, many failures	Lot history	Quantitative tests, coupled with qualitative ones
Member of the manufacturing team	Good reliability, some failures	Lot history, typical failure mechanisms, week points, etc.	Qualitative tests (quantitative tests executed periodically)
Providing a service for a product user	High reliability, no failures	?	Quantitative testing is a difficult task!

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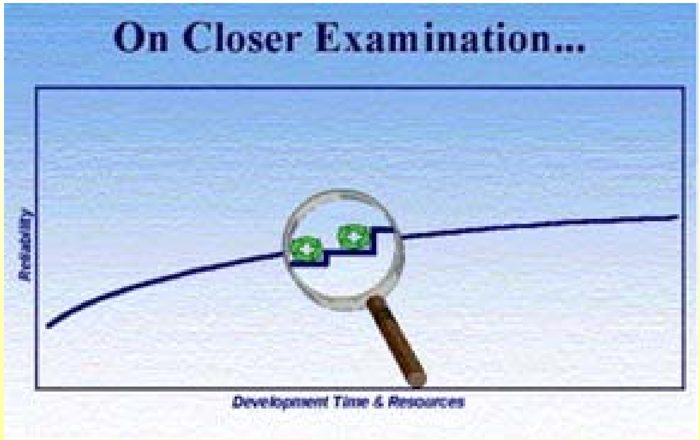


CHARACTERISTICS OF ELECTRONICS-ONLY DEVICES VS. MEMS - 1

Electronics-only devices	MEMS
Design methodology focused on fast manufacturing cycles (accelerated testing).	New devices, without a history allowing to design accelerated testing
Optimized standard processes, high yields.	The processes are not standardized.
The third dimension of the structures may be ignored.	The third dimension (the depth) of the structure cannot be ignored.

CHARACTERISTICS OF ELECTRONICS-ONLY DEVICES VS. MEMS - 2

Electronics-only devices	MEMS
Designers rarely know details about the manufacturing processes.	Designers must know details about the manufacturing processes (electronic / mechanical devices).
Package should separate the chip from the environment. Standardized cases.	Package should form a cheap but reliable interface between the active device and an often harsh, demanding environment.
Reliability problems are well-known.	New failure mechanisms (small distances between various functional elements, new phenomena).

Accelerated Life Testing of MEMS

Failure modes of MEMS:

- **Early life failures (**process / yield related issues, unpredicted, difficult to manage and can consume many resources to solve; Examples: particle contamination, surface contamination stemming from electrochemistry, outgassing, wafer-to-wafer hermeticity failures originating from microcracks, delamination, electrostatic discharge etc.)
- **Intrinsic failures** (wear, creep, deformation, dielectrics charging, thin film formation, electromigration, oxidation and corrosion, long-term outgassing, etc.)

Failure modes of MEMS:

Top five failure modes (production) by device type

Actuators	Sensors	Integrated systems	Passive Elements
Stiction	Electric short / open	Temperature	Contamination
Wear	Leakage	Contamination	Package stress
Electric short / open	Package stress	Clogging	Electric short / open
Package stress	Contamination	Package stress	Crack propagation
Contamination	Crack propagation	Leakage	Deformation

Failure modes of MEMS:

Ability to accelerate

Most able to accelerate

- Electrical short/open
  - Temperature
    - Wear
      - Crack propagation
        - Package stress
          - Leakage
            - Creep
              - Outgassing
                - Passivation
                  - Stiction
                    - Delamination
                      - Charge accumulation
                        - Deformation
                          - Contamination
                            - Micro weld
                              - Surface modification
                                - Clogging

Least able to accelerate

Field experience on failure modes of MEMS:

- Texas Instruments: a 40 persons team (including 2 reliability engineers) developed a technique for predicting stiction through accelerated tests for DMD (Digital Micromirror Device)
- Sandia: derived a wear formula for a microengine where frequency and normal force were the accelerating factors, by operating a large number of parts for long period of time to better understand the wear as a mechanism of failure.
- A small biomedical company: uses FMEA to rank failure modes; focused on customer satisfaction; no accelerated tests, because there are no available models for connecting data on tests with product lifetime.

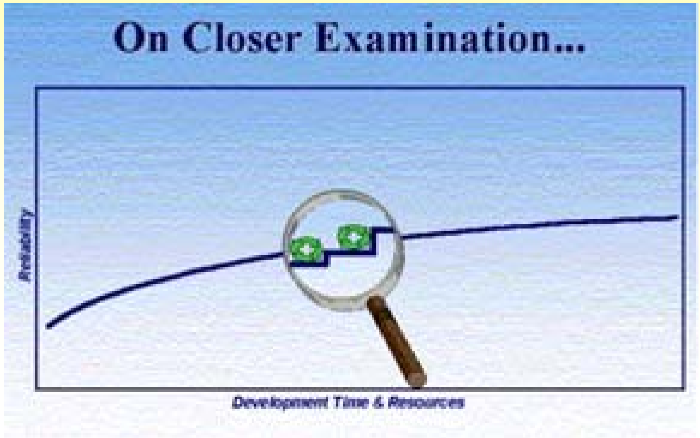
Teaching from microelectronics…

- MEMS industry must learn from Microelectronics industry, which offers a strong baseline of tools and controls development.
- Reliability problems are dramatically increased at MEMS, because:

  - the package must ensure not only the protection of the device, but also the connection with the environment;

  - to the well-known microelectronics issues , problems from mechanics, biology, chemistry, etc. are added;

  - MEMS industry is a young one, and information about techniques and processes are not yet available at large scale. Each company tries to obtain a breakthrough in the field…
- In MEMS industry, the reliability problems are basically the same as in Microelectronics (accelerated testing, failure modes, process reliability, etc.), only the particular solutions are (maybe) different
- The only way to build accelerated testing for MEMS is to follow the procedure used in Microelectronics (e.g Patent-DfMM project RELMETH)



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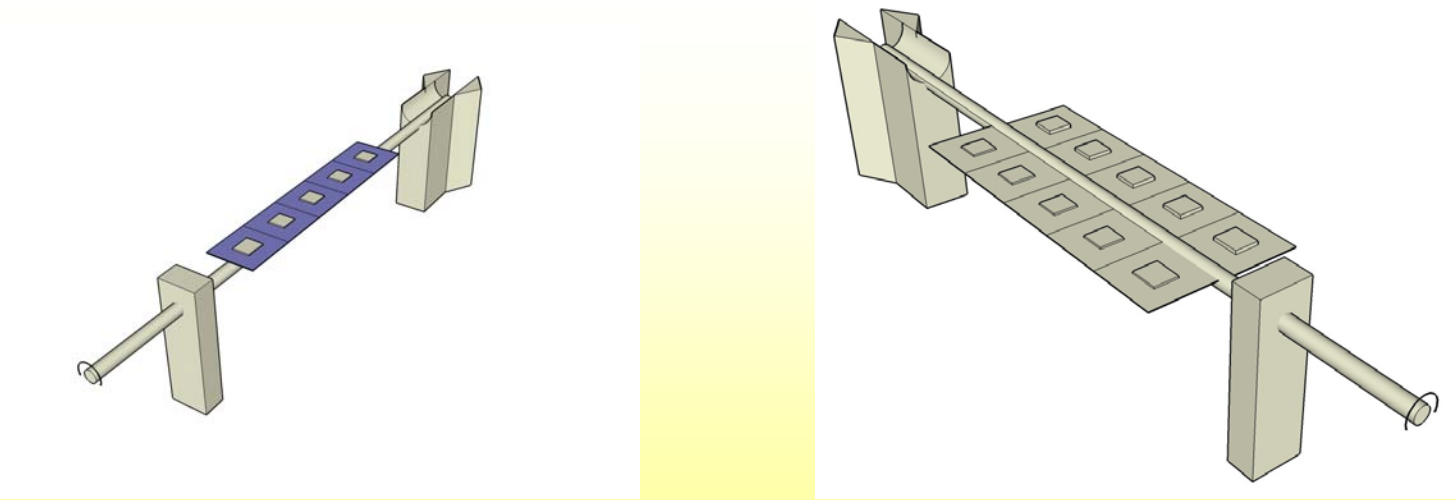
4. Case study and conclusions

- Quantitative Accelerated Life Testing of MEMS inertial sensor: 3-Axis - ±2g/±6g linear accelerometers LIS3L02AS4
- For obtaining a more significant acceleration, we used combined stresses (mechanical + thermal), in two variants:
- \- Vibration + temperature;
- \- Tilting + temperature (a new approach!).



Tilting variants: the axial type (left) and the wing type (right)

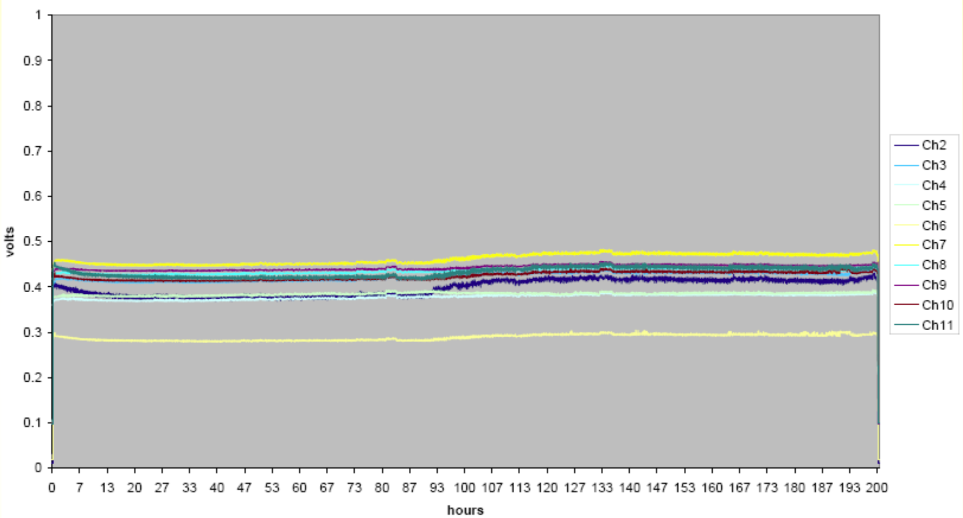
4. Case study and conclusions

Test plan

Sample (no. of items)	Ambient Temp.	Mechanical / Electrical Stress	Duration
S1 (9)	85°C	Frequency: 1500 Hz, Amplitude: 6 g	200 h
S2 (9)	145°C	Frequency: 1500 Hz, Amplitude: 6 g	200 h
S3 (6)	25°C	Tilting (wing) / Bias	1000 h
S4 (6)	100°C	Tilting (axial) / Bias	1000 h
S5 (6)	125°C	Tilting (axial) / Bias	1000 h

4. Case study and conclusions

- Measurements performed in situ, at the ambient temperature of the test
- **No failures – Good reliability!**



- *Vibration + 145°C: very small performance degradation, after 100 hours of testing*

- "Worst case" approach: one failure arising immediately after the last moment of the test
- This approach is applied for the test at the higher stress level.
- One failure after 201 hours of testing at vibration and 145°C.
- Possible failure mechanism: fatigue of the moving part
- Activation energy (Arrhenius law): 1.0 eV.
- **"The worst case" level** of the failure rate for operation at 25°C : **$6.10^{-8}h^{-1}$**

4. Case study and CONCLUSIONS

- The accelerate reliability testing is a "hot subject" for MEMS.

- Accelerated Life Testing is needed for both MEMS manufacturers and MEMS users.

- The main problems to be solved are:
  - A specific testing system,
  - Failure physics (specific analysing methods),
  - Statistical processing of data (use of "classical" distributions: lognormal, Weibull, etc.).

- Previous expertise in microelectronics is useful in developing a system for accelerated life testing in MEMS.