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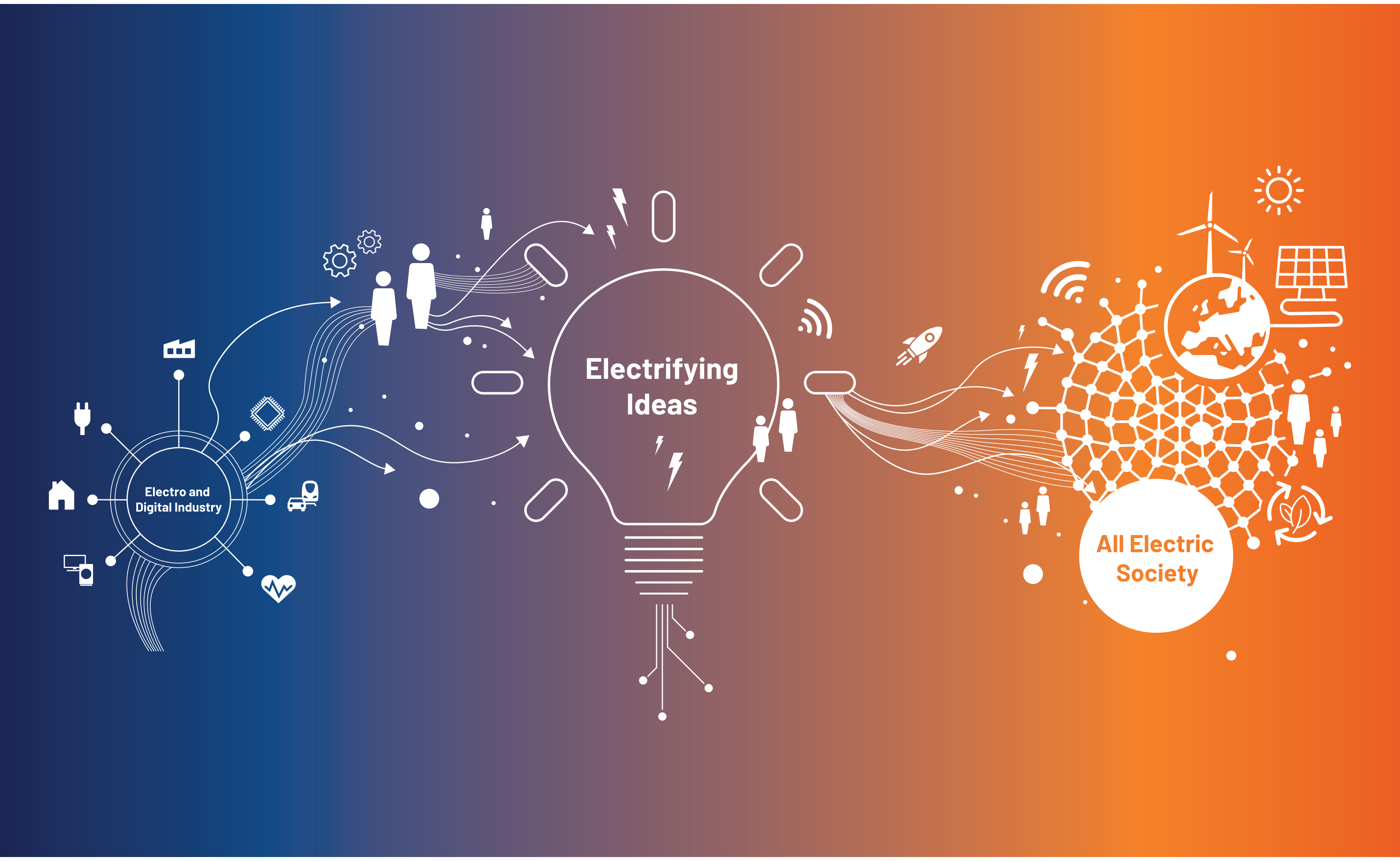

Handbook for Advanced Robustness Validation and Reliability Assessment (ARRA) for MEMS components

Electro and Digital Industry Association

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1 Scope of this Manual

1.1 Introduction to Advanced Robustness Validation and Reliability Assessment (ARRA)

Since the first published version of the Handbook for Robustness Validation of Semiconductor Devices in Automotive Applications in 2007 and the derivate of this Handbook for MEMS (Micro Electrical Mechanical System) Devices in 2008, over 15 years have passed. Since then the necessity for a revision of the Robustness Validation Handbook for MEMS (Micro-Electrical-Mechanical systems) has become obvious.

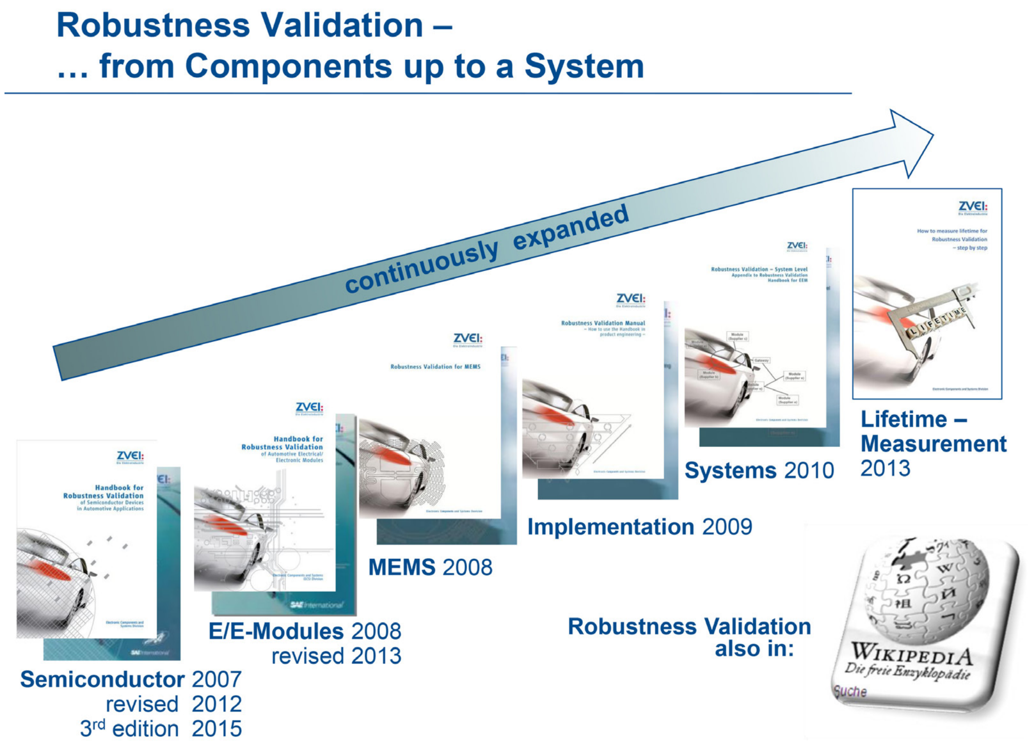


Figure 1: Robustness Validation history

However, implementing the Robustness Validation approach in the development of an electronic device is still a high hurdle, and especially small and medium size MEMS companies often do not have the resources to deal with this topic to the required extent. Furthermore, robustness of a MEMS device is not only restricted to a proper design of the device, but aspects of proper manufacturing play also an often-underestimated role. Additionally, zero-defect best practice strategies become more and more an essential part of a holistic automotive quality strategy.

The goals for the revision of this handbook were as follows:

- Simplify the implementation of the Robustness Validation approach for MEMS devices
- Stronger focus on MEMS-specific topics in this handbook
- Extend the scope of Robustness Validation with general reliability aspects and zero-defect best practice methods
- Standardized reporting of the results and alignment to the AEC (Automotive Electronic Council) Q103 [11]
- Precise definition of the term Robustness for MEMS Devices and definition of metrics as robustness indication figures

Because of those aspects, this working group decided to extend the idea of Robustness Validation for MEMS and add some new aspects, of an overall zero-defect strategy. This new approach is called Advanced Robustness Validation and Reliability Assessment (ARRA) and is explained in detail in the next chapters of this handbook.
To address the issue of the high effort to implement a proper Robustness Validation approach in the development of a component, three flavours of ARRA were created to allow a proper tailoring of the full-fledged ARRA approach.

Furthermore, the handbook now refers to the new AEC Q103 guideline for the automotive qualification of MEMS devices, especially pressure sensors, microphones and accelerometers.

We would like to point out that the ARRA approach as a method can also be applied to non-automotive applications, like for example MEMS accelerometers for mobile phones or MEMS pressure sensors for hydraulic sensing application. However, this handbook takes the automotive AEC (Automotive Electronic Council) Q103 respectively AEC Q100 (where AEC Q103 is not applicable) [11] as a starting point instead of the frequently referenced JEDEC (Joint Electron Device Engineering Council) JESD47 Stress-Test-Driven Qualification of Integrated Circuits for industrial application [40].

This new ARRA approach should support you to address the growing challenges of automotive and industrial quality requirements and it allows a more simplistic way to implement the ideas of Robustness Validation.

1.2 Motivation and Content

Robustness is the capability of functioning correctly or not failing under varying application and production conditions [8][28].

High device robustness is desired to guarantee a proper quality and reliability of the MEMS device in the end product/application.

The idea behind Robustness Validation is a knowledge-based approach which relies on three key components:
- Knowledge of the use conditions (Mission Profile)
- Knowledge of the failure mechanisms and failure modes and the possible interactions between different failure mechanisms (Knowledge Matrix)
- Knowledge of acceleration models for the failure mechanisms needed to define and assess accelerated tests

In practice, there are often hurdles to implement Robustness Validation in a specific project. The definition of the so-called ARRA level makes the implementation of Robustness Validation and the evaluation of the reliability of a specific MEMS device easier. The three particular levels – A, B and C – have increasing requirements and different scopes as stated in Figure 2:

ARRA Level A	**ARRA Level B**	**ARRA Level C**
Scope: Simplified implementation of the Robustness Validation (RV) Methodology for well-known technologies and components covered by the AEC Q103 or generic robustness requirements: • Qualification according to AEC Q100/Q103 Appendix 7, Figure A7.1 "Mission Profile Validation" • Usage of standardized Mission Profiles if available. • Equivalent test methods as AEC Q103 with adapted test conditions. • Standardized reporting in the style of the AEC Q103	Scope: New MEMS technology and/or higher reliability requirements. Additional items to ARRA Level A: • Customer and /or application specific Mission Profile • If necessary: Family based Weibull study for determination of failure modes and acceleration factors • Additional and extended test methods to cope with higher reliability requirements and longer test durations • Additional ZD (zero-defect) methodologies (Safe Launch, Ongoing reliability monitoring)	Scope: Full-fledged ARRA and RV approach for high reliability components and close alignment between MEMS manufacturer and customer. Additional items to ARRA Level B: • Component specific wear-out studies • Supply chain evaluation • Corner lot evaluation

Figure 2: The three pillars of ARRA

Particularly, level A addresses the implementation of the idea of Robustness Validation in a smaller development project with fewer resources and/or less stringent reliability requirements for known technologies or components. The AEC Q103 qualification plan for MEMs devices is used and tailored to a standardized Mission Profile, and test conditions, like the test time or cycle time, are adapted if required. As of now, the AEC Q103 is only

valid for pressure sensor and microphones. For other MEMS devices, as indicated in section 2.1, level B applies, because device specific qualification test might be necessary (e.g. radiation stress tests for micro mirror devices).
Section 1.4 explains the difference between the AEC Q10x and the idea of ARRA. In chapter 2 the different kind of MEMS devices that are scope of this document are summarized, as well as the delimitation between MEMS devices and standard solid-state semiconductor devices, which are addressed in [8]. In chapter 3 the content of each ARRA level is explained in detail, the necessary steps to achieve this level and the deliverables to the customer, as well as key zero defect methodologies and an approach to determine the robustness margin for MEMS.
The Appendix contains a form sheet for exchanging a Mission Profile between customer and supplier, standardized temperature and vibration Mission Profiles for MEMS devices as well as an exemplary best practice Knowledge Matrix.

We hope that this handbook is a useful addition to the AEC Q103 to increase the robustness and reliability of MEMS devices!

1.3 Robustness Validation Approach in AEC Q100/103

The AEC Q100/103 documents for automotive components are stress test-based qualification guidelines. Based on a generic acceleration model and generic acceleration factors for each stress test, the component is rated for a temperature grade and put into a standardized stress test e.g. a 1000h HTOL (High Temperature Operating Life) test at 105°C. Customer specific Mission profiles and other requirements, that differ from this approach are not considered initially.

In the scope of Appendix 7 of the AEC-Q100 [12], an optional Mission Profile-based approach is described, which was originally published in the ZVEI Robustness Validation Handbook for Semiconductor Devices in Automotive Applications [8].

For a given Mission Profile and the generic acceleration models of the AEC-Q10x, the test duration is calculated. If the calculated test duration exceeds or marginally meets the AEC-Q10x standard tests duration, a mission-profile based validation, even if exceeding the AEC-Q10x requirements, is strongly recommended.

In this case, specific acceleration models and factors should be determined and test durations of the proposed AEC stress tests should be re-calculated based on the new assumptions.

As a further step, an even more detailed Robustness Validation with alignment between semiconductor component manufacturer and Tier 1 is proposed as an additional step. Further explanations are given in [8], Chapter 9. This is where the ARRA approach comes into play. ARRA Level A extends the AEC stress test based qualification with ideas of the Robustness Validation and zero defect methodologies while using standardized Mission Profiles to calculate stress durations for the stress tests as defined in the AEC-Q103.

ARRA Level B and C represent a more detailed and strict interpretation of the Robustness Validation approach. However, additional zero-defect methodologies are added to cope for the new ARRA philosophy.

For both, the MEMS supplier and the customer, this approach provides an added value in comparison to the standard AEC-Q103 qualification flow, as
- A Mission Profile is used to calculate test times to reflect the overall lifetime of the MEMS device more precisely
- A Knowledge Matrix is created to learn more about the failure modes, mechanisms and acceleration models of the MEMS technology and to improve the MEMS technology as well as the design of the MEMS devices accordingly
- Zero defect methodologies are applied to include extrinsic failure modes in the overall assessment and to improve field quality

In the following sections the different ARRA levels are described in detail.

1.4 Differentiation between ARRA and AEC-Q10x

The AEC-Q100 (Failure Mechanism Based Stress Test Qualification for Integrated Circuits) is the common automotive industry guideline. It covers the minimum requirements for automotive reliability qualification of semiconductor components by a set of standard qualification tests, which are in the first place independent from the specific application condition of the semiconductor product.

MEMS devices are often exposed to harsh media environments or sophisticated mechanical conditions. Those devices are not covered by commonly referenced product qualification standards/guidelines like the AEC Q100. The AEC council provides the AEC Q103 family to address the special qualification requirements of MEMS devices. These new AEC guidelines are based on generic knowledge matrices and improve the qualification coverage of MEMS products.

The limit of the AEC MEMS guidelines and the delimitation to the ARRA approach is shown in Figure 3 with four different case studies.

The application requirements area in grey indicates the real application requirements of the MEMS sensor product including all environmental and functional loads. The blue box depicts the coverage of the AEC qualification. The four different cases are as follows:

- A perfect overlap of the application requirements and the AEC-Q100/103 stress test coverage is shown.
- The AEC-Q 100/103 stress test coverage exceeds the application requirement with the risk of over-engineering but without a reliability risk of the qualified device in the application.
- The application requirements exceed the stress test coverage of the AEC-100/103 with a high risk of reliability fails during lifetime in the application (e.g. a tread mounted TPMS – Tire pressure monitoring system - sensor with sophisticated requirements for mechanical loads like mechanical shock and vibration).
- A disconnect between application requirements and qualification test is shown. The AEC covers none of the reliability requirements of the application (e.g. a MAP – Manifold absolute pressure - sensor with sophisticated requirements for harsh media compatibility like iodine vapour or exhaust condensate).

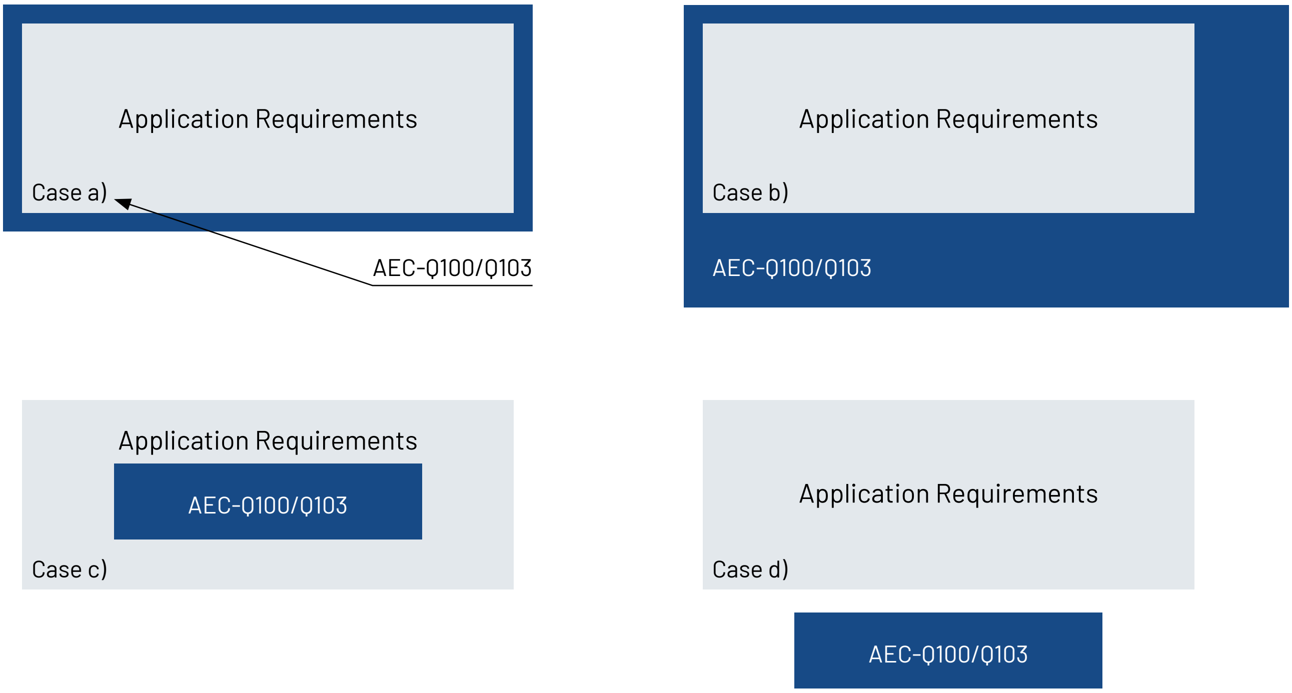


Figure 3: Differentiation of Robustness Validation MEMS and AECQ100/103

Cases c) and d) can only be covered by the specific ARRA approach which reflects the real application conditions of a MEMS device during its lifetime as described in the following chapters.

1.5 Intrinsic and extrinsic failures

The addition of zero-defect methodologies like safe launch, burn-in and ongoing reliability monitoring in the ARRA approach meet the concerns, that not only the intrinsic reliability of MEMS devices must be taken into account to meet the zero-ppm (parts per million) strategy of the automotive industry but also extrinsic failures. According to the JEDEC JESD659 [41] standard, intrinsic failures are "failure mechanism attributable to natural deterioration of materials processed per specification". Extrinsic failures are defined as a "failure mechanism that is directly attributable to a defect created during manufacturing".

Extrinsic failure modes, that are introduced by the actual manufacturing process, contribute to the overall field reliability with the same relevance as intrinsic reliability issues of a MEMS device. Hence, a robust and reliable product must be developed and manufactured considering both intrinsic and extrinsic failure sources.

Examples for intrinsic MEMS failures could be wear-out of the hinge of a MEMS micro mirror device or an improper seal ring width of a MEMS gyro, resulting in leakage and subsequent gyro failure.

Examples for extrinsic failures could be particles contamination in the movable structure of a MEMS accelerometer, failure of a hermetic bond seal of the pressure cavity of a pressure sensor due to remnants of the wafer process, or MEMS damage due to mishandling in the manufacturing process.

Furthermore, the initial qualification is not intended to detect failures with low occurrence rate (like e.g. particle defects) due to the limited number of qualification samples that can be tested with an economically justifiable effort. In this case, a proper safe launch approach and ongoing reliability monitoring activities can help to identify and safeguard those failures before defect devices are shipped to the customer. The zero-defect methodologies, which are referenced in this document, are described more detailed in chapter 3.6.

This handbook assumes, that besides the explicitly mentioned zero-defect methodologies, the MEMS-manufacturing line (frontend of line, assembly BE (backend), test facility, etc.) follows commonly accepted semiconductor quality methods and uses adequate soft- and hardware tools for MEMS manufacturing, like e.g.:
- Software-based MES (Manufacturing Execution System)
- Software-based SPC (Statistical Process Control) System for in-process and end-of-line data analysis [17]
- Defect Density Screening
- Process Control Monitoring (PCM)
- Yield Analysis
- Process Audits [20]
- Process FMEAs (Failure modes and effects analyses) [21][22]
- 8D, 5-Why, Pareto-Analysis, Fault Detection and Classification (FDC)
- Process characterization and capability [17][18]
- Measurement Equipment Calibration
- Preventive Maintenance
- Operator training
- Electrostatic Discharge Sensitive Device Handling procedures [19][23]
- Etc...

Both the Automotive Electronics Council (AEC) and the JEDEC Organization, as well as several other organizations publish a multitude of helpful standards, guidelines and handbooks that can be adapted to the needs of a MEMS manufacturing line [13] [16] [17] [18] [19] for a proper total quality approach.

To better understand the variability of the MEMS manufacturing process steps in terms of influences and the impact to the final product, a process characterization study should be performed before start of mass production [18].

2 MEMS components

2.1 Definition MEMS

The keyword MEMS encompasses a multitude of components with very different functions. We restrict this handbook to commercially available MEMS components, which are produced by surface or bulk silicon semiconductor manufacturing technologies, or LIGA (Lithography, Electroforming and molding) manufacturing technology, and a size of roughly 1µm to a few mm. A classification of those components into sensors, actuators, optical and RF-MEMS (Radio Frequency-MEMS) is done.

MEMS components usually have mechanical movable or interacting structures like membranes or cantilevers on a base substrate like a silicon wafer. Passive and/or active electronic components like resistors, diodes and transistors could be integrated on the same base material as the mechanical structure. Complex analogue and/or digital circuitries to read out or address the MEMS component are usually integrated into a separate chip, like an ASIC or ASSP/COTS (Application Specific Standard/Commercial off-the-shelf), and assembled together with the MEMS chip in a single package or mounted separately on a printed circuit board.

The MEMS component considered in this handbook encompasses:
- One or several MEMS dies without readout circuitry in a package
- One or several MEMS dies plus readout circuitry in the same package
- Unpackaged (bare die) MEMS

The following MEMS components families are addressed in this handbook:
- MEMS Sensors
  MEMS Sensors are electronic sensors with MEMS, like mechanical structures to detect physical properties by mechanical interaction.
  The concept of Robustness Validation according to this handbook could be applicable for the following silicon technology based MEMS sensors: acceleration and gyro sensors (inertial sensors) in one or several axes, silicon pressure sensors for the measurement of an absolute or differential pressure of gaseous and liquid media, MEMS microphones, Infrared bolometers, etc.

- MEMS Actuators
  MEMS actuators use mechanical structures, which can be moved by electrical energy to perform a physical action or to convert electrical current into a different physical property by mechanical movement.Examples for MEMS actuators could be: MEMS loudspeaker, micro motors and pumps, etc.

- Optical MEMS
  The combination of silicon micromechanics and optical components are called MOEMS (micro opto electro mechanical systems). Those systems can generate and/or influence electromagnetic waves, like e.g. micro mirror arrays (DLP (Digital light projection), DMD (digital micromirror device)) and thermal IR (Infrared) sources.

- RF MEMS
  The component group of RF-MEMS encompass resonators, switches, varactors, oscillators and other components for the radar frequency range.

2.2 Differentiation of MEMS vs. Solid State Semiconductor Device

Standard electronic devices as described in the AEC Q100, 101 and 200 are mainly based on the interaction of electrons and holes with a solid-state body, often a semiconductor like doped silicon, or metals like aluminium, tungsten or copper. No intended mechanical movement is involved in the functional principle of those components. Examples are resistors, diodes and transistors.

MEMS devices differ from standard semiconductor devices mainly by the interaction of the before mentioned microelectronic components with micromechanical components (springs, membranes, cantilevers, oscillating elements) in a combined system which encompasses mechanical movement as a key function of the system. Those mechanical movements create new and often unrelated reliability aspects of the whole system, which are not covered by classical reliability models of semiconductor devices as described in the JEDEC JEP122 [31], and the AEC Q100/101/200 guidelines. New failure modes and acceleration models have to be taken into account if the overall reliability of such a system shall be determined.

Packaging of MEMS component is more challenging than for standard semiconductor devices. The mechanical structure on the one hand must be protected against the detrimental effects of the outside world, on the other hand the mechanical system must work as intended and should be able to interact with the environment.

Another characteristic of MEMS devices is that, due to the manufacturing process and the interaction of the MEMS die with the package, a high reproducibility of electrical behaviour is difficult to establish. Even small differences in the mechanical stress of the housing acting on the micromechanical components lead to shifts in the properties, which can only be compensated by calibrating each individual packaged system and thus leads to the desired precision.

MEMS specific process technologies and tools like e.g. DRIE (deep reactive ion etching) for high aspect ratio patterning of silicon, or vapour phase HF etch techniques for releasing mechanical structures, are additional factors that sets apart MEMS process technology from standard semiconductor device manufacturing.

3 ARRA methodology

3.1 The five steps of the ARRA approach

The ARRA approach can roughly be divided up into five general steps in terms of a to-do list:

Step 1: Mission Profile
- The Mission Profile is needed for the ARRA approach to specify the exact use condition of the MEMS application. Depending on the ARRA level a standardized or customized Mission Profile is required. In combination with the Knowledge Matrix and the failure models and acceleration factors, the actual qualification plan can be created and tailored to the in-use field stress of the MEMS device.

Step 2: The Knowledge Matrix
- The Knowledge Matrix not only collects all known failure modes of the MEMS device in terms of physics of failure, but also the related failure models and acceleration factors. To determine failure modes and acceleration factors for new and unknown technologies and designs, Weibull- or End-of-life studies must be conducted or existing data from literature or experience must be used.

Step 3: Qualification
- After step 1 and 2, the actual device qualification can be planned in detail. Taking AEC Q103 as a starting point for MEMS, applicable stress tests to trigger the failure modes derived in step 2 must be defined. Stress duration and stress level like temperature must be determined with the use of the Mission Profile from step 1 and the acceleration factors from step 2.

Step 4: Zero-Defect Methodologies
- To include extrinsic failures from the manufacturing process in the ARRA approach, which are not addressed in the initial qualification, key zero-defect methodologies should be implemented throughout the whole supply chain to prevent defect parts from being shipped to the customer. Methods like Safe Launch, Burn-In and Reliability Monitoring are proposed in this handbook.

Step 5: Robustness Assessment and Reporting
- The final step is the actual robustness assessment for the MEMS device with regards to the customer Mission Profile and a standardized reporting of the results of the whole ARRA methodology for the device under test (see section 3.7).

In the following chapters the detailed content per step for each ARRA level is described. For a more in-depth consideration of the underlying Robustness Validation approach, please refer to the flow chart in [9].

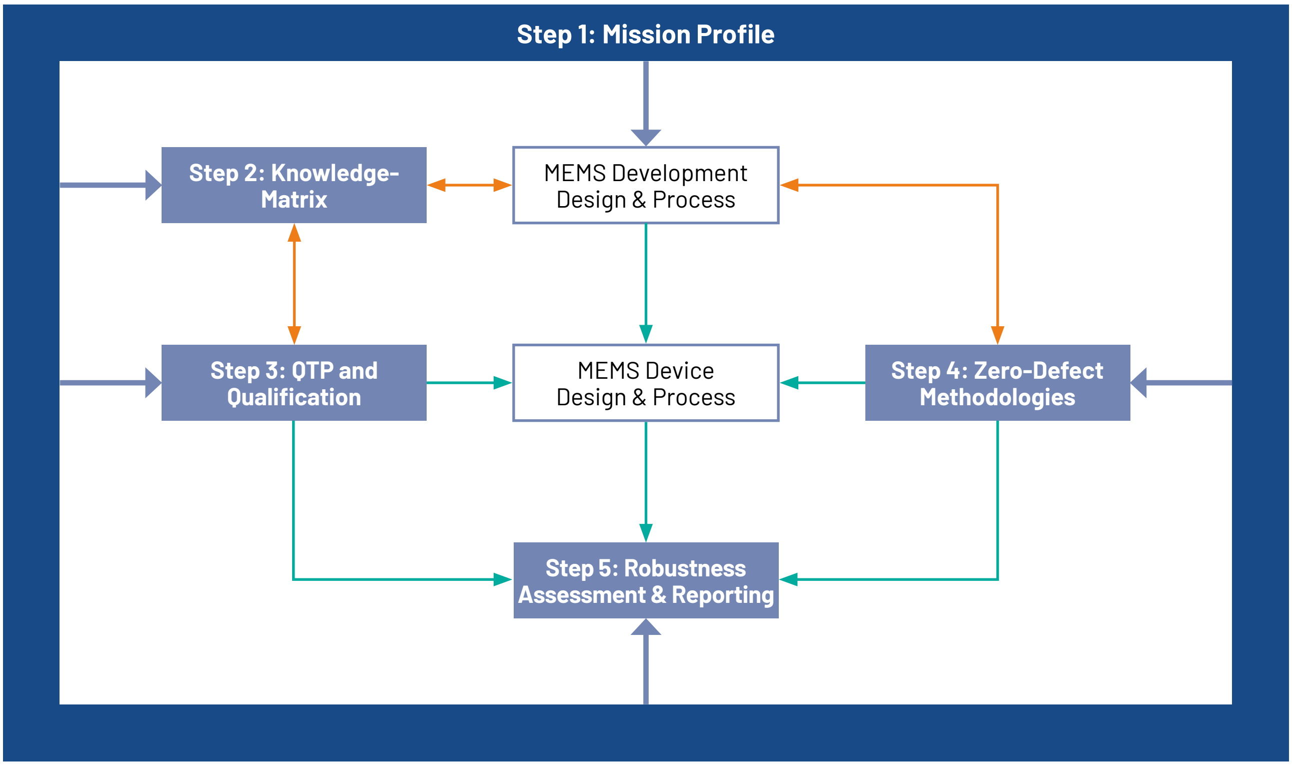


Figure 4: The five steps of the ARRA approach

3.2 Definition of ARRA Level

As explained in section 1.2, three ARRA level have been defined to implement the idea of Robustness Validation and advanced reliability assessment specifically for MEMS components for automotive electronic systems. This completely revised and expanded second edition of the Robustness Validation Handbook takes into account that the reliability requirements of modern automotive and non-automotive systems are constantly growing, as well as the project restrictions with regards to cost and time.

- Level A shall make the implementation of the ARRA approach easier in small projects with limited experience in Robustness Validation. A baseline of requirements has been extracted out of the original Robustness Validation handbook for semiconductor devices and merged with the content of the AEC Q103 for MEMS components. This level A resembles the approach of the AEC Q100 Appendix 7 for Robustness Validation.
- Level B adds further requirements to Level A and requires advanced know-how in Robustness Validation and supply chain management, as well as reliability physics and failure mode modelling.
- Level C is a further extension of Level B and reflects the full-fledged Robustness Validation Approach. It additionally requires an in-depth supply chain risk management and an early failure study.

From Level A to C, the knowledge of the technology, the typical failure modes and applicable failure models and acceleration factors increases. It makes it necessary to gain more information about the failure physics of the device and technology by for example performing dedicated end-of-life tests and Weibull studies or compare the new technology with existing ones. Alternatively, an additional safety buffer could be added to the intended qualification stress levels.

ARRA Level:			ARRA Level A	ARRA Level B	ARRA Level C
ARRA Step		Applicable for:	Well known technology. MEMS type covered by AEC Q103	New MEMS technology and/or higher reliability requirements.	Full-fledged ARRA and RV approach for high reliability components
I	Mission Profile	Usage of a generic Mission Profile for a specific application by MEMS supplier	X		
		Compilation of a Mission Profile by MEMS supplier based on load and application profile from customer	(optional)	X	X
II	Knowledge Matrix, Accelerated Testing	Knowledge Matrix: Determination of critical failure modes. Usage of generic acceleration models based on experience and literature	X		
		Knowledge Matrix: Determination of critical failure modes and acceleration models based on experience, literature and data of similar technology		X	
		Knowledge Matrix: Determination of critical failure modes and acceleration models based on experience, literature, family evaluated data and wear out studies			X
		Accelerated testing of technology carriers (e.g. wear out test, Weibull Analysis) to determine acceleration factors and lifetime of critical failure modes. Alternatively, delta assessment with similar technology and expert team assessment of relevant failure modes and acceleration factors. Additional safety buffer for acceleration factors may apply		X	X
III	Qualification	Qualification according to Mission Profile with AEC Q103 as basis with adapted test times and loads (temp., humidity, voltage, mechanical and chemical loads). Generic Data accepted as defined in AEC Q100 and Q103.	X		
		Qualification according to Mission Profile. AEC Q103 as basis with adapted test times and loads (temp., humidity, voltage, mechanical and chemical loads) or device specific qualification plan. Sample size according to expected failure occurrence. Limited acceptance of generic data.		X	
		Creation of a product specific qualification plan in cooperation with customer and subsequent reliability qualification. Sample size according to expected failure occurrence. Limited acceptance of generic data.			X
IV	Zero-Defect Methodologies	Corner lot evaluation	(optional)	(optional)	X
		Early Failure Study/Burn-in	(optional)	(optional)	X
		Structured on-site risk evaluation for whole supply chain by expert team	(optional)	(optional)	X
		Safe launch plan for MEMS supply chain based on risk evaluation	(optional)	X	X
		Definition of ongoing reliability monitoring plan	(optional)	X	X
V	Robustness Assessment, Reporting	Robustness Assessment for MEMS component	X	X	X
		Standardized reporting of qualification results, robustness assessment and zero-defect plan and results	X	X	X

Figure 5: Overview of the ARRA steps

- "X" means mandatory
- If one of the optional items are added to the ARRA Level A or B, the resulting ARRA Level is marked with a "+" (ARRA Level A+ or ARRA Level B+).

ARRA Level flow Chart

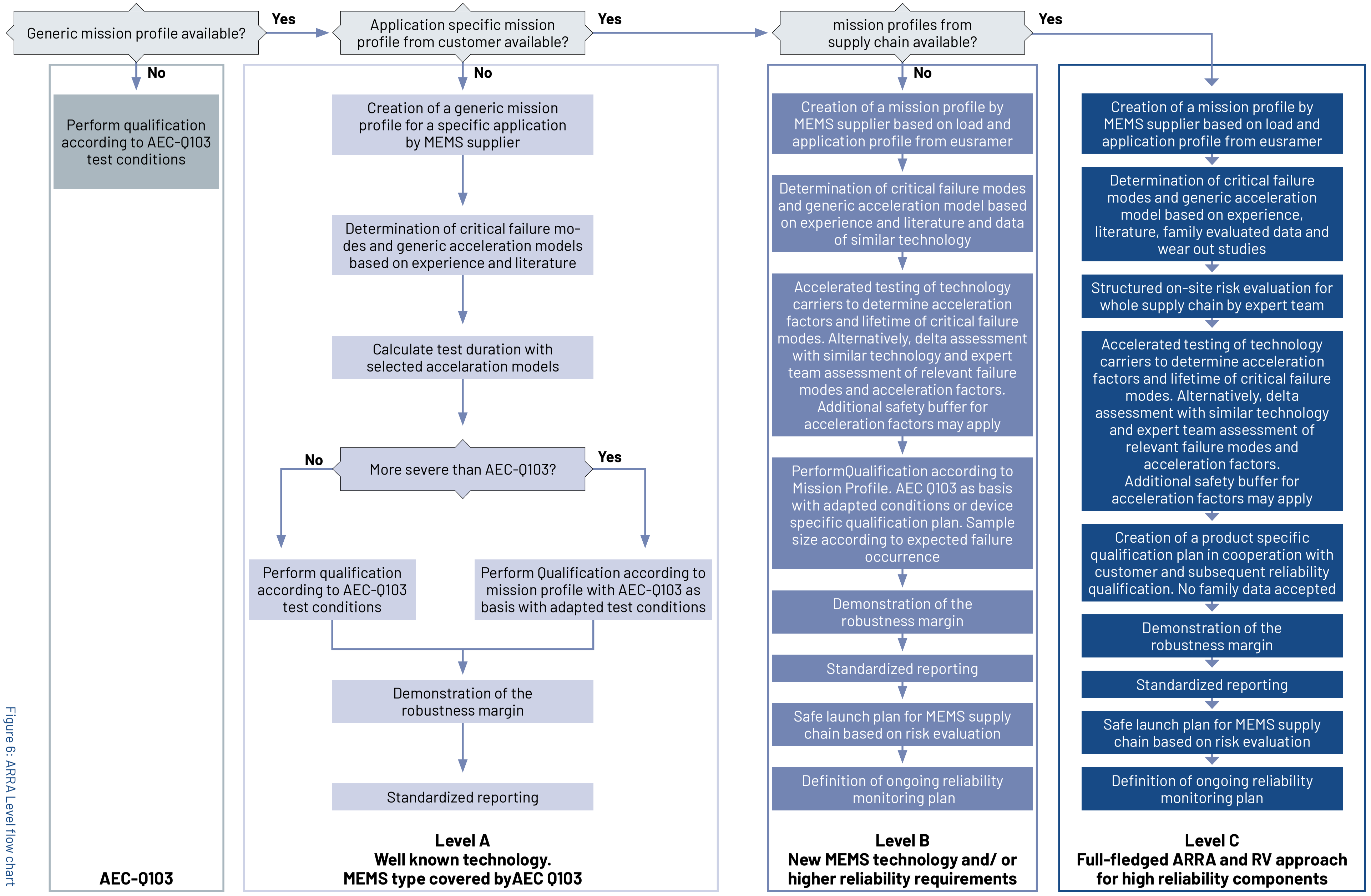


Figure 6: ARRA Level flow chart

3.2.1 ARRA Level A

In contrast to previously published Robustness Validation handbooks, a reference to the stress test based AEC-Q approach of the Automotive Electronic Council is desired and intentional.
Thus, ARRA Level A mainly refers to the AEC Q100/103 qualification guideline regarding the chosen types of stress tests, samples sizes and the general qualification flow. It must be emphasized, that as of the date of publishing of this document, the AEC Q103 standard is only available for pressure sensors and microphones. For all other MEMS devices as mentioned in section 2.1, ARRA level B applies.
The idea of Level A is a simplified approach for Robustness Validation without the need of a detailed physics of failure assessment of the component or technology of the MEMS. Instead, known failure modes and models from the literature or past experience are used in combination with the already existing AEC Q103 test methodology and test plan to create a component specific test plan, based on the test approach of the AEC Q103.
To simplify the approach, a standardized Mission Profile is sufficient to meet the requirements of Level A. Such a standardized Mission Profile describes the environmental loads for the component inside an automotive application.

Environmental loads for MEMS could be:
- Temperature
- Humidity
- Mechanical drop/shock loads
- Vibrational loads

Temperature and Humidity should be broken down to at least 5 individual steps from min. to max. temperature, including the required lifetime for operation and storage for each step. Further environmental loads like chemical loads and optical radiation, as well as further electromagnetic loads could be incorporated if required. Standardized Mission Profiles could be extracted from automotive OEM (Original equipment manufacturer) quality and reliability handbooks, published science literature or commonly agreed profiles between manufacturer and customer. Future standardization of Mission Profiles for individual locations in a car between several automotive OEMs and Tier x could help to support the quick and easy implementation of ARRA Level A. Further explanations are given in section 3.3. A standardized form sheet for exchanging a Mission Profile is provided in appendix A.1. Exemplary Mission Profiles for MEMS devices are provided in Appendix A.2.

The 5 steps of the ARRA approach look as follows for ARRA Level A:

Step 1. ARRA-Level-A: Mission Profile
- A generic Mission Profile for the assumed installation location of the ECU (Electronic Control Unit) inside the car should be used for the calculation of test durations. If no generic Mission Profile is available, a dedicated Mission Profile must be requested from the customer. Alternatively, Appendix A.2 provides some exemplary Mission Profiles for MEMS devices. Details regarding the use of Mission Profiles is provided in [8].

Step 2. ARRA-Level-A: Knowledge Matrix
- Critical failure modes, the related failure mechanisms and acceleration models must be determined for the specific MEMS technology. Literature and experience with earlier developments might be used to make an educated guess about the failure modes instead of starting a completely new program to determine the failure modes and mechanisms (ARRA Level B and C). An exemplary failure catalogue for MEMS can be found in [1] [2] [3]. A template Knowledge Matrix is attached in Appendix A.3. Established and proven qualification tests of the AEC Q103 or similar standards should be chosen to address this failure mode.

Step 3. ARRA-Level-A: Qualification
- For ARRA Level A the qualification tests as proposed in the AEC Q103 qualification flow chart are conducted, but with adapted tests times and stress loads, based on the calculation of stress test durations and loads with the information established under Step 2.
- If the calculated stress is less severe than the conditions of the AEC A103, the latter should be taken as reference.
- The usage of family data of previously qualified similar MEMS devices of the same technology is allowed, if the Mission Profiles do not differ significantly. Details are provided in the AEC Q103, Appendix A.1.
- At the time of publishing this document, the AEC Q103 only exists for pressure sensors and microphones. For all other MEMS devices, ARRA Level B applies. Alternatively, if the MEMS technology resembles the above mentioned, the proposed qualification plan of the AEC Q103 can be used as a guideline.

Step 4. ARRA-Level-A: Zero-Defect Methodologies

- The simplified ARRA Level A does not require application zero-defect methodologies. However, it is highly recommended to adapt best practice quality methods across the whole supply chain as described in section 3.6.1.
- ARRA Level A+: The MEMS manufacturer can decide in conjunction with the customer to implement one or several of the zero-defect methodologies of ARRA Level B or C in ARRA Level A. As detailed in table "ARRA level flow chart" the resulting ARRA Level is called ARRA Level A+.

Step 5. ARRA-Level-A: Robustness Assessment and Reporting

- The robustness margin of the MEMS device under test with regards to the Mission Profile and other conditions of use must be demonstrated as explained in detail in section 3.8.
- The result of the qualification and the robustness assessment are documented in a standardized reporting by the MEMS manufacturer and provided to the customer for proper and transparent documentation of the results of each single step of the ARRA methodology for the desired component.
- A checklist for a standardized reporting and the necessary deliverables is given in section 3.8.
- For ARRA Level A+, the additional zero-defect items are part of the reporting.

3.2.2 ARRA Level B

In a scenario where either the application has higher reliability requirements than usual or the knowledge about the technology compared to existing and qualified MEMS technologies and components is low, Level A is no longer applicable.
This may be relevant for the following scenarios and combinations thereof:

- Insufficient specified environmental conditions like unknown chemical load compositions and unusual stress factors
- Limited availability of acceleration models and factors
- High temperature, humidity and mechanical loads
- Aggressive media
- Long lifetime requirements
- Applications where verified FIT (Failure in time)-rates must be determined

Level B adds further points to the ARRA approach to cope for those scenarios.

The five steps of the ARRA approach look as follows for ARRA Level B:

Step 1. ARRA-Level-B: Mission Profile

- In contrast to ARRA Level A, Level B requires an application specific Mission Profile instead of a generic Mission Profile. This Mission Profile must be developed specifically for the application of the customer and must be tailored to the individual MEMS component.
- Self-heating of the whole application in a closed housing must be considered to determine the proper temperature range of the MEMS component.
- A close collaboration between the MEMS manufacturer and the customer is necessary to develop a valid Mission Profile. The car OEM should be incorporated as well.
- Details are described in [8].
- Step 2. ARRA-Level-B: Knowledge Matrix
- A Knowledge Matrix including the relevant failure modes and mechanisms for the specific MEMS must be created. The assessment could be based on literature, experience and results of similar technologies. A template for a Knowledge Matrix for a MEMS is given in Appendix A.3. Further details are described in [8].
- Acceleration factors are necessary to determine proper test times in the qualification. For this goal one or more of the following approaches could apply:

  - Based on the Knowledge Matrix, the main failure modes should be summarized and for each failure mode a
  - dedicated End-of-Life test could be performed to extract the acceleration model and the acceleration factor. Best practice methods of Weibull testing are recommended.
  - Alternatively, when a predecessor technology or MEMS design is established and qualified, and acceleration models are known, those can be taken over for a new technology or design, if

    - delta analysis (e.g. supported by a Design Review Based on Failure Mode (DRBFM, [10]) has been conducted to evaluate the gap between the existing technology and the new one,

    - and the gap between the two and the associated risks has been assessed by an interdisciplinary expert team and deemed low enough.
    - an additional safety buffer for the acceleration factors can be defined to cope for uncertainties during the evaluation.

Step 3. ARRA-Level-B: Qualification
- A qualification plan must be generated and shared with the customer. Based on the determined acceleration factors for each failure mechanism, the qualification tests must be tailored in terms of applied stress level and duration of the test. Starting point of the qualification plan can be the AEC Q103 qualification guideline. If stressors are not covered by those test (e.g. radiation stress for optical MEMS), additional tests for addressing those stressors must be performed.
- Based on the risk assessment in the Knowledge Matrix for the relevant failure modes and mechanisms, the required sample size and number of production lots should exceed the AEC Q103 recommendations.
- Limited acceptance of generic data, as differences in the MEMS design of the same technology platform could alter the reliability model significantly. An interdisciplinary expert team has to prove, that existing data can be accepted as generic data and transferred to the new MEMS component. The Appendix A.1 of the AEC Q100 and Q103 must be considered.

Step 4. ARRA-Level-B: Zero-Defect Methodologies
- Corner lots evaluation for MEMS specific process and material variations is recommended:
  - The evaluation of process windows for critical processes that influence the function and reliability of the MEMS could be covered by a proper design of experiment (DOE). The methodology described in [14] could for example be used for a comprehensive characterization of the MEMS design in the early engineering sample stage.
  - Critical mechanical properties of the MEMS device, as membrane thickness for a pressure sensor or beam width of an accelerometer, should be included into this evaluation.
  - Results of the evaluation should be available for on-site review at the manufacturer or part of the ARRA reporting.
  - Further details can be found [8], section 9.5.1 – 9.5.3.

- A Safe Launch procedure must be defined and put in place at the key manufacturing sites for the MEMS as an additional measure to improve quality and reliability of the MEMS specifically in the first weeks and month of a new product ramp up. Usually this incorporates the MEMS chip manufacturing FAB and the assembly site for the package. Early failures which were unintentionally not covered in the qualification phase of the device shall be caught in the production line instead at the customer. Furthermore, manufacturing issues which could evolve during the ramp-up phase and the initial learning curve, should not impact product quality and reliability. In terms of a total quality approach those factors cannot longer be ignored for a proper zero-defect strategy and must be incorporated into the ARRA philosophy. Further explanations and an example for a safe launch procedure is given in section 3.6.3.
- An ongoing reliability monitoring (ORM) plan after finishing the initial reliability assessment of the MEMS, should ensure that quality and reliability stay constant during the whole production phase. To ensure that no excursion in the production process deteriorates the reliability, an ongoing reliability monitoring must be installed at the key manufacturing sites. For a typical MEMS component this usually incorporates the MEMS chip manufacturing FAB (e.g. fast Wafer Level Reliability) and the assembly site for the package. The reliability tests should be derived from the initial qualification plan with adapted test times and statistical relevant sample sizes. Depending on wafer and assembly lot sizes and production volumes, samples from each MEMS wafer lot and from selected assembly lots should be put into the ongoing reliability test. Results should be available before final shipment to the customers, so that excursions could be identified and affected lots blocked prior to shipment. Further explanations and an example for an ongoing reliability monitoring plan is given in section 3.6.1.
- ARRA Level B+: The MEMS manufacturer can decide in conjunction with the customer to implement one or several of the zero-defect methodologies of ARRA Level C in ARRA Level B. In this case, the resulting ARRA Level is called ARRA Level B+ as detailed in table "ARRA level flow".

Step 5. ARRA-Level-B: Robustness Assessment and Reporting
- The robustness margin of the MEMS device under test with regards to the Mission Profile and other conditions of use must be demonstrated. Details are explained in section 3.7.
- The result of the qualification and the robustness assessment should be documented in a standardized reporting by the MEMS manufacturer and provided to the principal or customer for proper and transparent

documentation of the results of each single step of the ARRA methodology for the desired component.
- Applicable zero-defect methodologies for ARRA Level B should be described in the reporting and results documented if already available at the time of issuing the ARRA report.
- For a checklist for a standardized reporting and the necessary deliverables please refer to section 3.8.
- For ARRA Level B+, the additional zero-defect items are part of the reporting.

3.2.3 ARRA Level C

Level C represents the full-fledged ARRA approach with an extensive determination of failure mechanisms, acceleration models and factors for the specific MEMS technology and design.

This approach could be relevant for customer specific MEMS with very high reliability requirements (enhanced lifetime requirements, high temperature application, harsh media). This category needs close alignment between supplier and customer, which shall already begin in the early technology definition phase. Taking the ZVEI Handbook for Robustness Validation of Semiconductor Devices in Automotive Applications [8] into account is highly recommended!

A Level C assessment of a specific MEMS technology or design can also be used as a baseline, for future MEMS designs so that they can be assessed by a lower ARRA level.

On top of the Level B requirements, the following additional items are necessary to fulfil ARRA Level C:

Step 3. ARRA-Level-C: Qualification
- A pre-qualification with first engineering samples should be planned with at least one frontend lot. A final qualification with at least three non-consecutive frontend and backend lots have to be done.

Step 4. ARRA-Level-C: Zero-Defect Methodologies
- Corner lots evaluation for MEMS specific process and material variations is mandatory:
  - The evaluation of process windows for critical processes that influence the function and reliability of the MEMS should be covered by a proper DOE. The methodology of the AEC Q003 – Guideline for characterization of integrated circuits [14] could for example be used for a profound characterization of the MEMS design in the early engineering sample stage.
  - Critical mechanical properties of the MEMS, like membrane thickness for a pressure sensor or beam width of an accelerometer, should be included into this evaluation.
  - Results of the evaluation should be available for on-site review at the manufacturer or part of the ARRA reporting.

- Structured on-site risk evaluation for whole supply chain by expert team:
  - The mechanical nature of MEMS devices bare risks with regards to quality and reliability all along the whole supply chain (e.g. handling and transportation of MEMS, de-panelling and dicing, release process of mechanical MEMS structure, hermetic sealing of MEMS, delicate processes like wafer bonding, etc.).
  - General supply-chain assessments according to quality management systems like IATF16949 [7], VDA6.3 [20] or DIN EN ISO9001 [39] usually do not cover specific MEMS risks.
  - In order to cover those special MEMS characteristics, a dedicated risk assessment of the whole supply chain has to be incorporated in the project plan. This has to be performed by an expert team, familiar with MEMS technologies and manufacturing steps. It needs to be started as soon as key MEMS processes and handling steps have been defined.
  - A final assessment must be done before production release at the latest to check if all measures have been implemented and risks successfully mitigated, which have been identified during the project.
  - A cpk-assessment (process capability index) must be done after processing of the (at least three) qualification lots. Key cpk-values should be above 1,67. Otherwise a proper improvement plan must be in place.

- Early failure study for MEMS: during the safe launch phase a production ramp-up study with an accelerated test for a predefined quantity of all parts to detect early failures is recommended. Critical failure modes should be identified and addressed during this study (e.g. package swelling after moisture soak and subsequent offset-shift for pressure sensor). It is noted that the sample size must be such that it is in relation to the annual production or output quantity in order to achieve a desired statistical significance across component and lot variation as part of a zero-defect strategy

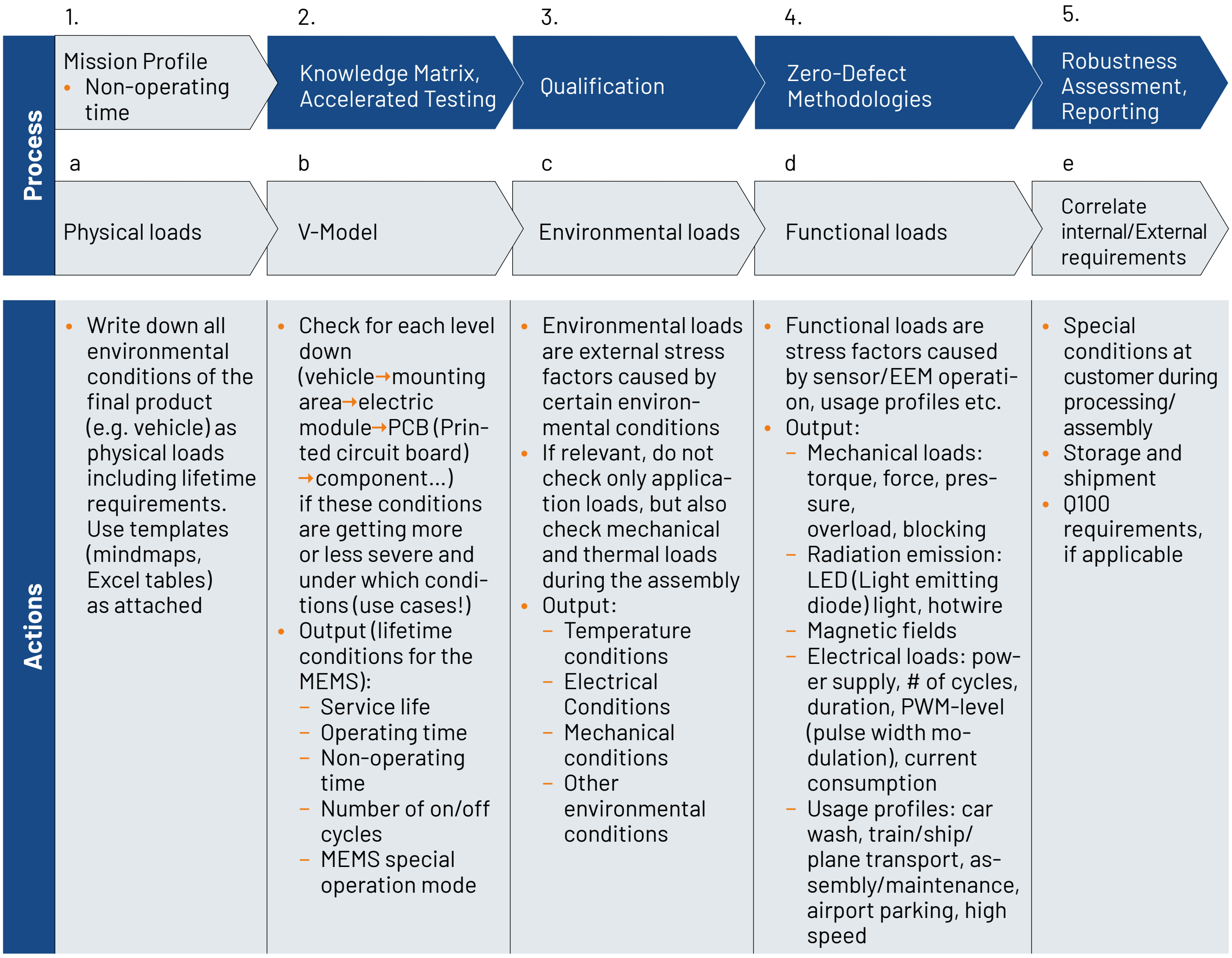
3.3 Mission Profile for MEMS

A proper collection of Mission Profile requirements for the MEMS component is a key success factor for the ARRA approach.

According to [28], a Mission Profile is "the simplified representation of all of the relevant conditions to which a device will be exposed in its intended application throughout the full life cycle".

Here in this handbook we focus on the environmental and electrical conditions, which could potentially affect the reliability of the MEMS device in the target application.

For ARRA Level A standardized Mission Profiles can be used for simplified implementation of the ARRA approach. Standardized Mission Profiles for automotive application are currently discussed across multiple car manufacturers and Tier1 suppliers. As no generally accepted set of standardized Mission Profiles are available as of the date of publishing this document, assumptions must be made by the MEMS manufacturer.



	1.	2.	3.	4.	5.
Process	Mission Profile • Non-operating time	Knowledge Matrix, Accelerated Testing	Qualification	Zero-Defect Methodologies	Robustness Assessment, Reporting
	a	b	c	d	e
	Physical loads	V-Model	Environmental loads	Functional loads	Correlate internal/External requirements
Actions	• Write down all environmental conditions of the final product (e.g. vehicle) as physical loads including lifetime requirements. Use templates (mindmaps, Excel tables) as attached	• Check for each level down (vehicle→mounting area→electric module→PCB (Printed circuit board) →component…) if these conditions are getting more or less severe and under which conditions (use cases!) • Output (lifetime conditions for the MEMS): – Service life – Operating time – Non-operating time – Number of on/off cycles – MEMS special operation mode	• Environmental loads are external stress factors caused by certain environmental conditions • If relevant, do not check only application loads, but also check mechanical and thermal loads during the assembly • Output: – Temperature conditions – Electrical Conditions – Mechanical conditions – Other environmental conditions	• Functional loads are stress factors caused by sensor/EEM operation, usage profiles etc. • Output: – Mechanical loads: torque, force, pressure, overload, blocking – Radiation emission: LED (Light emitting diode) light, hotwire – Magnetic fields – Electrical loads: power supply, # of cycles, duration, PWM-level (pulse width modulation), current consumption – Usage profiles: car wash, train/ship/plane transport, assembly/maintenance, airport parking, high speed	• Special conditions at customer during processing/assembly • Storage and shipment • Q100 requirements, if applicable

Figure 7: Mission Profile flow chart

For ARRA Level B and C, customer specific Mission Profiles are required to tailor the qualification plan and mitigate risk associated with critical loads for the MEMS device.

The general approach for creating a Mission Profile is explained in the ZVEI Handbook for Robustness Validation of Semiconductor Devices [8] and in other literature sources [25][4]. For that reason, only a short wrap-up of the process to create a Mission Profile is given with focus on the actual critical Mission Profile parameters for a MEMS component.

For a MEMS component, the MEMS supplier must compile the required information for a comprehensive Mission Profile. Requirements of the car maker for the specific target vehicle or car platform, as well as the Tier 1 for electric and electronic modules (EEM) must be encompassed.

Further requirements for a comprehensive Mission Profile for a MEMS device include critical manufacturing, transportation and handling steps. All relevant information must be collected along the whole supply chain (e.g. vibration due to PCB (Printed circuit board) singulation or ESD (Electrostatic discharge) requirements due to manual handling) and incorporated into the MEMS Mission Profile.

Due to the mechanical fragile nature of MEMS components, mechanical loads could be more critical than for other components. Those load requirements must be determined for each supply chain member (e.g. high g-shock events in test handler at test house).

If the translation of field load to test load is too difficult or the acceleration between field and test conditions is unknown today, the use of proven standards is encouraged. That is the reason why for several kinds of loads, such as vibration and corrosion, parameters for lab tests rather than typical values could be stated in the Mission Profile.

If the MEMS device is a sensor, the sensor interface as the main differentiator to a standard semiconductor component is a critical factor for the reliability of the device. The sensor interface should be considered for the generation of a Mission Profile (e.g. critical chemical loads that get in contact with the sensor interface).

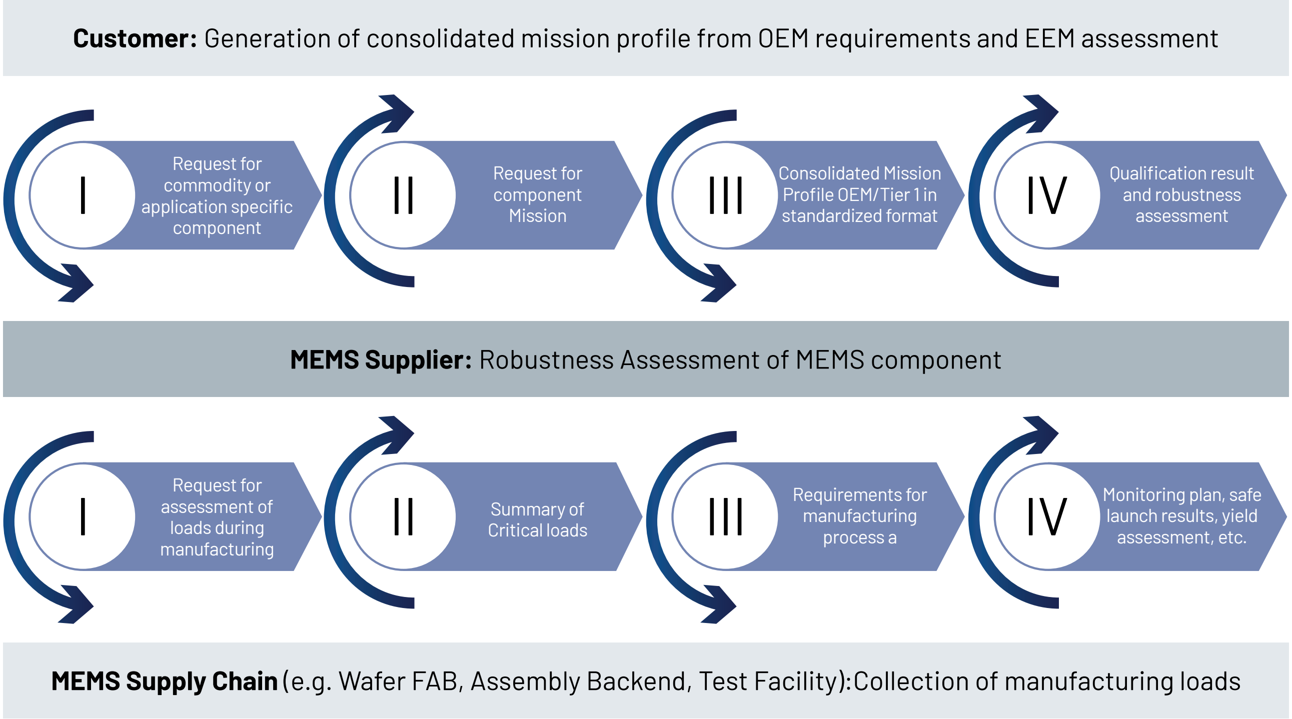


Figure 8: Communication of supply chain partners

The communication between the supply chain partners is extensively described in [9]. The general information flow between customer, MEMS supplier and supply chain is shown in the graph.

The MEMS supplier collects all the relevant information for building a proper Mission Profile. It is the task of the customer to provide the following information to the MEMS manufacturer in a standardized format to start the ARRA process:

i General Information and Lifetime:
  - Application information: Specific device application, application system background
  - Targeted lifetime of the application in hours for both biased operating mode and storage without biasing.
  - For passive storage without biasing, 15 years lifetime are usually required.
  - For application with different power and standby modes instead of on-off cycles, the classification of a storage time is not applicable.

ii Temperature and humidity conditions:
- Temperature Mission Profile with preferably 5 or more individual temperature steps or temperature ranges between the minimum and maximum operational temperature range of the MEMS device according to the data sheet, including the required lifetime for operation and storage for each step. A duty cycle could also be provided.
- If temperature intervals are provided, they must be transformed into single representing temperature values for using acceleration models.
- In Attachment A.2 four temperature Mission Profile classes are provided (reprint of [3]). Alternatively, in [25] five different temperature Mission Profiles are provided as a guideline. Those temperature Mission Profiles could be either used as a generic temperature Mission Profile, or as a starting point for a customer specific profile.
- Information about where in the application the temperature is measured (e.g. package temperature, or free airflow temperature above the MEMS)
- Preferably three individual relative humidity values in %.

Temperature [°C]	Rel. Humidity [%]	Maximum Absolute Humidity [g/m^3]	Lifetime Distribution	Storage Time [h]	Operation Time [h]
-40	90		6%	7,884	480
25	60	20	12%	26,280	1,600
40	24		65%	85,410	5,200
85	3		7%	9,198	560
95	3		2%	2,628	160
			Total	**131,400**	**8,000**

Figure 9: Example Mission Profile – temperature and humidity

iii Electrical Operation
- Parameters like minimum, typical and maximum operating voltage, current consumption and power dissipation could be provided case by case.
- Desired ESD (Electrostatic Sensitivity) robustness should be mentioned as well in terms of the HBM (Human Body Model) for manual handling and CDM (Charged Device Model) for automated component handling as specified in [26][27]. The following ESD component classification can be used in conjunction with an in-line measurements of the electrical charges in the production line.

HBM Component Classification	Maximum Withstand Voltage		CDM Component Classification	Maximum Withstand Voltage
H0	≤ 250 V		C1	< 125 V
H1A	> 250 V to ≤ 500 V		C2	125 to < 250 V
H1B	> 500 V to ≤ 1,000 V		C3	250 to < 500 V
H1C	> 1,000 V to ≤ 2,000 V		C4A	500 to < 750 V
H2	> 2,000 V to ≤ 4,000 V		C4B	500 to < 750 V with corner pins = 750 V
H3A	> 4,000 V to ≤ 8,000 V		C5	750 V to < 1,000 V
H3B	> 8,000 V		C6	= 1,000 V

Figure 10: Example Mission Profile – ESD

- EMC (Electro-magnetic compatibility) requirements
- Details of the operational mode in which the MEMS devices is biased in the application.
- High energy radiation requirements if applicable
- High Frequency requirements for RF-MEMS

iv Mechanical loads:

- Mechanical drop loads: Free falling drop load for mishandling during manufacturing process and for in-use drop.

- An example for a Mission Profile for a "keyless entry" application:

Drop Height	No. Of Drops	Floor material
1.2 m	100	concrete, carpet
2 m	10	concrete, carpet

Figure 11: Example Mission Profile – Drop test

- Mechanical shock loads:
  - For pressure sensors, the mechanical grades of the AEC Q103-002 apply:

Grade	Specification	Comment
M1	As per AEC Q103-002	Pressure Sensors General Requirements
M2	As per AEC Q103-002	Tire Pressure Monitoring System (TPMS)
custom	As per customer specification	

Figure 12: Example Mission Profile – shock loads (pressure sensor)

  - For all other MEMS:

Grade	Specification	Comment
M1	As per AEC Q103-002	Equivalent use of AEC Q103
Service Condition A-H	As per JEDEC JESD22-B110B	
custom	As per customer specification	

Figure 13: Example Mission Profile – shock loads (other MEMS)

- Vibrational loads and constant acceleration:
  - For pressure sensors, the mechanical grades of the AEC Q103-002 apply: For all other MEMS:

Grade	Specification	Comment
M1	As per AEC Q103-002	Pressure Sensors General Requirements
M2	As per AEC Q103-002	Tire Pressure Monitoring System (TPMS)
custom	As per customer specification	Example see Appendix A.2

Figure 14: Example Mission Profile – Vibration loads (pressure sensors)

    - For all other MEMS:

Grade	Specification	Comment
M1	As per AEC Q103-002	Equivalent use of AEC Q103
Service Condition 1-8 and A-I	As per JEDEC JESD22-B103	
custom	As per customer specification	Example see Appendix A.2

Figure 15: Example Mission Profile – Vibration loads (other MEMS)

- Further mechanical loads
    - Custom vibrational profile and constant acceleration requirements
    - Applied mechanical forces for MEMS actuators
    - Handling loads in the manufacturing line of the customer. Qualitative descriptions are sufficient (e.g. PCB singulation by sawing)
    - Mechanicals loads due to bending of PCB
    - Special or unusual storage and shipment conditions

v Pressure loads for Pressure Sensor MEMS:
- Pressure profile; maximum Proof and Burst Pressure according to AEC-Q103
- Pressure peaks and pressure rise and fall time
- Number of pressure pulses over lifetime; frequency of pressure pulses
- Example see next chapter for TPMS MEMS Sensor.

vi Optical and electro-magnetic loads for optical MEMS:
- A detailed description of the applied radiation (sunlight, LED lightning, Ultraviolet (UV)- or IR-light etc.) must be provided.

vii Other environmental loads
- Chemical loads
- Dust if applicable; IPxx protection classification if applicable

viii Soldering and Assembly Process
- Type of soldering technology, front or backside soldering, soldering profile if set by customer, rework requirements for manual soldering, etc.
- Requirements regarding board level reliability

ix Custom Requirements for other MEMS components
- Other than the above-mentioned loads and requirements for specific MEMS components

A standardized exchange of information regarding the Mission Profile is recommended. A questionnaire should be used by the MEMS supplier, to gather the information from the Tier 1 supplier. Alternatively, if the MEMS component is an application or customer specific part, the exchange of information about the Mission Profile can be achieved through the generation of a requirement specification by the Tier 1. Requirement management tools (e.g. Doors or JAMA) or other software base solutions are nowadays commonly used for this task.

In addition to that, the ZVEI Automotive Application Questionnaire [4] helps to generate templates for the communication between customer and supplier. Those standard templates for Mission Profile generation can be downloaded on the ZVEI website.

A Mission Profile template, that include the standardized items i. – viii. can be found in the appendix A.1 of this handbook. A Mission Profile case study is provided in the next chapter.

3.3.1 Case Study: Mission Profile for Tire Pressure Monitoring System Wheel Unit (TPMS)

In the Appendix A.1 an example for a mission profile is provided. It deals with a standard sensor that is the sensing part of a TPMS-wheel unit. It connects via RF to a receiving EEM in the vehicle. The significant climatic, electrical, mechanical, and chemical influences, which affect the sensor during its service life are summarized in the following Mission Profile.

Note: This is only an example, which is not necessarily accurate or complete. These profiles are estimations which represent typical operational profiles of different drivers in a passenger car and have to be validated.

For several kinds of loads, such as vibration, corrosion and water intrusion, parameters for lab tests rather than typical values are given. If the translation of field load to test load is too difficult or the acceleration between field and test conditions (e.g. for some chemical loads) is unknown today, the use of proven standards is encouraged.

An empty templated based on this example can be downloaded on the website of the ZVEI.

It summarizes some basic generic information for the most common MEMS components like pressure sensors and accelerometers as defined in section 2.1. As it is only a kind of guideline, it has of course to be adapted for any other specific MEMS component.

3.4 Knowledge Matrix and Accelerated Testing

Step 2 of ARRA puts emphasis on the knowledge-based qualification approach. The knowledge of failure modes, failure mechanisms, failure models and acceleration factors is one of the key items that sets apart the ARRA approach from the stress test based qualification approach.

Defintion by:

A failure cause is defined as the specific process, design and/or environmental condition that initiated the failure, and whose removal will eliminate the failure [15][6].

A failure mechanism is the specific process, by which physical, electrical, chemical and mechanical stresses act on materials to induce a failure [15][6].

A failure mode is the effect by which a failure is observed to occur. The failure mode describes how a failure occurs [15][6].

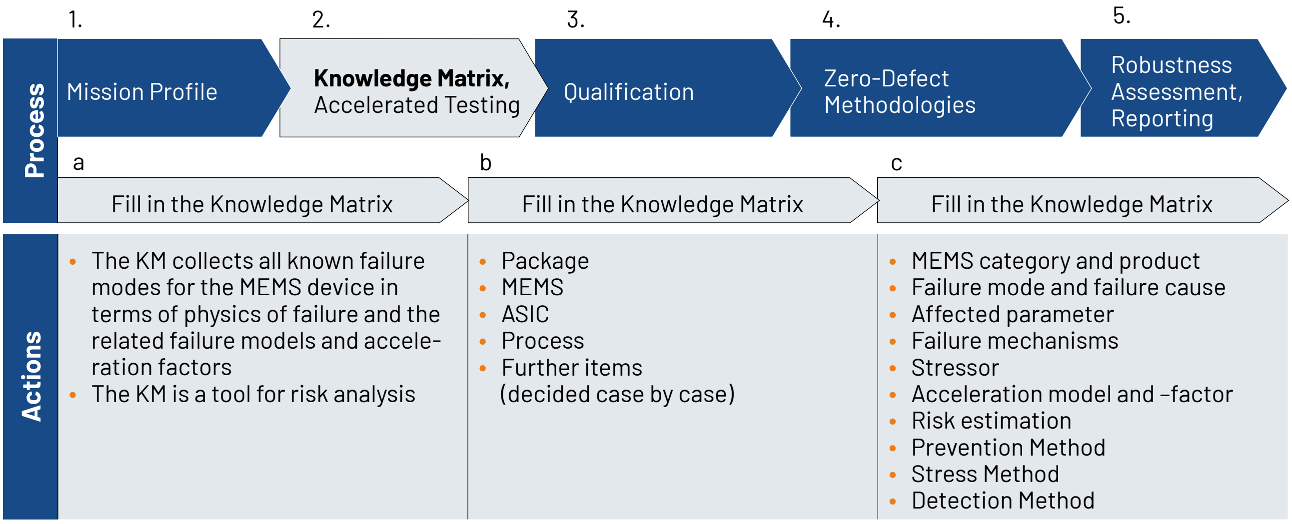
Figure 16: Failure definition

A failure mechanism is defined by how a degradation process progresses, e.g. whether driven by oxidation, diffusion, electric field, currents density. As the driving forces are known, an empirical or theoretical acceleration model can be proposed or derived that allows for failure rate modeling.

Examples for failure modes are a visual blemish, a bent lead, a foreign particle or material, an incorrect dopant profile or grain size, a scratch, an electrical fault (open, short, leakage, inadequate slew rate or noise margin, stuck at high or low, etc.).

For none of these modes failure rate modeling is possible until the mechanism is determined. Only when the mechanism is known, together with the relevant independent variables (forcing functions), the effects of the observed failure mode can be modeled.

The Knowledge Matrix not only collects all known failure modes for the MEMS device in terms of physics of failure, but also the related failure models and acceleration factors. It is also a tool for risk analysis.



- The KM collects all known failure modes for the MEMS device in terms of physics of failure and the related failure models and acceleration factors
- The KM is a tool for risk analysis

- Package
- MEMS
- ASIC
- Process
- Further items (decided case by case)

- MEMS category and product
- Failure mode and failure cause
- Affected parameter
- Failure mechanisms
- Stressor
- Acceleration model and -factor
- Risk estimation
- Prevention Method
- Stress Method
- Detection Method

Figure 17: Knowledge Matrix flow chart

The following items should at least be covered by a Knowledge Matrix:

- MEMS category and product: Short description of device.
  - E.g. Barometric Silicon MEMS Pressure Sensor

- Failure mode and failure cause: Name and typical cause of the failure mode.
  - E.g. Wire Bond fatigue due to EMC (Epoxy molding compound) delamination

- Affected parameter: The parameter to characterize the failure mechanism.
  - E.g. Bridge resistance, current consumption, etc.

- Failure mechanism: Physical, chemical, electrical, or other process that has led to non-conformance
  - E.g. mold compound adhesion degradation due to package moisture ingress

- Stressor: The environmental or functional load parameter, that triggers the failure mechanism.
  - E.g. humidity and temperature for mold compound delamination

- Acceleration model and acceleration factor (if available): Mathematical description of the failure mechanisms in dependence of stress parameters.
  - E.g. Power law time to failure model with power law exponent of 2.

- Risk estimation: Failure probability and/or failure impact for application.
  - E.g. High failure probability due to experience with similar device; customer line returns due to failure after solder reflow.

- Prevention Method: Methods to prevent the failure mechanism by design or during fabrication.
  - E.g. Dry bake and hermetic packing before shipment to prevent moisture ingress, or choice of a more robust mold compound.

- Stress Method: Optimum stress method to stimulate the failure mechanism.
  - E.g. Preconditioning test with moisture soak 168h/85% relative humidity and subsequent reflow simulation 3x 260°C, delamination check by C-Sam and functional test.

- Detection Method: Optimum functional test to characterize failure.
  - E.g. wire bond resistance measurement

On the website of the ZVEI an exemplary Knowledge Matrix is provided for reference.

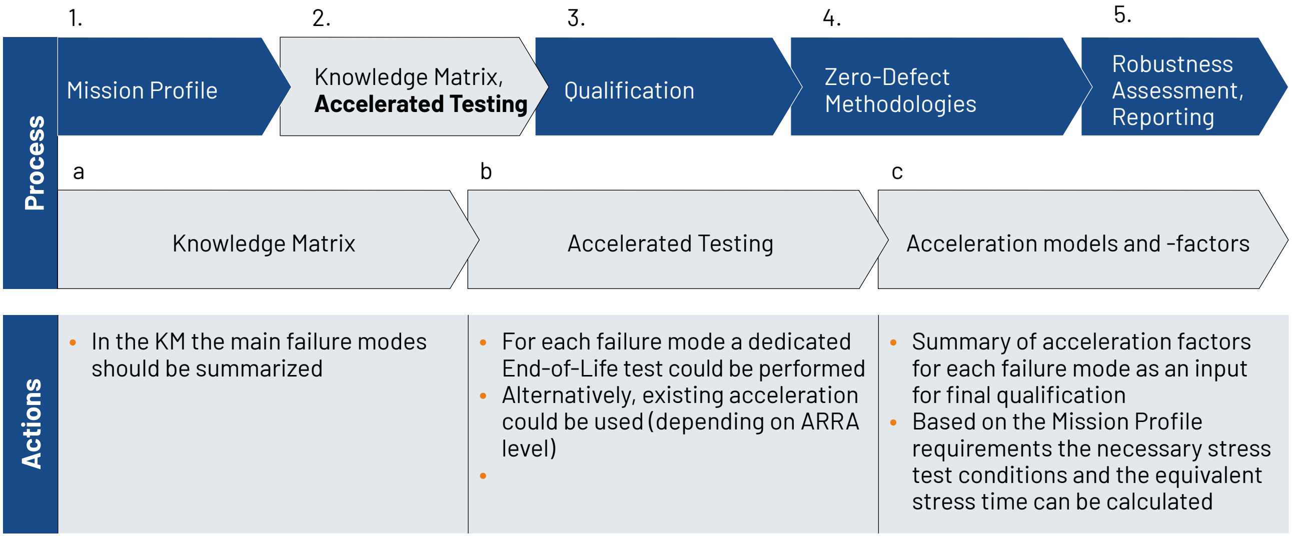
Lifetime assessment is done by extrapolation from accelerated stress testing to use conditions. For the necessary calculations a failure model is typically used. Applying a generic failure model and/or parameter values for e.g. activation energies could lead to predictions that are wrong by orders of magnitude. Hence, for ARRA Level A the choice of literature values for acceleration factors should be done very carefully. A collection of failure models and acceleration factors as given in [31] could be used as a starting point. Further MEMS-specific literature should be considered, as well as experience from past projects and devices.

To determine failure modes, failure models and acceleration factors for new and unknown technologies and designs for ARRA Level B and C, a Weibull- or End-of-life studies should be conducted [1][2][3][8][31][33][34].

Existing data from literature or experience should only be used in exceptional cases, if e.g. a Weibull study is not feasible. ARRA Level B and C have more stringent requirements in this regard than ARRA Level A (please refer to section 3.2).

The generation of failures during accelerated testing is necessary to be able to
- identify new or verify known failure modes,
- extract a proper mathematical failure model to describe the time-to-failure signature and the dependence of stressor, and
- determine acceleration factors that makes it possible to put the accelerated test results in relation to real-world environmental and operational conditions provided in the Mission Profile.

In most cases, lifetime requirements are beyond what is acceptable as test time. This implies that the stresstime must be compressed. Accelerated testing exposes the product to stress conditions that induce failures in shorter time than at normal use conditions; without changing the failure mechanism.



- In the KM the main failure modes should be summarized

- For each failure mode a dedicated End-of-Life test could be performed
- Alternatively, existing acceleration could be used (depending on ARRA level)

- Summary of acceleration factors for each failure mode as an input for final qualification
- Based on the Mission Profile requirements the necessary stress test conditions and the equivalent stress time can be calculated

Figure 18: Acceleration testing flow chart

Determination of lifetimes and acceleration models/parameters requires extensive testing and failure analysis to verify that the intended failure mechanism is really addressed. The tests must be examined with respect to their suitability for addressing a specific failure mechanism, taking into consideration the application requirements. Test conditions and sample sizes have to be chosen carefully.

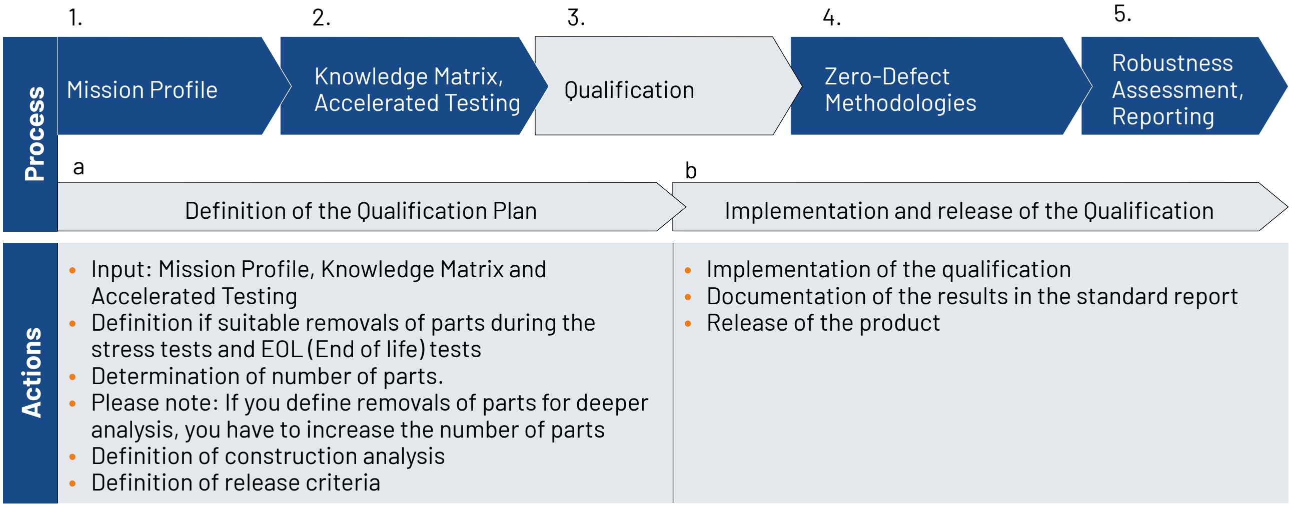
A product itself may not be the most suitable vehicle to investigate a specific failure mechanism.

Dedicated test structures should be considered, because they can be analysed more easily and allow better modelling. Thus, test structures are often indispensable for understanding a certain failure mechanism and improving the technology/product.

Accelerated testing is a broad and complex field and thus cannot be covered in this handbook thoroughly. Further information about accelerated testing can be found in e.g. [8][31][33][35].

3.5 Qualification Plan and Testing

In Step 3 of the ARRA methodology, a qualification has to be conducted to verify the reliability of the MEMS device with reference to the Mission Profile. In this chapter further details are provided for the qualification procedure.



- Input: Mission Profile, Knowledge Matrix and Accelerated Testing
- Definition if suitable removals of parts during the stress tests and EOL (End of life) tests
- Determination of number of parts.
- Please note: If you define removals of parts for deeper analysis, you have to increase the number of parts
- Definition of construction analysis
- Definition of release criteria

- Implementation of the qualification
- Documentation of the results in the standard report
- Release of the product

Figure 19: Qualification plan flow chart

As described earlier in this handbook, the AEC Q103 is a starting point for a suitable qualification plan for MEMS devices. For proper tailoring of the qualification tests according to the Mission Profile, the results from ARRA Step 2 are required: the Knowledge Matrix and acceleration factors. Only with this information it is possible to adapt the test plan to the application requirements.

Example: the AEC Q103-002 for pressure sensors, Test Group PS, requires a Pressure & High Temperature Operation Life Test (PS1) for a Tire Pressure Monitoring Sensor device from the example in section 3.3.1. A HTOL Grade 2 according to the AEC Q100 was determined. According to the AEC test plan, the PrHTOL (Pressure HTOL) has to be conducted for 1,000h at +105°C at a maximum operating pressure of 450 kPa. However, the duration of the test with reference to the required 5,000h of operating time is somewhat arbitrary. The temperature driven degradation of the parameter "pressure offset stability" was determined in a Weibull Study with an exponential failure model and an acceleration factor of 1 eV. With this information, the equivalent stress test time at 105°C according to the Arrhenius model was calculated to be about 1,500 h (see table below). Hence, the PrHTOL has to be extended to 1,500 h of test duration to cover the requirements of the temperature Mission Profile for this failure mode.

For each identified failure mechanism in the Knowledge Matrix, a suitable qualification test has to be performed to check if the device is robust enough to survive the stress in accordance to the Mission Profile. In the ideal case, proper acceleration models are available for each failure mechanism to accelerate the stress test to a manageable degree (see ARRA Step 2, section 3.1and 3.2).

Temperature [°C]	TPMS Duty Cycle	Lifetime in h per Temperature Step [h]	Acceleration Factor normed to +105°C	Testing time normed to +105°C [h]
-40	25%	1,250	0.0000000049	0.00
25	45%	2,250	0.0003	0.58
60	25%	1,250	0.0157	19.57
105	4%	200	1.0000	200.00
150	1%	50	26.4	1,319
Life Time [h]		5,000		
Testing Time [h]				1,539
Arrhenius Factor [eV]	1			
Required Lifetime [h]	5,000			

Figure 20: Example Mission Profile – temperature with acceleration factors

Unfortunately, the available literature does not provide a lot of information about failure mechanisms and failure models for MEMS devices due to the mechanical nature of those devices and the limited possibility to mathematically model its failure behaviour. If no acceleration factor is available, test time and stress level have to be chose either by referring to accepted standards like the AEC Q103 or chosen by experience and an educated guess.

In the absence of failure models, it is a valid and viable approach to test to a certain margin of strength, which is a usual practice in mechanical engineering. For example, if a pressure sensor is specified up to a certain pressure Pmax, it has to withstand a test up to a pressure of k*Pmax, where k is a factor for the robustness margin. Repeating that test for a number of times and inspecting of the device for potential damage gives some information on the robustness of the device. Thus, an additional margin for stress time and other stress factors could be added to increase confidence in the qualification results and to facilitate the calculation of a robustness figure (please refer to section 3.7). Please note the increasing requirements for acceleration models and factors from ARRA Level A to C (section 3.2).

To reduce the effort for the qualification and the evaluation of the MEMS device robustness, the following differentiation for ARRA.

ARRA Step		General Content	Source for Robustness Evaluation	Detailed Items/Case	ARRA Level A	ARRA Level B	ARRA Level C
V	Robustness Assessment, Reporting	Robustness Margin	Qualification Tests According to ARRA Step 3	Case Ia: Pass/Fail Evaluation of Qualification Tests	x	x	x
				Case Ib: Qualification Drift Analysis and Robustness figure calculation	(x)	x	x
			End-of-Life Test – Qualification Test with device failure or Weibull Study	Case IIa: Non-Parametric End-of-Life Test and Pass/Fail evaluation	x	x	x
				Case IIb: Parametric End-of-Life Test and Robustness Indicator calculation	(x)	x	x

Figure 21: ARRA Level flow chart excerpt

For ARRA Level A, less effort has to be spent for the qualification set-up and data logging.

In contrast to a Weibull Study, which is often performed as a test-to-fail, the qualification tests of ARRA Step 3 should lead to zero fails, if the stress tests properly cover the Mission Profile requirements. If failures occur during qualification testing, it has to be assumed in the first place, that the MEMS device cannot withstand the reliability requirements. A careful investigation has to be done in this case to check for device weaknesses and to calculate the robustness margin (see section 3.7).

A standardized form sheet for the qualification plan is recommended. The AEC Q103, Template 4a, could be used as a starting point [11][12] for ARRA Level A and B.

For ARRA Level C a product specific qualification plan has to be generated in cooperation with the customer to ensure, that all product requirements are covered.

Furthermore, generic data, that is used to support the qualification of a specific MEMS device in ARRA Level A and to a limited extend in ARRA Level B, can be summarized in AEC Q103 Template 4b [11][12]. The applicability of generic data must be demonstrated.

The stress tests must be performed according to the requirements specified in the Qualification Plan. The equipment must satisfy the requirements with respect to the stress test parameters as defined in the Qualification Plan, and the tolerances of the parameters must be known [8].

For a stress test to be called a "pass", the component must not only lie within the permissible absolute tolerances, but the permissible drifts must not be exceeded. Further information on drift analysis can be found in chapter 3.5.1.

Characterization data should be logged for all readout points. It is recommended to perform a full electrical and mechanical characterization over e.g. temperature, voltage and other critical parameters at each readout point for later drift studies. Characterization beyond spec limits could help to identify weaknesses.

Critical parameters should be monitored continuously during the entire characterization procedure in order to react quickly in case of failures and to facilitate a later Weibull analysis [8].

The qualification sample size for ARRA Level A follows the requirements of the AEC Q103. For ARRA Level B and C, sample sizes should reflect the expected failure occurrence.

For ARRA Level B corner lot studies are recommended, for ARRA Level C it is mandatory. Please refer to section 3.6.5.

For ARRA Level C, a pre-qualification with first engineering samples should be planned with at least one frontend lot. A final qualification with at least three non-consecutive frontend and backend lots has to be done (see section 3.2.3).

Further recommendations regarding qualification testing can be found in chapter 9 and 10 of [8].

3.5.1 Drift analysis

After the qualification, a drift analysis of the DUT (Device Under Test) should be performed in order to access the parameter drift due to the applied stress loads.

For all ARRA levels an agreement about drift analysis of relevant drift parameters between customer and supplier should be done.

Structure of a drift analysis:

- Quality targets need to be defined. For drift this is the likelihood that parameters exceed the specified limits. This can be e.g. 1 ppm, 10 ppm.
- Drift is derived from accelerated stress tests that simulate the product's lifetime.
- Drift analysis:
  - Measurement values of individual devices before, during and after the stress tests are used to calculate the drift per device.
  - This is done for all tested devices and it results in a distribution of drift values. This distribution can be corrected for measurement errors (e.g. GR%R, tester offsets, ...).
  - From this calculated distribution the quantile acc. to the quality targets can be derived (e.g. 1 ppm, 10 ppm, ...).

An example of drift of an electrical parameter is given in Figure 23. This figure shows the electrical parameter how it evolves over stress-time.

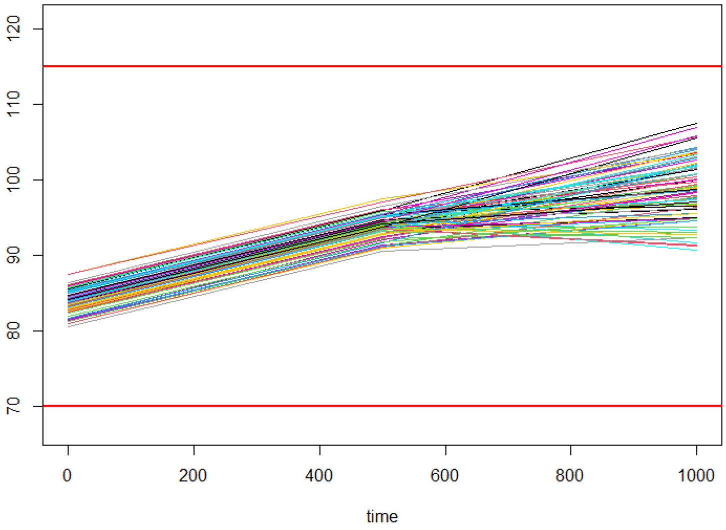


Figure 22: Example of drift of an electrical parameter

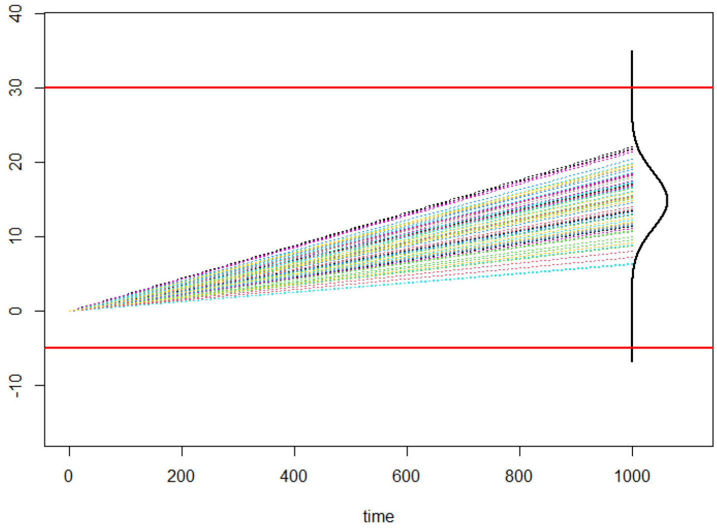


Figure 23: Example of a bare drift of each device

Further details regarding the drift analysis can be taken from relevant literature.

3.6 Key Zero Defect Methodologies for MEMS

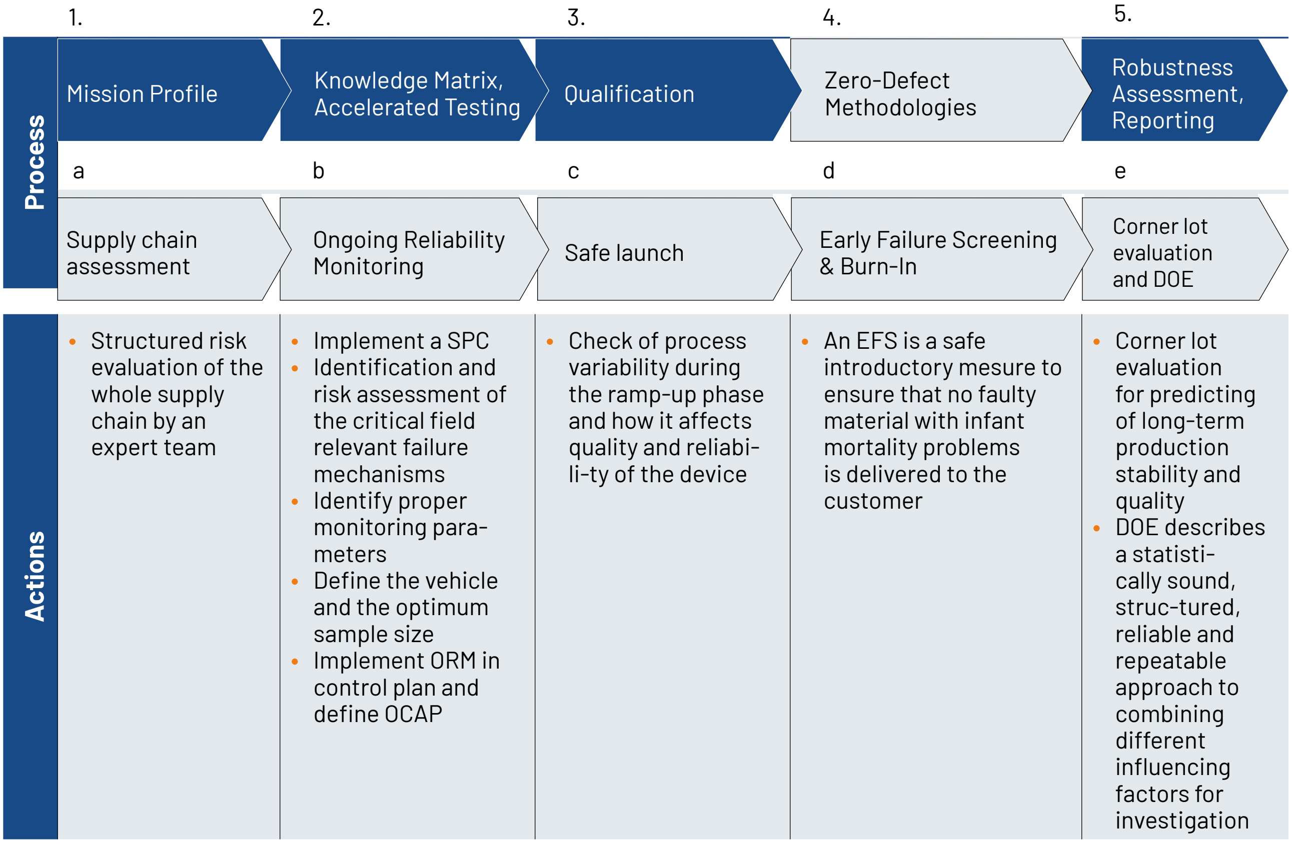
Zero defect methods are a fundamental part of the ARRA methodology to ensure, that extrinsic failures from the manufacturing process, which are not addressed in the initial qualification, are identified as early as possible. The goal is that no defect parts are shipped to the customer.

Those key zero-defect methodologies should be implemented throughout the whole supply chain during the project phase and should be in place and working at the start of mass production. Supply chain assessment, On-going Reliability Monitoring, Safe Launch, Early Failure Study, and Corner Lot Evaluation and DOE are described in the next chapters. Where necessary, literature sources for further readings are provided, as this handbook cannot cover each and every detail of the proposed zero defect methods.

3.6.1 Supply chain assessment

The supply chain assessment is a structured risk evaluation of the whole supply chain by an expert team. It shall cover critical topics during MEMS development, qualification and ramp-up, which is best covered by an on-site assessment.

In this handbook we assume, that the supply chain for developing and manufacturing a MEMS component according a certain ARRA Level consist of several (two or more) separate companies or at least several entities of one company.



	1.	2.	3.	4.	5.
Process	Mission Profile	Knowledge Matrix, Accelerated Testing	Qualification	Zero-Defect Methodologies	Robustness Assessment, Reporting
	a	b	c	d	e
	Supply chain assessment	Ongoing Reliability Monitoring	Safe launch	Early Failure Screening & Burn-In	Corner lot evaluation and DOE
Actions	• Structured risk evaluation of the whole supply chain by an expert team	• Implement a SPC • Identification and risk assessment of the critical field relevant failure mechanisms • Identify proper monitoring parameters • Define the vehicle and the optimum sample size • Implement ORM in control plan and define OCAP	• Check of process variability during the ramp-up phase and how it affects quality and reliabili-ty of the device	• An EFS is a safe introductory mesure to ensure that no faulty material with infant mortality problems is delivered to the customer	• Corner lot evaluation for predicting of long-term production stability and quality • DOE describes a statistically sound, struc-tured, reliable and repeatable approach to combining different influencing factors for investigation

Figure 24: Zero-Defect Methodology flow chart

A proper sourcing of a supply chain by the MEMS supplier will in most of the cases encompass a quality audit, that has to be passed successfully before a supply chain member like the wafer FAB or an assembly subcontractor can be officially nominated. Depending on the standard or questionnaire used, such a quality audit will cover general development and manufacturing related processes and procedures. Due to the nature of the available quality standards like IATF16949 [7], VDA6.3 [20] or DIN EN ISO9001 [39], specific MEMS risks are not covered. Those standards are even not at all focused on semiconductor development and production processes.

To assess the risks that a semiconductor and MEMS supply chain might bare, a dedicated assessment must take place for ARRA Level C. For ARRA Level A and B it is optional but highly recommended. However, it has to be pointed out, that such a supply chain risk assessment according to this handbook does not replace or equal a usual quality audit like an IATF16949 audit. It could however be combined with such an audit by adding suitable points and questions to the agenda. As a best practice approach a dedicated questionnaire could be created, covering quality audits items of the VDA6.3 or the IATF16949 in conjunction with semiconductor and/or MEMS specific topics of the ARRA handbook.

Some points have to be clarified upfront to a supply chain assessment:

a. Who is responsible for conducting the supply chain assessment?
   In a usual business case, the company who is the actual developer of the MEMS device and is leading the project planning, is responsible for defining the supply chain for the manufacturing steps, hereafter called MEMS supplier. Depending on the contractual details, this company is also the direct business partner for the customer, usually an automotive Tier 1 (see Figure 7). In this case the MEMS supplier is responsible to set-up an assessment team for conducting the supply chain assessment. The customer could be involved into the assessment. The assessment has to be performed by an expert team, familiar with semiconductor and MEMS technologies and manufacturing steps.

b. When shall the initial assessment be done?
   The mechanical nature of MEMS devices bare risks with regards to quality and reliability all along the whole supply chain (e.g. handling and transportation of MEMS, de-paneling and dicing, release process of mechanical MEMS structure, hermetic sealing of MEMS, delicate processes like wafer bonding, etc.). In order to cover those special MEMS characteristics, a dedicated risk assessment of the whole supply chain has to be incorporated in the project plan. It needs to be started as soon as key MEMS processes and handling steps have been defined per each supply chain member (wafer frontend, wafer backend, assembly, wafer test, final test, etc.). This is usually the case during the process development, when a preliminary control plan is available. A final assessment must be done before production release at the latest to check if all measures, that were defined based on the initial assessment, have been implemented and risks successfully mitigated.

c. What is the content of the assessment?
   The following MEMS specific topics should be addressed during the initial supply chain assessment (without any specific order):

- Mission profile:
  - Check if the existing requirements regarding the MEMS mission profile, especially handling requirements and other mechanical loads and ESD requirements are fulfilled.
  - Check if further loads and requirements have to be added to the mission profile for the MEMS device, like e.g. certain mechanical loads like drop or shock during handling and transportation of the MEMS.

- Do have all supply chain members procedures in place for a safe launch strategy, which is compliant to the requirements of this handbook (please refer to chapter 3.6.3).
- A statistical process control system must be in place (please refer to [17]).
- Reliability monitoring plan must be available according to chapter 3.6.2
- A Cpk-assessment (process capability index) must be done after processing of the (at least three) qualification lots. Key Cpk-values should be above 1,67. Cpk-Analysis for electrical test (on-wafer and/or packages part) Cpk should be between 1.67 < Cpk <= 10 explanation in case of deviation from this rule (e.g. Part Average Testing applied, guard banding applied, etc.) List of Test parameters incl. parameter explanation, USL, LSL, Mean, StDev, Cp, Cpk. Otherwise a proper improvement plan must be taken in place. However, the review of Cpk data must not necessarily be performed on-site.

d. How shall the results be reported?
   An assessment report has to be generated for the initial supply chain assessment, eventually in conjunction with a VDA or IATF audit report if it has been done in parallel. In this assessment report, the findings of the assessment, main risks, action items and further recommendations have to be summarized for each supply chain member. A final evaluation for the supply chain member has to be given in terms of:
   1. released
   2. conditionally released with restrictions
   3. not released

Furthermore, an evaluation has to be done if the conditions of the mission profile are fulfilled or followed within the supply chain (e.g. mechanical shock or vibration limits during handling in the manufacturing process, ESD requirements during handling and test, etc.).

Due to the complexity of the topic, sufficient time should be spent for a supply chain assessment. As a rule of thumb, at least 2-3 full days should be available for each location. If the assessment is combined with a quality audit, one or two additional days are usually necessary to cover the required topics. In general, the preparation of such an assessment should follow the rules of a quality audit like the VDA 6.3:2016. For more information, please refer to Chapter 4 of [20].

The assessors should have access to all relevant data and information for the assessment, like e.g.
- process flow chart and control plan
- work instruction, quality procedures, handling instructions, etc.
- FMEAs
- quality data of the MEMS manufacturing process (e.g. SPC data, wafer probe and final test results)
- access to the manufacturing floor (clean room, test floor, etc.) for an in-line assessment

If necessary, non-disclosure agreements must be signed for the protection of intellectual property.

Further assistance might be offered by the Advanced Product Quality Planning (APQP).

The APQP manual [41] issued by the Automotive Industry Action Group (AIAG) provides the guidelines for accompanying all phases of the product development, since early planning and design phases until the implementation of all manufacturing processes and their controls, fulfilling the respective customer requirements. When applying the APQP process the supply chain assessment is conducted in a structured and continuously way during the product and process development.

3.6.2 Ongoing Reliability Monitoring

The initial qualification of the MEMS components reflects the reliability and quality of the device at the point in time when the qualification lots had been produced [8]. Hence, the qualification lots only represent a temporary status of the MEMS manufacturing process. Furthermore, the limited number of qualification samples do not necessarily show intrinsic or extrinsic failures with low occurrence rate and natural process variations could change the behaviour of the technology and have a major impact on quality and reliability during ramp-up and mass production phase. For that reason, an ongoing reliability monitoring is mandatory for fulfilling ARRA Level B and C.

According to JEDEC JESD659C, statistical reliability monitoring is "a statistically based methodology for monitoring and improving reliability involving identification and classification of failure mechanisms, development and use of monitors, and investigation of failure kinetics, allowing prediction of failure rates at use conditions" [16].

Such monitors could be a multitude of measures, like e.g. accelerated stress tests on process or product level. Based on [16] and [8] the following steps help to implement a proper reliability monitoring in MEMS manufacturing:
- A Statistical Process Control (SPC) has to be implemented. As a guideline [17] can be used.
- Identification and risk assessment of the critical failure mechanisms that contribute significantly to the field failure rate. Tools like the Process- and Product-FMEA and the Knowledge Matrix could be used to make a proper risk assessment. Results of the reliability assessment in conjunction with device characterization, process capability measurement, experience and lessons learned should be incorporated into the risk assessment.
- As an outcome of this assessment, a set of failure mechanisms for reliability monitoring should be identified.
- Proper monitoring parameters should be identified to stimulate the relevant MEMS failure mechanisms. The Knowledge Matrix could help to define proper accelerated stress tests in a similar manner as already done in the actual Robustness Validation. Further monitoring parameters could be derived from in-line process parameters, electrical parameters in wafer probe or final test and defect density screening.
- The vehicle for the monitoring must be defined. It could be the actual MEMS component, or a similar component or test structures that shares the same failure mechanisms.
- The following features must be defined: proper sampling size to identify excursions, acceptance level or accepted failure rate level, frequency and time interval for monitoring activities, proper documentation and exit criteria.

- The ongoing reliability monitoring should be included into the control plan.
- In case of nonconformities, root cause evaluation must be done, and corrective actions have to be implemented as OCAP (Out of Control Action Procedure) on a short-term basis. Products that are affected by the nonconformities should be contained.
- Customer notification is necessary, if nonconforming products have been shipped or significant changes to the process or the product must be made.
- Each supply-chain member (e.g. MEMs foundry, ASIC – Application specific integrated circuit - foundry, assembly) should have its own monitoring plan. Both the ongoing reliability plan and result reporting format shall be defined upfront.
- Monitoring activities should be optimized on a regular basis to address new failure modes or if failure mechanisms are no longer relevant.

Fast tests with short duration could help to enable the production to react immediately to support short PDCA (Plan-Do-Check-Act) cycles.

With respect to the ARRA methodology and the goal of this handbook to help to develop a robust and reliable MEMS product, attention should be paid to accelerated stress tests as a key measure to measure the reliability of the MEMS product after the initial qualification during ramp-up and mass production.

The following table shows an example for a reliability monitoring plan for a MEMS gyro, which showed a weakness of hermeticity and mechanical robustness during the qualification. The first identified failure mode is a MEMS structure damage due to drop or shock during handling in the assembly line and the subsequent manufacturing steps at the customers. Drop tests are conducted on a sample basis per wafer lot to address this concern. Furthermore, a proper hermetic bond seal was identified as a key reliability parameter. Failure of the bond seal due to temperature and humidity aging could lead to catastrophic field failures and was addressed by a UHAST (Unbiased highly accelerated stress test). As long as the tests are running, the corresponding lot is on hold and cannot be shipped. If no fail occurs, the respective lot can be shipped. Tested units will be scrapped. When a single unit fails in a test, then the entire assembly lot will be scrapped.

Failure mode	Stressor	Monitoring test item	Sampling plan			Containment in case of failure
			Sample Size	Frequency	Acceptance level	
MEMS structure breakage	Drop shock	Drop 1.2 m	10 pcs	1x per frontend lot of 24 wafers	Zero failures in final test	Scrap lot
Hermetic seal failure	Temperature and humidity	UHAST 110°C/85% RH, 264h	10 pcs	1x per frontend lot of 24 wafers	Zero failures in final test	Scrap lot

Figure 25: Example of a reliability monitoring

3.6.3 Safe Launch (SL)

The safe launch methodology for a manufacturing process is conducted right after start of production (SOP). Intention of the safe launch is to learn more about process variability during the ramp-up phase and how it affects quality and reliability of the device. Often higher volume production is necessary to identify instabilities of the manufacturing process, which could not be observed during process development, when lower number of units were produced. If the process or the design is not fully mature, the safe launch methodology helps to ensure, that only parts free of defects are shipped to the customer or to the next stage of the supply chain. Furthermore, gathered data of the safe launch can be used to quickly improve the manufacturing process with a short reaction time, e.g. short PDCA cycles (Plan-Do-Check-Act).

Typical issues due to immature MEMS manufacturing processes could be:
- Instabilities in the etch process for defining and releasing the mechanical structures of the MEMS
- Insufficiently defined optical inspections
- Improper training of manufacturing operators

- Variations in wafer bond processes
- Particle contamination of mechanical structures and wafer bond surfaces
- Insufficient test coverage
- Electrical drift of the MEMS device due to mechanical stress or processing variations
- Etc.

The safe launch methodology can be applied to most of the supply chain steps. Generally, the MEMS wafer frontend, MEMS assembly and functional test are the most critical supply chain steps, that should be addressed with a proper safe launch plan.

For product specific safe launch items, like the electrical test specification for a specific MEMS device, the safe launch should be done for each MEMS product separately. If a platform technology is ramped-up for several similar MEMS products, a lead product could be chosen in order to cover the safe launch activities.

Critical items have to be identified in a risk assessment and covered in the safe launch plan. Tools like the process and product FMEA (Failure Mode and Effects Analysis) and lessons learned can be used as well as experience from the past product qualifications. Process data from similar products or platform technologies or from first qualification wafer lots should be incorporated into the risk assessment, too.

A Safe Launch plan should cover quality characteristics like for example:
- Critical characteristics as defined in the FMEA, the control plan, the datasheet and the drawing
- Critical characteristics defined by the customers
- Items which have shown quality issues in the past
- General production characteristics that are covered by process control monitoring
- WAT (Wafer Acceptance Test) or PCM (Process Control Monitoring) data of test structures on the MEMS wafer

Several different measures could be applied to those characteristics including but not limited to:
- Increased inspection frequency (e.g. 25 dies per wafer instead of 5 dies per wafer visual inspection) in the control plan of the manufacturing line
- Tightened process controls (e.g. adapted control limits for Statistical Process Control [SPC])
- Tighten DPAT (Dynamic part average testing according to AEC-Q001) limits during SL
- Additional SPC rules (e.g. follow additional Western Electric SPC rules)
- Tightened scrap limits (e.g. 5 out of 5 PCM sites must meet test limits instead of 3 out of 5)
- Increased number of inspection sites for wafer acceptance test (WAT) or process control monitoring (PCM) (e.g. 8 instead of 5 PCM inspection sites per wafer)
- Functional test at more than one temperature (e.g. additional functional test at upper and lower operating temperature)
- Adapted statistical yield limits as described in AEC-Q002
- Burn-In or other reliability screening methods, see section 3.6.5 use of advanced outlier detection (example: NNR, GDBN, GDBC, DPAT,ULPY, etc.)

The recorded data should be thoroughly and promptly reviewed by the MEMS manufacturer. Suspicious lots or other critical excursions should be reported to the customer.

Proper inspection methods must be available for each item. Suitable inspection methods could be for example:
- Visual aids like low and high-power optical microscopes for manual visual inspection of quality characteristics. A failure catalogue should be available to showcase acceptance and reject criteria for pictures(e.g. pass and reject pictures for chipping of MEMS dies after sawing)
- Measurement microscopes for checking against mechanical specifications (e.g. die tilt after die attached of MEMS die)
- X-ray microscope for non-destructive analysis of internal structures (like e.g. voiding in die attach film or checking for wire sweep after molding).
- Scanning Electron Microscopes (SEM) for measurement of small critical dimensions on wafer (e.g. beam width of mechanical structures of accelerometer after release etch).
- Early Failure Screening (see next chapter)

Measurement data should be gathered and fed into a suitable SPC System.

The duration of the safe launch depends on the ramp-up curve and the criticality of the process and could be defined in a combination of time and manufactured quantity.

As a rule of thumb 3 months or ten wafer lots is assumed for a minimum duration of a safe launch activity for a MEMS device. This ensures, that a sufficiently large process variation of the wafer manufacturing process is covered during the safe launch period, as unexpected or unwanted process variation could significantly impair product quality and reliability.

After the minimum duration for the safe launch, a final review of the gathered data should be done. Excursion in the production and quality issues during the safe launch phase should be addressed with a proper 8D report; the root cause of the excursion must be identified, and corrective actions defined to ensure that the excursion will not occur later during the mass production phase.

Predefined exit criteria could help to determine, whether those criteria have been met. In case the exit criteria have not been met, an extension of the safe launch should be considered.

- Possible exit criteria could be for example:
- A Yield of 85% for the MEMs wafer manufacturing process is reached or exceeded
- A yield of 95% or more is reached for final functional test of the MEMS device
- Cpk of critical process parameters in front- or backend equals or exceeds 1.67.
- No critical failures in final electrical test, that could indicate design weaknesses or manufacturing issues.

Lessons learned from the safe launch phase can be used to improve the final control plan. Additional items could be added to cover identified weaknesses. For uncritical control items inspection frequency or sample size could be reduced.

A reporting should be provided to the customer if requested, as well as a special marking of shipments from the safe launch process.

Further details regarding the safe launch methodology are given in [15].

An example of a safe launch inspection plan, based on a control plan of a MEMS assembly process, is given in the following table.

Process	Insprection Step	One Assembly Lot = 1,000 pcs.			Test Method
		Sampling Size C-Samples	Sampling Size Safe-Lauch	Sampling Size Full Production	
Die Attach MEMS Die	Optical Insprection Leadframe	10 Leadframe	10 Leadframe	5 Leadframe	Microscope, 10x
	Optical Inspection MEMS on Wafer	50 Dies per Wafer	50 Dies per Wafer	25 Dies per Wafer	High Power Microscope, 50x
	Post Dispensing Inspection	100% AOI	100% AOI	100% AOI	AOI Camera Inspection in Dispensing Tool
	Die Placement (Tilt, Roation, x-y Offset)	50 pcs per Lot	50 pcs per Lot	10 pcs per Lot	Measurement Microscope
	Fillet Height	5 pcs per Lot	5 pcs per Lot	3 pcs per Lot	Binokular Microscope
	Visual Inspection According to Failure Catalogue	100%	100%	100%	Binokular Microscope
Die Attach Cure	Dry Bondline Thickness	10 pcs per Lot	10 pcs per Lot	3 pcs per Lot	High Power Microscope
	Die Shear Test	10 pcs per Lot	10 pcs per Lot	3 pcs per Lot	Shear Tester
	Vold Inspection	10 pcs per Lot	10 pcs per Lot	5 pcs per Lot	X-ray Microscope
Post Die Bond Inspection	Manual Visual Inspection	100%	100%	50 pcs per Lot	Binokular Microscope
Wire Bond	Ball Shear Test	20 Balls on 10 Dies per Lot	20 Balls on 10 Dies per Lot	3 pcs per Lot, all Pads	Shear Tester
	Wire Pull Test Cratering Test	5 pcs per Lot, all Pads	5 pcs per Lot, all Pads	4 Wires per Lot	High Power Microscope
	Loop Height	4 Wires per Lot	4 Wires per Lot	n/a	Messurement Microscope
	IMS Inspection	1 pcs per Lot	1 pcs per Lot	100%	High Power Microscope
Optical Inspection	Automated Visual Inspection	100%	100%		AOI System
Moldin	Wire Sweep	100%	100%	1 Die per Leadframe	X-ray Microscope
	Vpöd Omsüectopm	100%	100%	1 Strip per Lot	X-ray Microscope
	Visual Inspection According to Failure Catalogue	100%	100%	100%	Binokular Microscope
Laser Marking	Visual Inspection	1 Strip per Lot	1 Strip per Lot	1 Strip per Lot	Binokular Microscope
Trim&Form	Lead Spam	25 pcs per Lot	25 pcs per Lot	5 pcs per Lot	Messurement Microscope
	Stand Off Height	25 pcs per Lot	25 pcs per Lot	5 pcs per Lot	Messurement Microscope
	Coplanarity	25 pcs per Lot	25 pcs per Lot	5 pcs per Lot	Messurement Microscope
	Package Dimensions	25 pcs per Lot	25 pcs per Lot	5 pcs per Lot	Messurement Microscope
	Delamination	5 pcs per Lot	5 pcs per Lot	3 pcs per Lot	Acustic Microscope
Final Visual Inspection	Manual Visual Inspection	100%	100%	250 pcs per Lot	Magnifier Glass

Figure 26: Example safe launch inspection plan

3.6.4 Early Failure Screening and Burn-In

In this chapter the Early Failure Screening (EFS) methodology is summarized. For the differentiation between Early Failure Screening and Burn-In, the whole procedure of screening for infant mortality failures is called Early Failure Screening, and the actual process of applying stress is called Burn-in.

Early Failure Screening is mandatory for ARRA Level C and optional (but recommended) for ARRA Level A and B.

An EFS is performed on a sampling basis or for 100% of the shipped material as a safe launch measure (see section 3.6.3), to ensure that no defect material with infant mortality issues is delivered to the customer [1]. However, the stress applied during an EFS should not impede the long-term lifetime of the device.

According to [37], the goal of burn-in is to screen out early life defects. Variations or anomalies within the wafer fabrication process and the assembly process could lead to significant reduction in the lifetime of the device. Those extrinsic effects were not or only in a limited extend assessed during the initial qualification. Applying a stress to the MEMS device, similar to the applied stress during the qualification, but with a lower stress level or duration, can trigger early failures of weak parts.

The EFS is a temporary measure during e.g. safe launch phase to identify infant mortality issues and to allow fast implementation containment measures and finally corrective actions to resolve the issue. The EFS is performed in conjunction with appropriate measures in the MEMS production process to ensure consistency of the production process, minimize process variation and extrinsic failures.

Example: Burst pressure test for absolute pressure sensor according to control plan for 5 pcs. per wafer lot to record SPC data for the burst pressure value to check process consistency of pressure membrane formation. Additionally, for an EFS of the first three month of production, 100% of the packaged devices will undergo a proof pressure test according to AEC-Q103-002.

Proper SPC monitoring and other established methods as described in section 1.5 are mandatory.

Proper design for testability and a built-in self-test of the MEMS, potentially in conjunction with an ASIC, can help to facilitate testing, as defect identified in an electrical test more easily [1].

For a proper implementation of an EFS, some key questions have to be clarified:
1. What are the key test parameters for the MEMS components? Definition of test parameters during device and test development and appropriate test limits are essential. A Cpk study and guard banding might also be necessary during development phase, based on three or more lots for proper covering of device-to-device variation. The guard bands shall be implemented in the initial testing in order to guarantee variations within the specification limits over lifetime. The results of a DOE according to chapter 3.6.5 could be used. Maverick lot procedures should be in place as well [37]. Methods like Statistical Yield Analysis [30] and Part Average Testing [38] should be applied.
2. Which failure modes or design or process features have to be covered and what are the associated failure mechanisms? The Knowledge Matrix (section 3.4) and the FMEA should be used as a guideline to address this question.
3. Which stressors are suitable to trigger the identified failure mechanisms? What is the acceleration factor? Once more the Knowledge Matrix and the results from the accelerated testing can be consulted, as well as applicable standards like [31].
4. Is the wafer frontend fabrication process affected, or the assembly and packaging process? Should the stress be applied on wafer level or the packaged part? Generally, burn-in in conjunction with final electrical a mechanical test for a packaged part is often easier to conduct. However, depending on the failure mode, burn-in stress level for a wafer-associated failure mode might be to high for the packaged part.
5. How are the MEMS specific properties covered in the Early Failure Screening? The mechanical nature of MEMS devices could be covered during an Early Failure Screening by applying a mechanical stimulus.

Electrical and mechanical testing of the MEMS devices after the applied stress during EFS is mandatory to identify devices that fail the test parameters or show an unusual large drift after applied stress. It has to be decided case by case, if an electrical and mechanical testing before the Burn-in stress is necessary. As an option test before burn-in stress could be implemented during a safe launch phase and subsequently reduced or stopped if no relevant fails occur.

Reasonable exit criteria must be defined upfront. Such exit criteria could be:

- No additional electrical or mechanical failure after Burn-in. This is only possible if testing is done before and after the actual Burn-in.
- Burn-in triggered failure modes are below a threshold limit, like e.g. 10ppm. In this case physical failure analysis of failed parts is necessary.
- A limit just by time or number of test parts, e.g. 100k parts or 3 month. This only applies if other conditional criteria have been defined.

It is recommended to incorporate the EFS into the overall Safe Launch procedure. Below is an exemplary process flow chart for burn-in and final test for the Safe Launch duration.

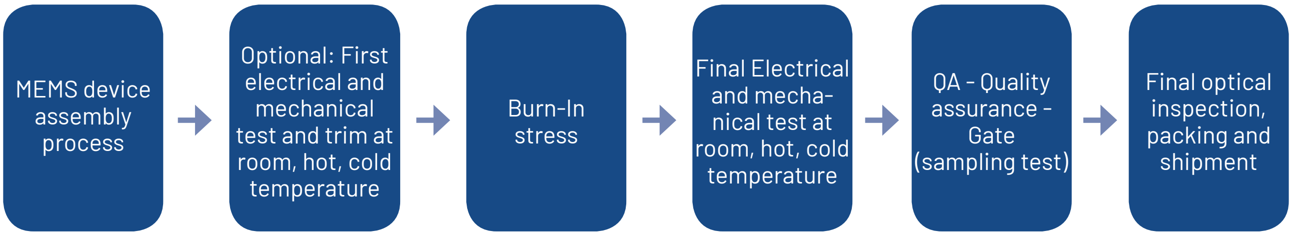


Figure 27: Exemplary process flow chart for burn-in and final test

For MEMS device, the following exemplary risks and failure modes could be addressed by an EFS:

- Membranes typically used for pressure sensors and other MEMS devices could be prone to fracture due to misprocessing. For pressure sensors a proof pressure test could be implemented during EFS.
- Moisture induced swelling of the mold compound could lead to an offset drift of a MEMS device (e.g. pressure sensor, accelerometer). Changes in mold compound behaviour in comparison to initial qualification could lead to field failures. Implementation of a Temperature-Humidity Stress Test during EFS could screen out weak devices.
- Ionic contamination could lead to a drift of MEMS device performance, e.g. an offset drift. A temperature burn-in like e.g. 24h at upper operating temperature could screen weak devices and identify lot or wafer dependent behaviour for further root cause analysis.
- Sensitivity of the MEMS device for failure mode stiction, especially for gyros and accelerometers. Implementation of a simulated mechanical shock during the EFS could sort out stiction sensitive devices. If a physical drop test is conducted, only a sampling test is possible, as dropped devices have to be scrapped afterwards.
- If the MEMS device is combined and assembled together with an ASIC or any other IC (integrated circuit) component, failure modes of both parts have to be taken into account if an EFS is planned. Considerations as shown in [37] can help to define proper Burn-in conditions.

Further information about EFS and Burn-in procedures can be found for example in [37] and [1] and other technical literature.

3.6.5 Corner Lot Evaluation and DOE

3.6.5.1 Basics and Definitions

Long term production stability and quality can be predicted if the inherent variability of the production process is considered and investigated during development and qualification of an application. This can be done through evaluating material for which the production process has been modified to intentionally replicate the existing variability at the specific production site or sites under investigation.

In the industry and throughout literature different terms are used to describe the sets of material used in these investigations, like process lot, matrix lot or corner lot. In this document we will further-on use corner lot. One experiment within such a lot will be called a split or corner split in this document (elsewhere also called matrix cell or corner cell).

The method by which a corner lot is composed is called Design of Experiments (DOE). It describes a statistically sound, structured, reliable and repeatable approach to combining different influencing factors for investigation. More information on this can be found in literature, e.g. [37].

According to the JEDEC JESD88F, a process corner characterization is a "method of determining the functional robustness of a process by varying parameters across their design limits" [28]. The samples for process corner characterization could be either taken from the extremes of a random distribution or by varying the input parameter of a process technology to intentionally generate the corner parameters [28].

According to AEC-Q003, a corner lot is a lot composed of wafers that are based on manufacturing site's process of records and manufactured to the process corners for identifying design/process weaknesses and improvement as well as indicating yield sensitivity corners [14].

For a new device, in particular of a new technology or process, a cross-factored experiment comprising such a corner lot should be prescribed to estimate the effect of long-term process drifting. The corner lot design should be chosen to maximize the estimation of all desired factors and their interactions. The centre value run of the corner lot is called the nominal split. The other variants are called corner splits [14].

The following reviews and methods will help in determining corner lots and have to be considered in their definition:
- Tool capability as a source of parametric variation
- FMEA and DFMEA
- MEMS critical geometries and the process steps that influence them
- Simulations (e.g. corner or Monte Carlo) can be used to determine application sensitivities

3.6.5.2 Various Methods for matrix lot/process characterization [14]

In a corner lot characterization (or simulation), processing variables are forced to certain values (to form corner splits) and the product performance is evaluated. The goal of the characterization is to determine if the device performance will stay within specification limits when processing variables are forced to their worst case values.

The device parameters are the values measured (or modelled), or tests performed, to ensure that the device meets all of the electrical requirements defined in the part specification. In general, the device parameters measured on parts taken from different splits of the corner lot will have different values. Each part parameter, then, will have a performance range, the result of parts being tested from different splits of the corner lot. When characterizing a corner lot, the number of splits, samples per split and the data analysis methods should also be defined in the plan.

In the context of Robustness Validation for MEMS devices corner lots also have to be analysed with regard to the Mission Profile of the application. An overall robustness margin for long term production can then be determined on the basis of the corner lot results.

While corner lot characterization is recommended for all developments of robust MEMS devices, it is mandatory for ARRA level B and C.

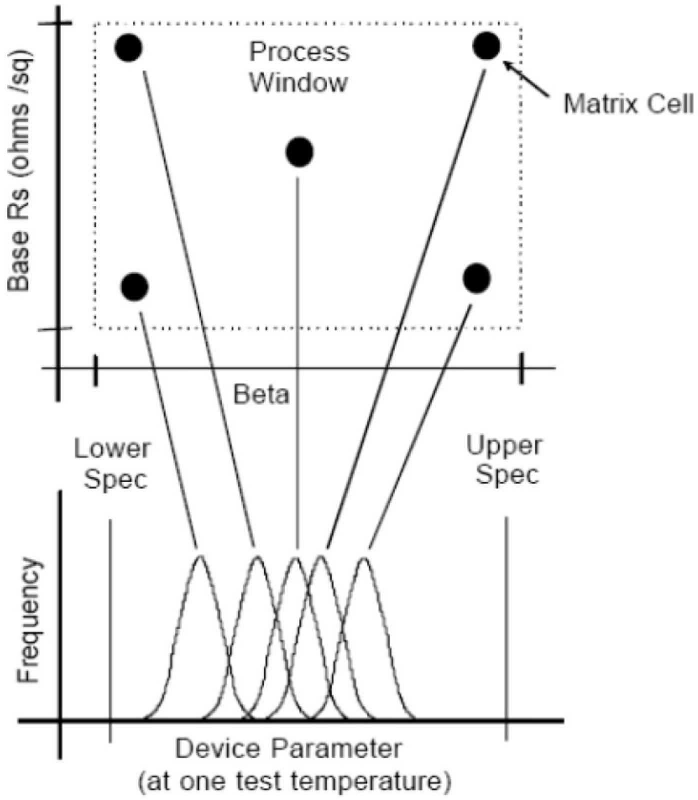


Figure 28: Typical matric cells (top) and parameter performance range (bottom) [14]

3.7 Robustness Assessment of MEMS Devices

In the 5th step of the ARRA methodology the robustness for the MEMS device under test has to be assessed. The results of the accelerated tests and Weibull Studyas well as the qualification tests and further results of family qualification have to be compared with the Mission Profile. A judgement has to be made whether or not the MEMS device has sufficient robustness. This has to be summarized in a standardized report (see section 3.8).

In contrast to the AEC Q standard, the ARRA methodology strives for a mathematical description of the robustness, where ever possible (see next chapter). The AEC Q standard only requires test fulfilment with zero fails and no further calculation of any robustness figure.

Furthermore, the robustness of the MEMS device against process variations have to be proven as well. For intrinsic failures, this could be demonstrated by e.g. performing Corner Lot Studies for ARRA Level B and C. For extrinsic failures, methods like e.g. DOEs, Burn-in, Safe Launch, Ongoing Reliability Monitoring and Corner Lots Studies are suitable and applied according to ARRA Step 4.

Robustness: According to [28], robustness in terms of semiconductor devices means the capability of functioning correctly or not failing under varying application and production conditions with reference to the Mission Profile.

Robustness Validation: In [8] Robustness Validation is explained as "is a process to demonstrate the robustness of a semiconductor component under a defined Mission Profile"

Robustness Assessment: the evaluation and judgement of the results of the Robustness Validation in terms of reliability for each failure mode or parameter of concern.

Reliability Metrics: mathematical description of the reliability of a specific parameter, e.g. ppm, MTTF, FIT

Robustness Figure: a specific reliability metric that is used for the robustness assessment

Robustness Margin: Difference between the evaluated robustness of the device and the targeted robustness per Mission Profile

Figure 29: Robustness terminology used for ARRA

In contrast to the existing ZVEI Handbooks [8][29], it is recommended to use existing reliability metrics that are defined and explained in established literature, e.g. [33][36].

Within the scope of the ARRA methodology, a robust MEMS device must survive the qualification tests that are derived from the application Mission Profile with zero fails or, from a statistical point of view, with an acceptably low statistical failure probability. An over-fulfilment of the Mission Profile could be targeted in specific cases but is not mandatory. However, this can only be proven by a test-to-fail approach or by adding a margin to the reliability tests.

3.7.1 Robustness figures and case evaluation

The mere fulfilment of the qualification tests and therefore the Mission Profile might not be suitable for a mathematical description of the robustness. Hence, advanced statistical methods and proper metrics could be used to further describe the robustness of the MEMS device with regards to the Mission Profile. Both the results of the qualification tests according to ARRA Step 3 and the findings of the Weibull Study of ARRA Step 2 could be used for a mathematical description of the device robustness.

The calculation of the robustness figures from the results of the conducted reliability tests requires advanced statistical methods and a proper background in those mathematical theories. A detailed explanation of all the required mathematical tools can be found in the respective literature [33][36]. Below a short outline is given and further reading is recommended.

The following reliability metrics could be used as robustness figures to determine the robustness of a MEMS device:

- Mean Time to Failure (MTTF): A robust lifetime until device fails for a specific failure criterion and given environmental conditions. From a Weibull plot the MTTF can be calculated. See [34] and [33] for more information on how to calculate the MTTF.
  - e.g. Offset drift of a pressure sensor during 150°C HTOL testing. A Weibull Plot of the failures gives a Weibull parameter of b=3 and a characteristic time T63%=2,000h. 0,1% of the population will fail after 200h at 150°C. Activation Energy for temperature dependence of failure was determined as 0,65eV. At an average operation temperature of 85°C, 0.1% of the population will fail after 5,000h.
    ppm-Values: Failing devices in parts per million for a specific Mission Profile, that means a fixed operational time with well-known environmental and operating conditions. Further information can be found in [1].

- FIT-Rate: Failure in time for 109 device operating hours. Detailed description and examples for FIT- rate calculation can be found in [33], Chapter 19.
  Important for Functional Safety assessment failure rate assessment are necessary to demonstrate that the MEMS is suitable for the safety concept.
- Robust Operating Condition: maximum environmental or operational condition or stress load for which the device survives the required lifetime with a pre-defined acceptable failure rate;
  - e.g. a pressure sensor can be operated at 105°C without failure within the targeted lifetime of 8,000h under nominal biasing conditions;
  - e.g. an accelerometer survives 100 drops from 1.2m height with zero fails.

- Stress Profile Safety Margin: Compliance in % for a given Stress Profile without device failure; e.g. 50% Safety Margin for a device with zero fails after 1,500 HTOL if only 1,000h HTOL are required.
  - e.g. crack propagation in a wafer bond connection of a gyro during temperature cycling has been observed. After 1,200 temperature cycles the maximum allowable crack size has been reached. The Mission Profiles require 1,000 cycles. 20% safety margin.

- Number of failing devices: simplest form of test evaluation, required by AEC Q [11][12].
  - e.g. 2 out of 3x77 devices failed after HTOL testing and functional testing.

Robustness Indicator (RI): according to [29], Chapter 11, this is a value calculated from the qualification test results and the requirements of the Mission Profile, where RI ≥ Robustness Margin

$$Robustness\ Margin \leq RI = \frac{estimated\ strength, min}{required\ spec}$$

estimated strength = measured or calculated value of the item being considered, e.g. time to failure, CpK, shift, Failure level, ect. – min. value required, not the mean value required spec. = requirement value based on Mission Profile or specification, which can also be associated with certain failure level criterias (e.g. 10 years with 1% accumulated failure level).

To better distinguish between real world application conditions and accelerated stress test conditions, the following definition of a use case versus a test case is being used:

- Use case: is the condition, in which the device will work in the actual application, mostly determined by the Mission Profile, e.g. 65°C equivalent ambient temperature for 8,000h of operation at 3.3 V operating voltage and 1 bar pressure.

- Test case: is a specific environmental and functional parameter set for a stress test, which tests the use case accelerated via an acceleration factor, e.g. 1,000h HTOL at +105°C at 3.3 V operating voltage and 2.5 bar pressure for a barometric pressure sensor. The parameters for the test case are derived from the mission profile and the acceleration factor for each specific test.

The robustness can be determined in several ways, depending on type of test case. The following cases can be distinguished.

I. Qualification according to ARRA Step3 without device failure

a. Non-Parametric Qualification Test

- Simple pass/fail criteria; e.g. destructive construction analysis and optical inspection after stress test; proof-pressure test, ESD test; vibration test of accelerometer, etc.
- Only general statement about passing certain test criteria is possible. In most cases no calculation of a robustness figure of a specific parameter with regards the use case and the Mission Profile is possible.
- A robustness indicator (RI) according to [29] can only be evaluated, if test time and/or conditions exceed educated guess about minimum requirements, means RI ≥ RM.

b. Parametric Qualification Test

- Logging of functional parameters during test or in regular intervals (e.g., current consumption, bridge resistance, pressure sensitivity, etc.).
- If a Drift Analysis can be performed to determine time to fail by extrapolation, a Weibull Analysis could be conducted, as well as the calculation of a robustness indicator for the test case.

II. End-of-Life Test with device failure or Weibull Study

a. Non-Parametric End-of-Life Test

- Failure if device stops operating per spec after test conduction; e.g. particle abrasion in gyro after drop test; catastrophic ESD defect; cracked membrane during burst pressure test
- If test criteria exceed educated guess about minimum required stress, a general statement about passing certain test criteria is possible. A robustness indicator in terms of a safety margin for the test case between required stress and conducted stress tests is possible.
- E.g. particle abrasion in a MEMS gyro leads to failure after 150 drops from 1.2m height. Required are 100 drops. 50% safety margin.
- Otherwise qualification has failed. Device does not meet minimum stress tests requirements or any determinable robustness margin.
  - E.g. Gyros fails after 50 drops, although 100 are required.

b. Parametric End-of-Life Test

- Logging of functional parameters during test or in regular intervals necessary; failure if drift exceeds predetermined parameter limit; e.g. leakage current during HTOL, offset drift in PPTC (Pulsed pressure TC), etc.
- A Weibull Analysis can be done. A calculation of a Robustness indicator for the test case is possible.
- If Acceleration Models and factors can be extracted, a mapping of the accelerated stress tests to the Mission Profile is possible. A calculation of a Robustness indicator for the use case is possible.
- If no Acceleration Models and -factors can be extracted, an educated guess about required reliability test conditions can help to evaluate results.
- If Stress Time before failure exceeding educated guess about required reliability test conditions, an estimation of the robustness indicator can be done. Otherwise the test has failed, and the device does not meet the requirements. No robustness indicator can be calculated.

Figure 30: Overview of test cases for the determination of the robustness margin

For the user of this handbook, this means that the results of the stress tests have to be evaluated according to the above-mentioned cases. The robustness figures can be calculated with the use of the before mentioned reliability metrics.

This evaluation has to be summarized in the ARRA reporting (see section 3.8). The used statistical methods and detailed statistical charts (Weibull Plots, drift charts, etc.) should either be part of the reporting or should be available for on-site review.

The evaluated robustness figures have to be compared with expected or target values. Robustness parameters and target values are derived from the Mission Profile. For MEMS devices the mechanical robustness should be in focus.

If the robustness figures for one or more results do not meet the target values, a clear description of the issue and appropriate countermeasures are required and should be provided in the report.

3.8 Reporting

A standardized reporting shall be created by the MEMS manufacturer and should be presented to the customer on demand and transparent documentation of the results of each single step of the ARRA methodology for the desired component.

3.8.1 Content of report

The report should be shared with the customer. Sensitive information with regards to information that deserves protection, could be shared under NDA or disclosed on location at the manufacturer. In the next Chapter a checklist is provided for reference.

The reporting should include the following information:

- General information about the component under test: The AEC-Q100/Q103 CDCQ can be used as a template. A datasheet must be provided as well. The datasheet should include min and max tolerances for all relevant datasheet parameters. Drift limits for temperature and aging shall be included as well.
- The Mission Profile: The Mission Profile that was used to qualify the device must be added to the report (see section 3.3). For ARRA Level A this is the standardized Mission Profile, for Level B and C the customer specific Mission Profiles. The physical variables temperature, humidity, mechanical and chemical loads must be encompassed into the Mission Profile, as well as the desired lifetime in hours for operation and storage (please refer to section 3.3 for more information and Appendix A.1 for a Mission Profile template). Critical failure modes and models should be disclosed, as well as acceleration factors. Literature sources for the applicable reliability models should be mentioned.
- Knowledge Matrix: The MEMS supplier could share the Knowledge Matrix with the customer. If it is treated confidential, it should at least be shown during an on-site visit of the customer for a consistency check. The same applies for accelerated testing results for ARRA Level B and C.
- Qualification plan: the attached template or the template in the AEC-Q100 Table 4a and 4b should be used for standardized reporting. Included information should be: name of test, number of samples, duration, applied stressor like temperature, humidity or vibration, details of electrical biasing if applicable, intermediate readout points. The deviation to the generic AEC Q103 test plan should be clearly noticeable.
- Results of the qualification test:
  - Summary of number of passed samples vs. samples in test. All fails should be addressed by individual 8D reports. Pass and fail criteria must be clearly stated in the test report for each individual electrical, mechanical and optical test, with reference to the latest datasheet.
  - Fit calculation for customer Mission Profile if required.
  - A drift analysis according to AEC-Q100-009 could be provided for Level A parts. For Level B and C a drift analysis of individuals according to AEC-Q100 -009 must be performed.
  - Furthermore, a full PPAP according to [24] or other PPAP standards could be requested by the customer and should be provided together with the ARRA assessment. A summary of the PPAP documents of the subsupplier could be provided as well.
- Zero -Defect Methodologies: Details and results of the required zero-defect items as per ARRA Level (see checklist).

- Robustness margin: with regards to customer application, the robustness margin must be clearly explained in terms of robustness figures as described in section 3.7, based on the test results and the load boundary of the application. A final written risk assessment should be provided as well.

Alternative, if a similar documentation has already been agreed between customer and manufacturer, this agreement could replace the ARRA report.

3.8.2 Exemplary checklists for ARRA report

ARRA Step		General Content	Detailed Items	ARRA Level A	ARRA Level B	ARRA Level C	Checklist
I	Mission Profile	General Information	Table of Content	x	x	x	☐
			Datasheet/Specification Min/Max Tolerances and Drift Limits	x	x	x	☐
			AEC-Q100/Q103 CDCQ	x	x	x	☐
		Mission profile	Generic Mission Profile	x			☐
			Customer Specific Mission Profile		x	x	☐
			List of critical Failure Modes, including Acceleration Models and Factors	x	x	x	☐
II	Knowledge Matrix, Accelerated Testing	Knowledge Matrix	Knowledge Matrix (if confidential, then on-location assessment at supplier)	x	x	x	☐
		Accelerated testing	Results of Accelerated testing (if confidential, then on-location assessment at supplier)		x	x	☐
III	Qualification	Qualification Plan	Qualification Plan according to AEC-Q103/Q100, Table 4a and 4b	x	x	x	☐
		Qualification results	Qualification results pass/fail, including pass/fail criteria. 8D reporting for deviations and fails Summary and general statement about result FIT (Failures in time) calculation is requested	x	x	x	☐
			Electrical distribution assessment and drift Analysis according to AEC-Q100-009	x	x	x	☐
IV	Zero-Defect Methodologies	Zero-Defect Methodologies	Test results for Corner Lots; Results of DOEs if applicable	(optional)	x	x	☐
			Early Failure Study/Burn-in	(optional)	(optional)	x	☐
			Supply Chain Risk evaluation and quality audit results	(optional)	(optional)	x	☐
			Safe Launch Plan for each supply chain members Exit Criteria and schedule	(optional)	x	x	☐
			Ongoing Reliability Monitoring Plan and preliminary results if available	(optional)	x	x	☐
V	Robustness Assessment, Reporting	Robustness Margin	Robustness Assessment	x	x	x	☐
			Final Risk assessment	x	x	x	☐

Figure 31: Checklist for ARRA report

Additional zero defect items	**ARRA Level A**	**ARRA Level B**	**ARRA Level C**	**Checklist**
Cpk-Analysis for electrical test (on-wafer and/or packages part) Cpk should be between 1.67 < Cpk <= 10; explanation in case of deviation from this rule (e.g. Part Average Testing applied, guard banding applied, etc.) is needed. List of test parameters incl. parameter explanation, USL, LSL, Mean, StDev, Cp, Cpk	x	x	x	☐
Proof of use of advanced outlier detection (Example: NNR, GDBN, GDBC, DPAT)	(optional)	x	x	☐

Remarks: "x" means mandatory
If one of the optional items are added to the ARRA Level A or B, the resulting ARRA Level is marked with a "+" (ARRA Level A+ or ARRA Level B+).

Figure 32: Additional zero defect items

4 Summary and Outlook

With the present handbook the Robustness Validation approach for MEMS devices has been completely revised. A new methodology, named Advance Robustness Validation and Reliability Assessment (ARRA) has been developed and specified for MEMS devices. A link to the well-known and widely accepted AEC-Q qualification standards, which is based on a stress test-based qualification, has been established and extended by a knowledge-based qualification methodology.

The ARRA methodology with its three level A to C simplifies the implementation of the Robustness Validation approach and makes a proper tailoring of a MEMS qualification to the actual needs of the market – whether for established technologies or less stringent reliability requirements of the application, or for new technologies or critical applications with high reliability requirements.

A qualification workflow has been presented with well-defined work products and a detailed reporting, which helps the user to implement the ARRA methodology in the companies process landscape and to communicate the result of the robustness assessment.

Furthermore, best practice zero-defect methods have been added to the overall ARRA approach and clear requirements with regards to three ARRA level have been defined. This shall improve the quality level of MEMS with with regard to manufacturing related defects and extend the actual scope of Robustness Validation with influences of extrinsic failures.

We hope that this handbook with its new ARRA approach and its toolset is a valuable and helpful addition to cope for the upcoming challenges in MEMS component development and qualification for future automotive high reliability application.

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7 Terms, Definitions, and Abbreviations

7.1 Terms and Definitions

“Shall”, the imperative form of the verb, is used throughout this document whenever a requirement is intended to express a provision that is mandatory. The words “shall” and “must” are used in the same way of understanding.

The words “should” and “may” are used whenever it is necessary to express nonmandatory provisions. “Will” is used to express a declaration of purpose.

7.2 Abbreviations

AEC	Automotive Electronic Council
ARRA	Advanced Robustness Validation and reliability Assessment
ASIC	Application specific integrated circuit
ASSP	Application specific standard product
BE	Backend
CDCQ	Certificate of Design, Construction and Qualification
CDM	Charged device model
CofDC	Synonymously used with CDCQ
COTS	Commercial off-the-shelf
Cp / Cpk	Process capability index
DFMEA	Design FMEA
DLP	Digital Light projection
DMD	digital micromirror device
DOE	Design of experiments
DPAT	Dynamic PAT
DRBFM	Design Review Based on Failure Mode
DRIE	Deep reactive ion etch
DUT	Device Under Test
ECU	Electronic Control Unit
EEM	Electric and electronic modules
EFS	Early Failure Screening
EMC	Epoxy molding compound or electro-magnetic compatibility (depending on context)
EOL	End of life
ESD	Electrostatic discharge
Fab/FAB	Production site for wafer manufacturing
FIT	Failure In Time
FMEA	Failure Modes and Effects Analyses
Foundry	Semiconductor processing facility
GDBC	Good die bad cluster
GDBN	Good die bad neighbourhood
HAST	Highly accelerated stress testing
HBM	Human Body Model
HTOL	High Temperature Operating Life
HTSL	High Temperature Storage Life
IC	Integrated circuit
IR	Infrared
JEDEC	Joint Electron Device Engineering Council (www.jedec.org)
LED	Light emitting diode
LIGA	LIthography, Electroforming (German: Galvanoformung) and molding
MAP	Manifold absolute pressure
MEMS	Micro Electrical Mechanical System
MES	Manufacturing execution system
MOEMS	Micro Opto Electro Mechanical Systems
MTTF	Mean Time to Failure
NNR	Near neighbourhood residual

OCAP	Out of Control Action Plan
OEM	Original equipment manufacturer
ORM	Ongoing reliability monitoring
PAT	Parts Average Testing
PCB	Printed circuit board
PCM	Process Control Monitoring
PDCA	Plan do check act
P-FMEA	Process FMEA
PPTC	Pulsed pressure TC
PPM	Parts per million
PrHTOL	Pressure HTOL
PWM	Pulse width modulation
QA	Quality Assurance
RF	Radio frequency
RI	Robustness Indicator
RV	Robustness Validation
SEM	Scanning electron microscope/micrograph
SL	Safe Launch
SOP	Start of production
SPC	Statistical Process Control
TC	Temperature Cycling
THB	Temperature Humidity Bias
TPMS	Tire pressure monitoring system
TTF	Time to Fail
UHAST	Unbiased HAST
ULPY	Unit level predictive yield
UV	Ultraviolet
WAT	Wafer Acceptance Test
ZD	Zero defect
ZVEI	Verband der Elektro- und Digitalindustrie

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A1 Appendix

A.1 Mission Profile Case Study and Example

Mission profile case study for a TPMS pressure sensor. See chapter 4.3.1 for more information.

Mission Profile for TPMS Pressure Sensor MEMS			
i. General Information and Lifetime			
Application information	Tire pressure wheel unit module. Mounted on rim/valve inside the tire to measure tire pressure and temperature. Regular RF transmission of measured data		
Service life [years or h]	10 years, 240,000 km		
Operating time [h]	5,000 h		
Non-operating time [h]	83,000 h		
Number of on/off cycles	n.a.		
MEMS special operating load cycles	Learning mode		
	Short cycle transmission in case of pressure loss		
	Transport mode (disabled RF transmission)		
Other general information	n.a.		
ii. Temperature and Humidity Conditions			
Ambient operation temperature Tamb,min/Tamb,max [°C]	-40°C / +125°C		
Operating temperature (operating temperature is measured inside the wheel on the rim surface)	Temperature [°C]	Duration [h]	Duty Cycle [%]
	-40°C - +10°C	1,250	25
	+10°C - +60°C	2,250	45
	+60°C - +90°C	1,250	25
	+90°C - +120°C	250	5
	+120°C - +150°C	3	0.06
Temperature cycling (passive) of Tamb	Base Temperature [°C]	ΔT [K]	# Cycles
	outside air temperature	30	7,300
Rise of average junction temperature for active operation ΔTj	n.a.		
Non-Operating temperature	Temperature [°C]	Duration [h]	Duty Cycle [%]
	-40°C - +10°C	35,690	43
	+10°C - +60°C	47,310	57
Other Temperature conditions (e.g. thermal shock, paint curing temperature)	n.a.		
Required Aec Q10x Grade	n.a.		
Humidity	Relative humidity up to 100%; Condensation and icing possible		
Storage/shipment temperature	-40°C - +125°C		
Storage/shipment time [years]	2		
Storage/shipment environment (e.g. humidity)	Relative humidity up to 100%; Condensation and icing possible		
Other temperature and humidity loads	n.a.		

iii. Electrical Operation		
Operating voltage(s) [V] Min-Typ.-Max	1.2 - 3 - 3.6 V	
Maximum operating currents(s) [A]	10 mA	
Typical operating current(s) [A]	typ: 1-3µA	
Operation pulse conditions	n.a.	
Transients (voltage/current vs. time)	n.a.	
(Outside) Electric fields [V/cm]	n.a.	
(Outside) Magnetic fields [T]	n.a.	
ESD robustness HBM [V]	+/- 3KV HBM	
ESD robustness CDM/SDM [V]	+/-750V CDM	
Latch-up robustness	+/-100mA	
special memory requirements	n.a.	
Requirements for special devices	n.a.	
Special customer requirements:	ESD 15kV discharge gun on pressure channel	
Electromagnetic radiation	n.a.	
Particle radiation	n.a.	
Other electrical loads	n.a.	
iv. Mechanical Loads		
Mechanical Drop	Drop (free fall 1.2m) 10x on concrete and carpet	
Required AEC Q103-002 Mechanical Grade for pressure Sensors	M2	
Required AEC Q103-002 Mechanical Grade for other MEMS	n.a.	
Required JEDEC JESD22-B110B Service Condition for Mechanical Shock	n.a.	
Required JEDEC JESD22-B103 Service Condition for Mechanical Vibration and Acceleration	n.a.	
Mechanical Shock (custom requirements)	± 6,000g shock in each axes (rarely riding over big pebbles at high speed)	
	± 1,000g shock in each axes (often riding over small pebbles at average speed)	
Vibrational loads (custom requiremnents)	Frequency [Hz]	Power spectral density $[(m/s^2)^2/Hz]$
	20	200
	40	200
	300	0.5
	800	0.5
	1,000	3
	2,000	3
	6,000	3
	11,000	3
Constant acceleration (custom requirements)	Broadband RMS acceleration	107,310 m/s^2
	up to 2,500g due to radial acceleration at high speed	
Mechanical loads during handling	Robustness against mechanical shock during rim handling to be tested	
Applied mechanical force for MEMS acutator	n.a.	
Special requirements due to PCB bending	n.a.	
Other mechanical loads	n.a.	

v. Pressure Loads for Pressure Sensor MEMS	
Required Pressure Range (Min, Max)	100 - 450 kPa
Required minimum Burst Pressure	2,000 kPa
Required minimum Proof Pressure	450 Pa
Number and height of Pressure Cycles over lifetime	10 cycles from 0-350 kPa
Number and height of pressure peaks over lifetime	1 Mio peaks up to 1,000 kPa
Maximum differential pressure	n.a.
Other requirements	n.a.
vi. Optical and electro-magnetic loads for optical MEMS	
Interconnect method	Lead free soldering
Solder profile	JEDEC 20D, MSL2
Maximum number of solder cycles	3
Pick and place vacuum pressure	300 mbar
Pick and place force	10 N
PCB singulation method	Sawing process
Oher assembly requirements	n.a.
Programming condition	n.a.
ix. Custom Requirements for other MEMS components	
TBD.	n.a.
TBD.	n.a.
TBD.	n.a.

A.2 Exemplary Mission Profiles for MEMS

1. Temperature Mission Profile

The following exemplary Temperature Mission Profiles have been published in [4].

Temperature [°C]	Lifetime Distribution Class Ia	Lifetime Distribution Class Ib	LifetimeDistri-bution Class II	Lifetime Distribution Class III	Lifetime Distribution Class IV
-40	6%	6%	6%	6%	6%
25	65%	20%	65%	20%	20%
60	20%	65%	20%	65%	
80	8%	8%			
85	1%	1%			
100			8%		65%
105			1%		
120				8%	
125				1%	
150					8%
155					1%

Component mounting location	- Insulated areas in cold box in engine compartment - Insulated areas away from heat sources on Chassis, suspension, under body and wheels - Instrument panel, console, doors, headliner-not exposed to direct sunlight - Cabin Floor or any other space	- Away from heat sources in engine compartment	- Near engine, transmission or other heat sources in engine compartment - Vehicle exterior receiving direct sun light	- Engine/ transmission mounted units, or adjacent to exhaust manifold - Near transmission, exhaust manifold, brake/ wheel-hubs

2. Temperature Delta Mission Profiles

Class	Temperature Delta
I	35°C
II	40°C
III	45°C
IV	55^C

The following exemplary Temperature Mission Profiles have been published in [4].

N = Number of Cold starts per day x 365 x Service Life in Field [years]

Number of Temperature cycles N is calculated as [4]:

Usually, two cold starts per day are assumed for a standard passenger vehicle. Different assumptions may be valid for taxis, trucks and other vehicles. The service life in the field is usually 10-15 years.

3. Vibration profiles:

Alternatively, to the Vibrational requirements of [11, 12] and [32], the following vibrational test profiles as published in [4] could be used.

Random Vibration Frequency (Hz)	**Power spectral density (PSD) [(m/s2)2/Hz]**			
	Vibration Distribution Class I	Vibration Distribution Class II	Vibration Distribution Class III	Vibration Distribution Class IV
4				200
5	0.884			
10	20	10	10	
20				200
55	6.5			
100		10	10	
180	0.25			
300	0.25	0.51	0.51	0.5
360	0.14			
500		20	5	
800				0.5
1,000	0.14			3.0
2,000	0.14	20	5	3.0
RMS	30.8 m/s^2	181 m/s^2	96.6 m/s^2	107 m/s^2
Component mounted on	• Instrument Panel • Body sheet metal • Overhead console • Doors • Lift Gate • Trunk	• Engine	• Transmission	• Suspension • Wheel
Remark	Test duration per axis: 20h for 10 years lifetime or 30h for 15 years lifetime. (The first 8h with thermal profile)	Test duration per axis: 20h for 10 years lifetime or 30h for 15 years lifetime. (The first 8h with thermal profile)	Test duration per axis: 20h for 10 years lifetime or 30h for 15 years lifetime. (The first 8h with thermal profile)	Test duration per axis: 20h for 10 years lifetime or 30h for 15 years lifetime. (The first 8h with thermal profile)

Sinusoidal Vibration Frequency (Hz)	Amplitude of Acceleration [(m/s2)]	
	Vibration Distribution Class II	Vibration Distribution Class III
100	100	30
150	150	
200	200	60
240	200	
255	150	
440	150	60

A.3 Best practice Knowledge Matrix

The priciple structure of a Knowledge Matrix as described in chapter 3.4 was used for an general template which can be easely adapted for the needed requirements. This temaplate can be found on the ZVEI homepage.

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Lobbyregisternr.: R002101 • EU Transparenzregister ID: 94770746469-09 • www.zvei.org

Datum: Juni 2024