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Reliability Qualification of Semiconductor Devices Based on Physics of Failure Risk and Opportunity Assessment

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RELIABILITY QUALIFICATION OF SEMICONDUCTOR DEVICES BASED ON PHYSICS OF FAILURE RISK AND OPPORTUNITY ASSESSMENT

Contents

Introduction

The penetration of semiconductor products into an increasing variety of application segments together with the economic forces of cost and time-to-market require efficient qualification concepts. This requirement influences the organization of the qualification process in conjunction with the development / innovation process as well as the qualification methodology. Proactive practices such as advanced quality planning, "incremental qualification" and confirmation during development have to be practiced in order to meet time to market goals. Results of these activities including the use of further available knowledge will be the basis for the qualification as evidence for the readiness of the product for the market.

These aspects are considered here by a straightforward approach to qualification being part and result of careful development work.

Semiconductor devices specialize to application segments

The different application segments drive the increase and specialization of functionality, and also require optimum solutions for economic integration of components into their systems, their application conditions and application times. This is achieved by

- specific technological adaptation of the product construction (chip internal construction, package or module design) frequently associated with new materials and new or modified technologies, and
- use of products of mature designs and technologies by extending the knowledge about their applicability in more demanding applications.

Time-to-market requires efficient quality planning and confirmation

Shortening time to-market period forces one to consider

- integration of qualification into the innovation process with early start of the qualification activities replacing qualification as a separate and sequential activity,
- effective use of knowledge, i.e., applying existing results for qualification, and
- compatibility with simultaneous engineering practices.

Reliability qualification will refer to physics-of-failure knowledge

As a consequence, the practices of qualifying products for reliability are changing

- from reactive activities at the end of a development cycle applying uniform and predefined stress testing with generic qualification plans
- to measures deliberately integrated into the development cycle making proactive use of stricter physics-of-failure based testing with respect to the product construction and the use conditions of the application segment
- to approaches to measure the robustness with respect to well specified application conditions.

The approach taken is to:

- apply a systematic procedure which enables concentration on those product properties with respect to product construction and application conditions which really need to be qualified (part I), and
- arrange the qualification methodology to correspond to the relationships between designs; technology, manufacturing and product life phases at use conditions (part II).

RELIABILITY QUALIFICATION OF SEMICONDUCTOR DEVICES BASED ON PHYSICS OF FAILURE RISK AND OPPORTUNITY ASSESSMENT

(From JEDEC Board Ballot JCB-25-62, formulated under the cognizance of the JC-14.3 Subcommittee on Silicon Devices Reliability Qualification and Monitoring.)

1 Scope

This publication provides a consistent framework for reliability qualification using the Physics-of-Failure (PoF) concept, which

– is flexible with respect to the requirements of the intended application and market, and

– makes optimum use of the supplier's advanced quality planning and demonstration results gained during design and development and applicable knowledge based on design and technology similarities.

Planning quality and reliability in advance and gaining reliability results with the progress of a design and development process is efficiently supported by a systematic procedure for risk and opportunity assessment.

The qualification concept is based on customer - supplier partnership in order to achieve optimized efforts. The methodology applies to the reliability qualification of semiconductor devices and the processes for their development and manufacturing.

2 Terms and Definitions

For the purpose of this publication, the following terms and definitions apply.

acceleration model: A mathematical formulation of the relationship of rate (speed) of a degradation mechanism or time-to-failure to stresses or use conditions.

application requirements for quality and reliability: The quality and reliability properties of the product required for the intended specified use conditions.

defect, (physical): A physical anomaly that adversely affects function or performance.

defect density: The number of defects on a chip divided by its area.

design rules: The basic rules and regulations for circuit design with electrical and geometrical parameters specified for the range of application conditions and time.

mission profile: 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.

2 Terms and Definitions (cont'd)

physics-of-failure (PoF) concept: An approach to the design and development of reliable product to prevent failure, based on the knowledge of root cause failure mechanisms.

NOTE The PoF concept is based on the understanding of

- the relationships between requirements and the physical characteristics of the product and their variation in the manufacturing processes, and
- the reaction of product elements and materials to loads (stressors) and interaction under loads and their influence on the fitness for use with respect to the use conditions and time.

qualification: The process of demonstrating that an entity is capable of meeting or exceeding the specified requirements.

qualification requirements: The quality and reliability properties of the product suited to demonstrate compliance to the application requirements.

reliability qualification: The process of demonstrating that an entity is capable of meeting or exceeding the specified reliability requirements, usually by tests using accelerating conditions and proven models.

robustness: The capability of functioning correctly or not failing under varying application and production conditions.

risk and opportunity assessment process: The systematic procedure intended to; 1) proactively avoid problems such as unfulfilled requirements, demands, and expectations, 2) take advantage of capabilities (opportunities) that may exceed the requirements for a given approach, and 3) initiate appropriate measures to exploit opportunities and avoid, reduce, or prevent risks that would influence the user.

Safe Operating Area (SOA): The parameter space which guarantees functionality within specification.

service life: the total lifetime of a system.

useful life (of an unrepairable unit): The time interval between the start of use of an unrepairable unit and its statistically expected failure in an application.

validation: The process of confirming the verification process under use conditions.

verification: The process of confirming that the specified requirements are fulfilled, excluding reliability requirements.

wafer level reliability (WLR): The characterization of product or technology reliability on wafer level by applying stress to specific test structures.

3 Planning for Quality and Qualification: Situation, Approach and Procedure

3.1 Application Requirements

The requirements of the customer or the application segments in general refer to:

– application conditions and time (use mission profile, service life),

– processing conditions at the equipment manufacturer,

– storage and transportation conditions, and

– expected statistical reliability properties, e.g., tolerable early failure rate and period.

The different application segments vary concerning their system requirements, application conditions and planned time of use ranging from benign environments and short-term use to harsh environmental conditions and long-term application. This is represented e.g., by chip cards, mobile phones, consumer electronics, computers, automotive applications, telecom networks, each with individual use or mission profiles.

Requirements are specified in terms of:

– robustness against external loads, and

– expected statistical reliability properties, e.g., tolerable early failure rate and period.

3.2 Qualification Concepts

Qualification of products means to confirm their fitness for use as a result of appropriate processes for their realization. This includes:

– verification of their function and performance,

– validation in the system application (less for commodities), and

– qualification for processability (OEM board assembly) and reliability.

There are two different approaches to the part qualification for processability and reliability:

a) examination of the product as a "black box" by comparing its properties to specified requirements as "final inspection" after product development at the manufacturer (or “incoming inspection” at the user). It is, in this sense, reactive,

   – it adds, in general, an additional phase to development, and it hardly differentiates in giving focus on those issues which really need to be qualified,

   – it applies for reliability the “stress test driven qualification“, which confirms a stress test capability by which “a certain level of quality/reliability“ can be expected in the application. The intention of this traditional method is to test for the existence of failure modes, which have been observed in application, by stress tests at elevated conditions. This means, it is mainly based on experience with products of mature technologies. The variable parameters of test and stress conditions are restricted to those, which can be set and varied from outside of the products. These are mainly electrical operational conditions within data sheet limits and environmental conditions. Also the control of the resulting internal stresses is limited or not feasible. The evaluation is essentially <u>qualitative</u>, as the relations between applied stress test conditions and lifetime at use conditions to be covered by tests are usually not established. Therefore the meaningfulness of results is questionable in case of new or changed materials or technologies.

3.2 Qualification Concepts (cont'd)

b) conclusive derivation of qualification targets and activities from application requirements and planned product construction in a proactive way as described in failure mechanism specific knowledge based qualification [11, 12, 13, and 14]:

- it considers qualification as an integral part of design and development with early involvement in this process, i.e., starting in the definition phase and agreeing to requirements and checking their feasibility,
- it makes extensive use of applicable results, e.g., by considering the technological and design properties common to all products or product elements of a technology (family) or results gained on similar products, and
- it adjusts the qualification to the application conditions and the time period of the intended application on a quantitative level with knowledge of active stresses and potential failure mechanisms based upon the "Physics-of-Failure Concept".

3.3 The Physics-of-Failure Concept

The Physics-of-Failure (PoF) concept is an approach to design and development of reliable product to prevent failure based on the knowledge of root cause failure processes [1, 2, 3]. It is based on understanding

- the relationships between requirements and the physical characteristics of the product (and their variation in the production process), and
- the interactions of product materials with loads (stresses at application conditions) and their influence on product reliability with respect to the use conditions.

Reliability results from adequate stability of product properties at the intended conditions of use and time. Products may change with time by physical mechanisms as reaction of materials to loads and as material interactions influenced by loads occurring in use. Materials, their interactions, and the stresses acting on them principally determine potentially active mechanisms.

The PoF concept considers the potential failure mechanisms individually. Their investigation provides the different stress-time-relationships, known as reliability models. Application of these models (and developing them where necessary) enables one to design and qualify a product for the intended application. In detail this has to be done on the level of individual product elements, as their design determines materials, imposed stresses and related mechanisms. More details of this approach to reliability qualification are outlined in clause 5.

3.4 The Systematic Procedure: the Risk & Opportunity Assessment Process

Developing and qualifying a product (and its technology) successfully requires understanding how product performance and reliability (as a result of construction/design, process, materials) relate to use requirements (functional properties and application conditions).

The basic approach of identifying design and qualification aspects is to compare the requirements for the product to the presently available abilities of fulfilling them, see Figure 1. The differences that will be found are gaps requiring solutions or opportunities that can be exploited. Appropriate measures to be taken depend on the level of opportunities or of risks associated with gaps.

3.4 The Systematic Procedure: Risk & Opportunity Assessment Process (cont'd)

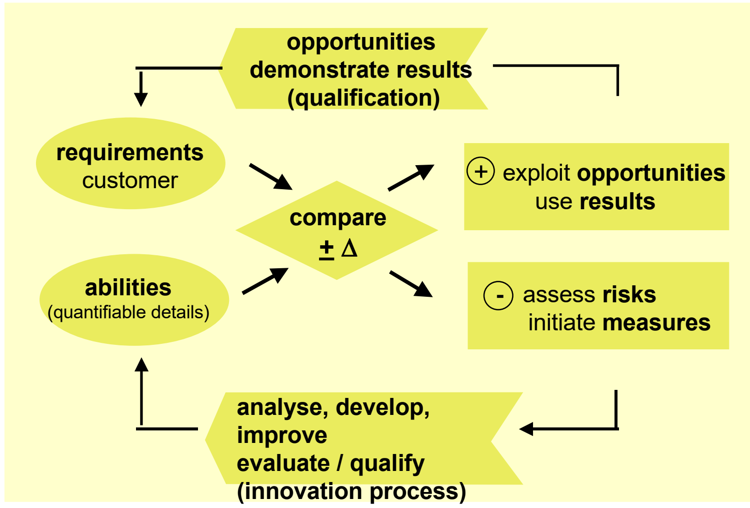


Figure 1 — Principle of Comparing Requirements to Abilities and Taking Appropriate Actions

It is a systematic process including a deductive approach looking at the transformation of requirements by product and process properties (view from outside to inside) and an inductive approach looking at potential faults in the product and processes and their effects for the use of the product (view inside to outside) with the following consecutive steps (for details, see Table 2):

1) collection of requirements and expectations as inputs,
2) identification of product/process elements which have influence on meeting the requirements,
3) definition of their appropriate target values to satisfy function and reliability requirements,
4) checking for potential faults and their effects (inductive approach),
5) stating the actual ability to realize them for function and reliability,
6) evaluation of the risks/opportunities,
7) definition of required actions to exploit opportunities respectively to avoid or control risks, including the background information or references to them.

3.4.1 Product Tree Analysis

The systematic procedure for step 1) and step 2) requires an ordering scheme, which enables one to see in detail, how requirements can be fulfilled by individual product properties. One approach that may be used to do this is the Product Tree Analysis (PTA). It represents the structure of the product decomposed into its elements, where each element is the result of a process step or section (see Figure 2a), and also for checking the propagation of potential faults at process steps and product elements (inductive approach, Figure 2b) into the product application. Thus, it also allows one to trace properties of an element to the relevant process step at a measurable level.

As an example, a semiconductor component would be separated into the package parts and the chip, each with the associated process sections. This procedure can be continued to further levels of detail, e.g., going into wafer manufacturing, provision of masks, design process, etc. The PTA also may serve for structuring of work packages for different specialist groups (chip design, package design, etc.).

3.4.2 Target Values

In principle, the functional requirements propagate from the requirements for the complete product down to the elements and process steps of the PTA in a hierarchical manner (step 3 of process). This serves as the basis for answering questions such as:

– Which element or which property is "responsible" for the fulfillment of a specific functional requirement?

– Which target values and acceptable tolerances of the influencing element characteristic(s) and / or process are needed to meet the requirement?

This is answered using physical relationships between the influencing elements parameters and a requirement. Thus, if the target can be achieved, then the requirement will be achieved, Figure 3a. Interactions between elements will show up, when different elements have an impact on the same requirement or one element has an impact on various requirements.

For reliability and processability, the requirements are the conditions of operation and time in application respectively, and the processing conditions at the equipment manufacturer (OEM). Corresponding questions are (step 4 of process):

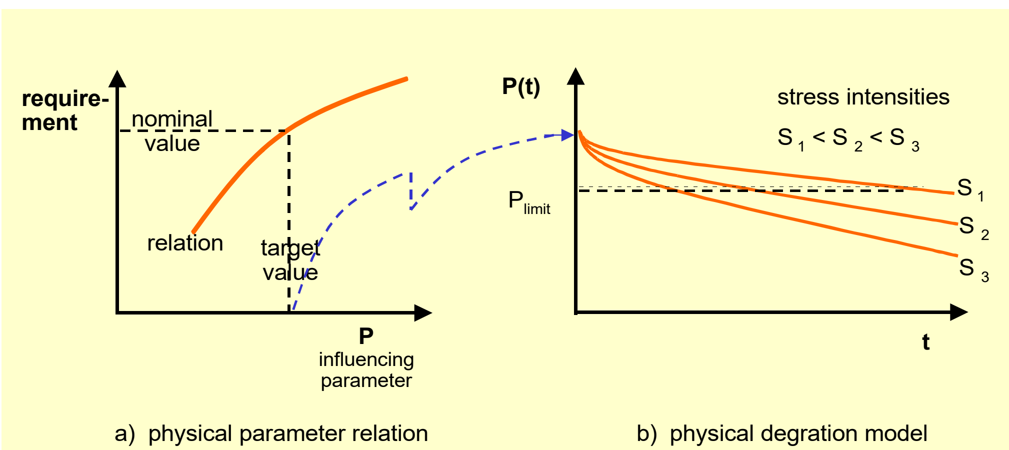
– Which kind of stress (load) acts during operation at an element and which mechanisms may stimulate degradation of an element property?

– Which stress intensity drives the degrading mechanism?

– What level of degradation results in a failure (failure criterion)?

– What is the resulting useful life period?

Here, the physics based reliability models apply, which describe the relationship between the target of acceptable stress intensity and the planned application time. Figure 2b gives an example how a parameter P degrades over time for three different stress intensities starting with $P_{target} = P(0)$. The lifetime ends when P_{limit} is reached.



NOTE Sufficient stability of these characteristics, influenced by stress, is required for the planned application time.

Figure 2 — Fulfillment of Requirements Results from Appropriate Target Values of Element Characteristics

3.4.3 Abilities

The next step (step 5 of process) is to identify the present abilities for realizing the individual target values in terms of

- product/element parameters for the range of operating conditions and intended time
- process capability for the target values at process level.

For reliability the ability refers to the time period during which effects of mechanisms do not drive product properties out of functional limits (P_{limit} in Figure 3b).

The actual ability may result from element specifications (electrical parameters, geometric design rules) of an existing qualified process, and / or simulation, experience, test etc. If the ability cannot be determined in the first approach due to lack of available information, further in depth information gathering is required, e.g., by investigation, simulation, etc. as part of the development work.

During these analytical steps applicable knowledge and data are introduced at the highest possible level, i.e., whenever a requirement can be related to an element (which again may include sub-elements). With known influencing parameters and values, there is no need for going into further details, i.e., into sub-elements. This enables the most efficient use of engineering resources.

An effective way for introducing applicable knowledge and results is, e.g., by asking:

- What requirements are covered with respect to qualified similar products / processes incorporating the same elements / parameters and how?
- What is new / changed?

<u>The data of abilities meeting the requirements are qualification data</u>.

3.5 Risk and Opportunity Assessment

The found opportunities provide advantages in savings of resources or increased performance or safety margin of the product (step 6 of process). Found gaps can be evaluated by assigning risk levels, e.g., as given in Table 1. They indicate the necessity and importance of appropriate measures of development and qualification which shall be taken as consequence.

Table 1 — Example for the Definition of Risk Levels

Risk Level	Target vs. Ability
UNKNOWN	target value and / or ability missing
LOW	stable process / product, parameter clearly can be met
MEDIUM	parameter can be met
HIGH	parameter worse than target
UNACCEPTABLE	not feasible within the frame of the present resources

3.6 Advance Quality Planning and Qualification

Applied as a support tool to an innovation process, a Risk and Opportunity Assessment Process (ROAP) starts with the beginning of a project. It accompanies the project updating the individual abilities by new or improved data gained from closing gaps, which are qualification data and their evidences.

One of many methods and formats for translating requirements into fulfillment during development is the "We-Know-Matrix" (WKM) is depicted in Figure 3. It is organized for documenting the individual steps and data gives evidence,

- HOW the requirements and expectations of the customer/application are fulfilled,
- WHY a specific qualification measure is necessary.

In addition it serves as

- a planning tool,
- guidance through the process
- information and overview representing actual status at any time.

The procedure challenges and promotes the interdisciplinary teamwork of people involved in a project to a common working base.

Completed "WKMs" contribute to the common knowledge base/expert system providing information for future projects, e.g., applicable for DFR/BIR (designing for reliability/building-in reliability) or serves as reference base for modifications.

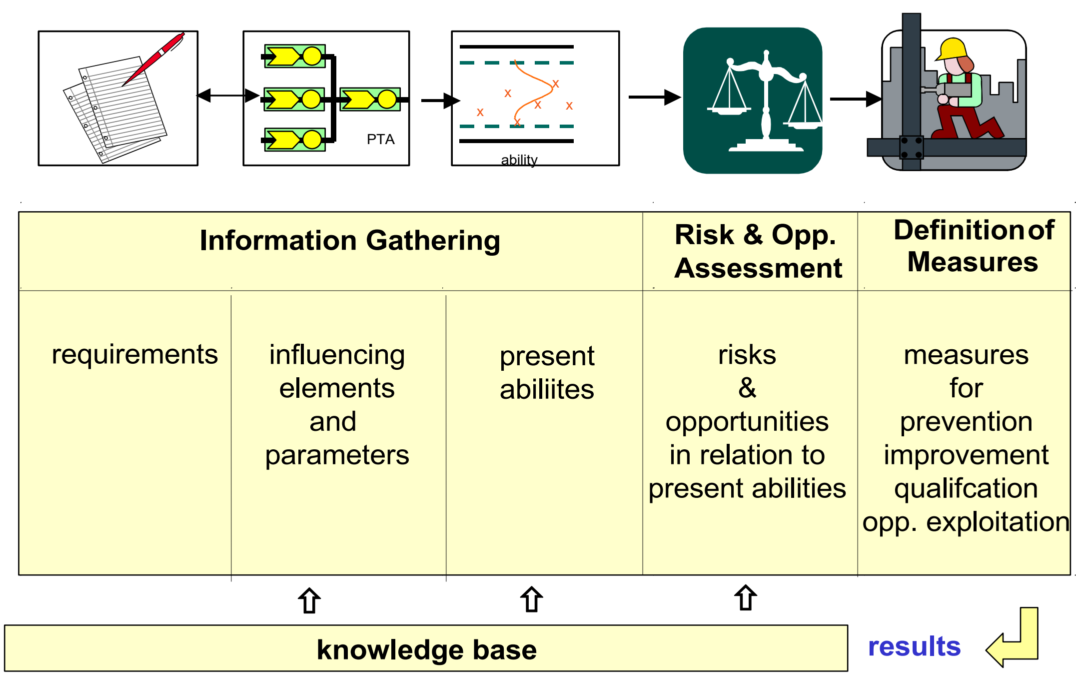


Figure 3 — Basic Recording Scheme for Application of the Risk and Opportunity Assessment Process

3.6 Advance Quality Planning and Qualification (cont'd)

With reference to known quality management tools the procedure applies elements of

- QFD (Quality Function Deployment): relationships between requirements and properties of product elements, and
- FMEA (Failure Modes and Effects Analysis): estimate of the ability together with risks and measures (potential problems) to achieve the necessary properties.

The complete procedure readily gives the focus on the issues of interest, their solution and qualification. More details are given in [4].

The overview (Figure 3) illustrates on a generic level, how the risk and opportunity assessment process is combined with the innovation process and how qualification plans and data in different stages result from and grow during completion of the ROAP.

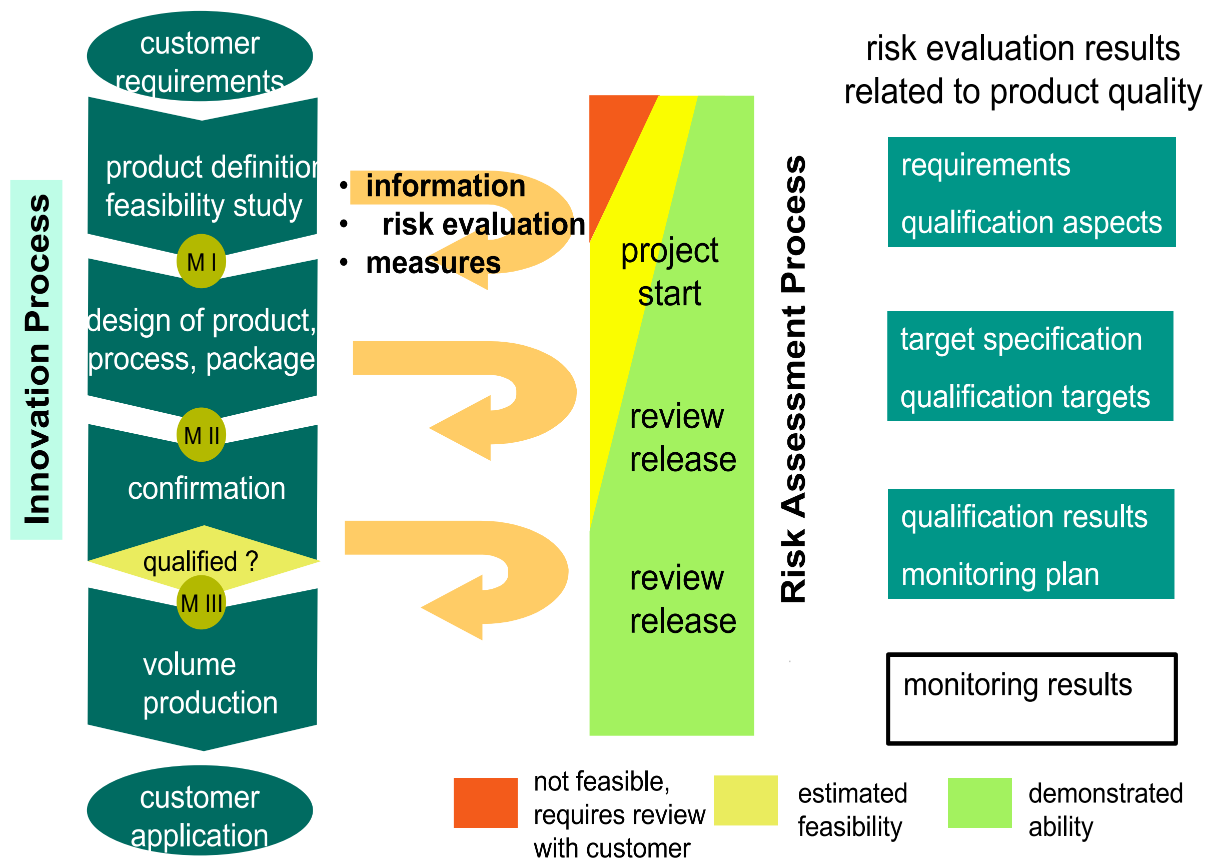
The innovation process is represented with the phases product definition / feasibility, development (design of product, wafer and package technology), confirmation of collected results, volume production, each terminated by a major milestone for review and release. Assessing risks and opportunities starts with the definition phase and provides feedback for taking measures in the innovation process. Doing this continually along the innovation process will steadily up-date results and close gaps.

From the qualification point of view the relevant issues for qualification planning, the qualification results, the required activities for ensuring reproducibility in manufacturing will be generated [e.g., statistical process control (SPC), screening and reliability monitoring (both WLR / product)].

The coarse structure depicted in the overview will be more detailed in practice, e.g., including steps assigned to the differing maturity levels of the development results, as defined by the statistical confidence of achieved data or the reproducibility of results, e.g., determined by SPC.

3.6 Advance Quality Planning and Qualification (cont'd)

As an alternative the ROAP and WKM could be integrated into the innovation process to trigger risk assessment at the relevant phases (see Figure 4).



NOTE The risk and opportunity assessment process (ROAP) "accompanies" the innovation process, it initialize actions, up-dates results including those for qualification and monitoring.

Figure 4 — The Risk and Opportunity Assessment Process (ROAP)

A typical risk pareto develops with the project's progress:

– At MI after feasibility study of concept has been performed some open topics with unknown or insufficient abilities (red) have been resolved and there are still some topics with estimated ability (yellow). For many requirements the ability can be demonstrated by referencing to other projects.

– At MII, at the end of the design phase, most of the estimated abilities have been transferred to demonstrated ones.

– At MIII the product and technology is now qualified and ready for mass production. All intrinsic abilities have been demonstrated.

– After MIII maturity is demonstrated using volume ramp up.

3.7 Guide Through the Process (How to Use the WKM)

Record the results of the individual steps in a tabular format as “We-Know-Matrix”. Three examples how to apply the methodology are given in Annex A.

Table 2 — Process Steps to Generate WKM Input

Process Steps	Activities
What are the requirements?	Collect the requirements for - function and parametric performance - application conditions and time - processing conditions at the equipment manufacturer - robustness against random external loads - expected statistical reliability properties (tolerable early failure rate, useful life) It is useful to distinguish MUST and WANT requirements for potential trade-offs.
How do the requirements relate to the product elements and their processes?* (deductive approach)	Dissect the product into its elements and related processes (Product Tree Analysis) to the necessary level, determine per element and/or related process - the relevant parameters - the target values and tolerances needed to meet the requirements (process capability)
Which stressors are active for what time?*	Determine per element: - the external and internal stressors which are active at the individual elements - their value (intensity) and active time
Which failure mechanisms may be relevant?*	Check which potential failure mechanisms may be active at the individual elements under the identified stressors.
What are the abilities to meet the requirements for* - useful life† ? - processability? - robustness? - early failure rate?	State the ability to realize the target values and record evidences, use applicable knowledge, e.g., - What is known and applicable from qualified similar products and processes incorporating the same elements / parameters? -What is new or changed? The data of evidential abilities meeting the requirements are qualification data.
Which faults may occur? (inductive approach)	which faults are likely to occur in the product/process having an impact on the application of the product?
What are the risks and opportunities?	perform a risk and opportunity assessment (abilities vs. requirements) and classify, e.g., - target value and / or ability missing: risk unknown - ability clearly exceeds the requirement: opportunity - stable product / process parameter, parameter clearly can be met: risk low - parameter can be met: risk medium - parameter worse than target risk high - not feasible within frame of present resources: risk unacceptable
What actions are required?	- determine necessary activities in case of risks, e.g., investigations; modeling, improvements, corrections and /or opportunities, e.g., better offer to the customer - return them to the relevant business process - evaluate the result of the activities by restarting this process for the relevant items

* The required level of detail will be reduced by applicable knowledge. If a product element satisfies the requirements as can be shown by available data, further detailing of this element is not necessary.

† Useful life: use the stress vs. time relationships (models) for the individual mechanisms

3.7 Guide Through the Process (How to Use the WKM) (cont'd)

The "We-Know-Matrix", see Figure 5, provides the working tool for the results of the individual steps. A template can be used as provided by standard software tools. Apart from fairly simple projects it will be necessary to refer to more details than can be filled into this basic form. Options are:

– The use of WKMs per product element.

– The provision of links from individual cells to more detailed information.

– ...

The sorting mechanisms of the software tool will help

– to find, e.g., element parameters that influence several requirements (>> interactions),

– to allocate measure packages to expert groups for specific product elements,

– ....

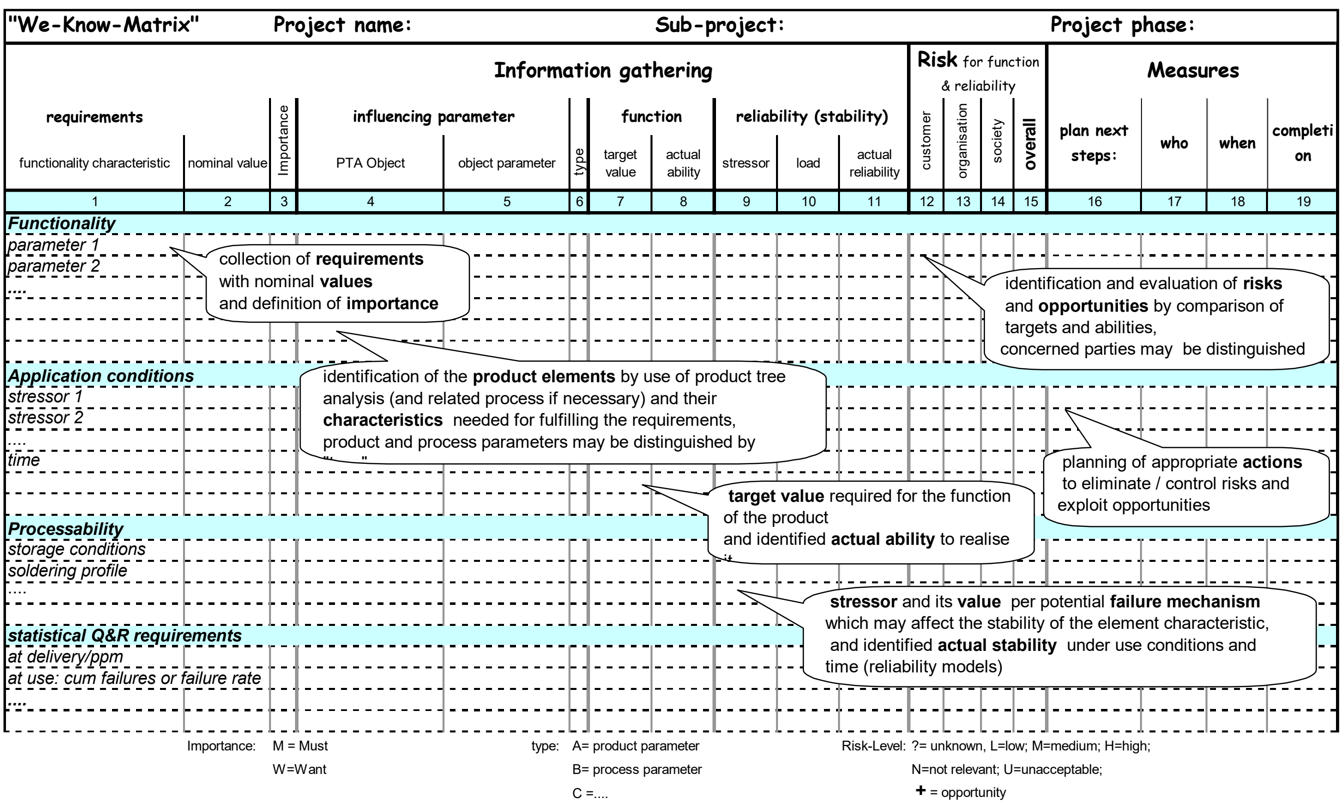


Figure 5 — Overview We-Know-Matrix

4 Reliability Evaluation of Integrated Circuits - the Methodology

This clause describes in general the methodology for reliability evaluation by testing. The specific selection, i.e., which product elements and reliability properties are to be evaluated by this methodology, is determined using the risk and opportunity assessment process (ROAP).

4.1 Reliability: the Stability of Product Properties under Stresses of Use

As described with the PoF concept, the properties of product elements, their materials and their interactions change in response to stresses applied in use by physical/chemical processes. The stresses may be external, like environmental conditions acting on the product, or internal, like internal electrical and thermal operating conditions.

The groups of processes inherent in a product construction under stress are in principle:

- diffusion and reaction processes in or between materials due to concentration gradients, temperature and electrical potential,
- fatiguing of materials and material joints resulting from mechanical and thermo-mechanical stresses, and
- transport, accumulation and trapping of charges driven by electrical fields resulting in changes of characteristics of integrated devices (transistors, ...).

These processes are intrinsic (wear-out) failure mechanisms, which change properties of product elements and ultimately may cause failure of the product, if limits required for the product function are exceeded.

The combinations of materials and stresses determine the kind of failure mechanisms; the specific stress intensity as a function of the stress and dimensioning of an element determines the rate (speed) of the process and time to failure.

Figure 6 illustrates the modeling of a failure mechanism by experiments. The value of a characteristic (parameter) changes with time as a result of a failure mechanism. Failure occurs, when the tolerance limit of the characteristic required for a product function is exceeded. This behavior is redrawn as the relationship between stress intensity and time to failure and thus a “safe operating area” (SOA) is defined limiting the applicable stress versus time. The functional dimensioning of an element taking into account the acting stress determines the tolerable P_{limit} and as consequence the time to failure.

4.1 Reliability: the Stability of Product Properties under Stresses of Use (cont'd)

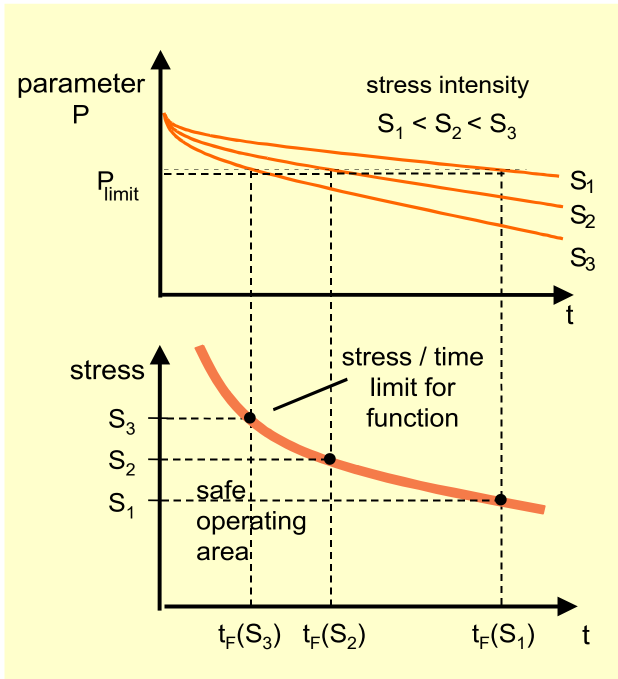


Figure 6 — Change of a Product Characteristic under the Influence of Different Stress Intensity Levels and Resulting Safe Operating Area

Figure 6 also shows two options for establishing a model experimentally by

– observing a parameter which is indicative of the degrading mechanisms, and

– recording the times to failure, if access for direct observation is difficult.

The first option, if feasible, has the advantage that the drift of the parameter can be reasonably projected into the future and thus allows failure prediction.

General plausibility of a model is achieved, if the physical mechanism is understood, confirmed for the stress range of interest (failure analysis) and its kinetics can be related to first principles. If materials, technology or dimensions are changed, the established models frequently need to be reconfirmed concerning the stress sensitivity of a mechanism or scaling of the SOA. The models serve as tools for reliability testing at accelerating conditions.

Examples using this basis for qualification with respect to use conditions are given in [5, 6]. In addition, models are increasingly used for simulation of reliability properties and thus, simulation becomes a tool for "virtual qualification" as an alternative for confirmation by tests on hardware [7, 8].

4.2 Reliability Requirements and Evaluation Concept

The requirements for reliability address different aspects of the product life phases:

– endurance of the product to perform at application conditions for the planned time of use (time to failure by an intrinsic mechanism > time of use),

– fraction of products failing in the early phase of use (early failure rate) due to latent defects undetectable by final test,

– robustness against random external loads in application, e.g., ESD, EMI, voltage transients (latch up), radiation, which may cause failures occurring randomly distributed versus time, and

– compatibility with assembly, transportation and storage conditions.

These different groups of properties contribute to the typical overall reliability characteristics as represented by the different sections of the cumulative failure or the failure rate versus time, as seen in Figure 7.

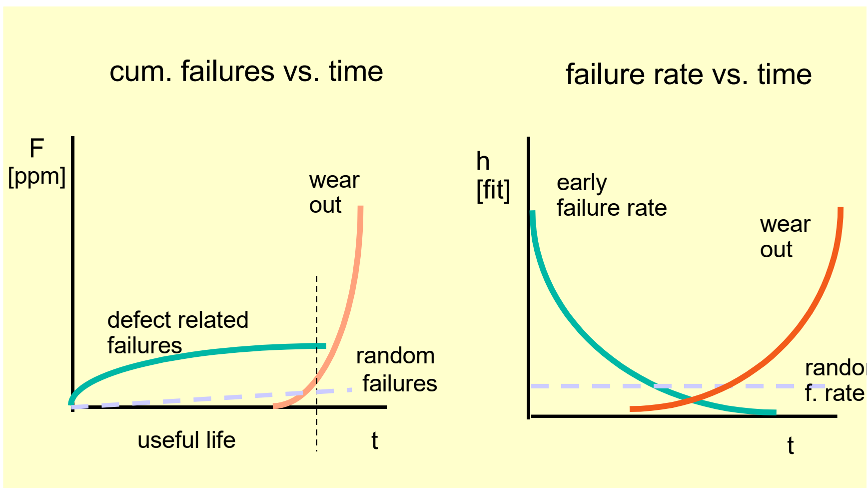


Figure 7 — Phases of Product Life Characterized by Different Causes of Failure, the Combination of the Failure Rate Curves is Known as the "Bath-tub Curve".

Each of these different sections is covered by a specific approach for evaluation based on the PoF knowledge. Table 3 gives an overview of the basic evaluation concept. Table 4 shows details for tests.

Table 3 — Basic Evaluation Concept

Purpose of Evaluation	Reliability Risks	Evaluation Concept
product useful life	effect of failure mechanisms dependent on construction of elements and functional and environmental stress	evaluation of the individual mechanisms using - mechanism related test devices (may include the product) - acceleration models, simulations
defect related reliability	frequency of (early) failures	test of representative product or monitor products of a technology, limited use of models
processability & handling at OEM	see product useful life	simulation of assembly stress, storage and transportation
electrical robustness	level of sensitivity to random external electrical loads (transients, discharges, radiation)	specific tests per product type e.g., - ESD - latch up - EMI, radiation

4.2 Reliability Requirements and Evaluation Concept (cont'd)

Table 4 — Reliability Test Scheme

Test Intention	Sample Size
electrical function and performance test for verification of correct design as **intrinsic** property (use of design rules, defined elements, cells including manufacturing variation) within the range of the defined use conditions	small: adequate for functional verification and characterization of the distribution of the specified parameters
intrinsic capability concerning - electrical **robustness** - **processability & handling** at OEM	small: adequate for verification of product design/construction by appropriate tests, e.g., distribution of strength vs. stress
intrinsic stability of properties during **useful life**	small: adequate for the characterization of the failure distribution for individual mechanisms with respect to the requirement for useful life
defect related (early) **failure rate** (**extrinsic**)	large: adequate for characterization of the low rate of failures (usually requires cumulating of data for a period of time on technology representative product respectively collecting field data)

Part of investigating and modeling mechanisms is the derivation of indicators for mechanisms, which are directly measurable. These serve for control of manufacturing and are accessible e.g., at suitable on-wafer test structures.

4.2.1 Evaluation of Useful Life Time

Products are qualified for useful life by checking that the effects of inherent mechanisms due to materials and design of product elements under application stresses do not limit the planned application time as systematic (intrinsic) properties, i.e., the SOA covers the planned conditions.

The relationships (models) are typically established in context with the development of a new/changed technology and its pilot product. They are introduced into the electrical specification of elements, the geometrical design rules and libraries of functional elements and circuit cells for future products, which will be designed and manufactured using this technology. Thus, these relationships are applicable to all products using the same technology and design basis (rules).

The methodology for the establishment of models and also for evaluation testing applies specific test devices as sensors for the individual mechanisms, e.g., discrete circuit elements, usually with special packages or at chip / wafer level. They are designed

– for stimulation and good observability of the individual potential failure mechanisms, and

– for applicability of much higher stresses for test acceleration than can be done on a product.

The test devices later also serve as process monitors, preferentially at wafer level.

Table 5 lists essential reliability aspects relevant for useful life for integrated circuits. There are some specific cases where a product serves as an appropriate sensor for an individual mechanism, like products with a single core function, e.g., EEPROMs, when tested for stability of data retention.

4.2.1 Evaluation of Useful Life Time (cont'd)

Table 5 — Essential Reliability Aspects Relevant for the Useful Life of Products with Indication of Mechanisms and Relevant Stresses

Reliability Aspects for Product Elements	Examples of Mechanisms	Stressors (loads)
stability of electrical characteristics of active and passive devices	- trapping of injected charges (hot carrier effects) - ion drift, surface inversion	E, T E, T
time dependent breakdown and leakage of dielectrics (thin oxides)	- trapping of charges	E, T
stability of conductors, contacts	- interdiffusion of different metals with growth of voids - electro- and stress-migration	T J, T
robustness of product construction: - thermo-mechanical mismatch of product elements materials - protection against humidity	- cracking - mechanical fatigue at material interfaces - corrosion	ΔT # cycles ΔT relative humidity
T = temperature ΔT = temperature interval E = electric field strength J = current density		

More details on mechanisms and models are provided in [9, 10, 11], where accepted models are given.

In contrast to this concept, direct testing of products at maximum rated conditions of operational and environmental stresses at reasonable test durations (e.g., 1000 hours) usually is not capable to simulate many years of application, as the standard test procedure "High temperature operating life test" might suggest. This is discussed in more detail in 4.3 and in [11].

4.2.2 Evaluation of Defect Related Reliability

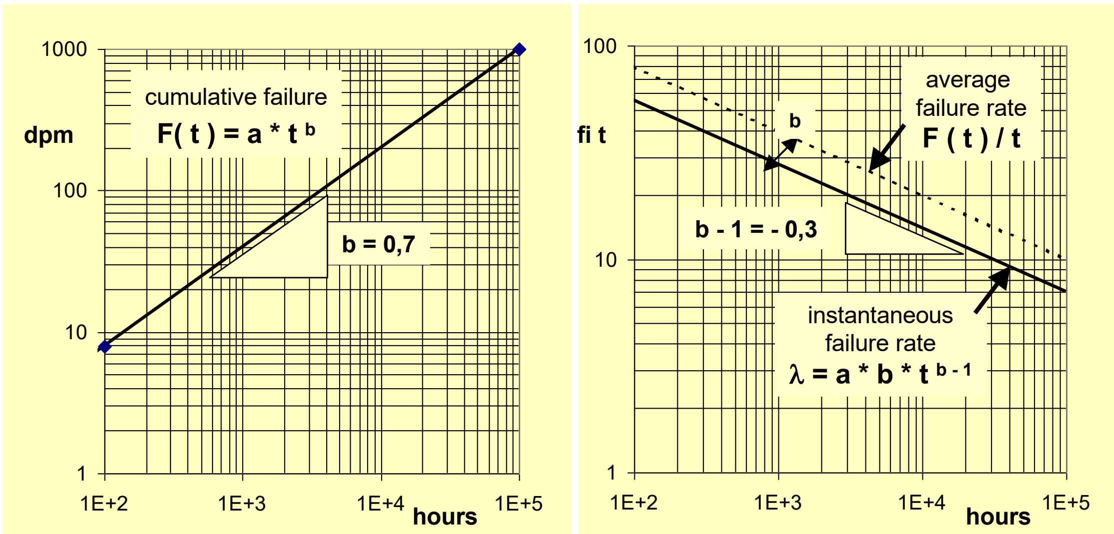
Defects induced during manufacturing ("extrinsic defects") appear to a small extent as latent i.e. undetectable by the final test of the product. These latent defects are small local anomalies in materials or structures of product elements and may cause early failure ("infant mortality") under application stresses. Type and site of the defects are randomly distributed in a product quantity.

At the defect sites the stress intensity is strongly increased, as the weak spots do not have the designed properties, e.g., element dimensions. This typically is observed as an increased rate of failure in the early period of application.

This reliability concern is a statistical characteristic related to the defect density of the specific manufacturing process and respectively of the state of art of controlling defect density. Determination of the defect related product failure rate nowadays requires large sample sizes, frequently accumulated by periodical tests (monitoring). Therefore, this typically is performed on a representative high volume product or equivalent monitor product of a manufacturing line. The common test procedure is operation under maximum specified or manufacturer-determined conditions.

4.2.2 Evaluation of Defect Related Reliability (cont'd)

The defect related part of the cumulative failure distribution and the decreasing failure rate curve usually can be represented by a simple power function, see Figure 8.



NOTE The model curves are drawn for cumulative failure of 1000 ppm after 10^5 hours. The parameter value b = 0.7 used here, has been found experimentally for logic circuits from different processes and sources.

Plotted are the number of cumulative failures and failure rate (instantaneous and average) versus time.

Figure 8 — Model for the Description of Defect Related Reliability

Once the starting level and the slope of the cumulative failure or failure rate curve has been established, it is quite reasonable to extrapolate the curves for longer application periods towards the limit of useful life determined by the procedure in 4.2.1.

4.2.3 Robustness Against Random External Loads; Random Failure Rate

This aspect considers the product sensitivity to unusual electrical loads during handling, like electrostatic discharge (ESD), during application like latch-up, electromagnetic interference (EMI) and radiation. Under the aspect of physics-of-failure, the stresses are considered as overloads with immediate transient failure or damage to the product (e.g., ESD). The properties for robustness depend largely on the circuit design and layout of the specific product. Frequently trade-offs are necessary between functional performance and robustness.

The required specified values of robustness are directly checked by dedicated tests. Due to the random occurrence of over-stress events, random failures occur when the robustness against external influences is exceeded. For these stress levels the estimation of random failures is not within the ability of the component supplier. Control of random failures means control of disturbing influences during application.

4.2.4 Processability & Handling

The process of assembling components on circuit boards or into modules, transportation and storage is simulated at defined conditions. Under reliability aspects, this simulation also serves as “preconditioning” stress before reliability tests are performed. The capability to endure these stresses without damage is a property mainly of the construction of component packages.

4.3 Applicability of Models to Complex Products

The PoF concept addresses failure mechanisms individually. Tests that are applied to completed complex products usually will address more than one mechanism. Thus the models involved need some consideration concerning their proper use and limitations. The models commonly used are discussed in detail in JEP122.

4.4 Basic Reliability Test Scheme

This test scheme represents the fundamental structure and conditions of reliability testing with respect to the requirements (3.1) and failure mechanisms relevant for application. Stresses are <u>local</u> stresses at the product element under consideration. The test conditions are usually defined by standards (an overview is given in JEP143), qualification gates should be chosen according to application conditions.

4.5 Statistical Model Distributions and the Choice of Sample Sizes

Reliability evaluation is performed on samples, which represent products of the same kind. Same kind means: the products can be designed for different functionality but use the same construction principles, elements and design rules based on one manufacturing technology (product families).

By testing until failure the results of stress tests are failure distributions. Usually, two distribution types are of interest;

- lognormal distributions: random variables contribute multiplicatively to the times to failure, and
- extreme value (Weibull) distribution: the individual time to failure is determined by the “weakest point” among similar weak points of a sample.

Sample sizes should be adequate for the characterization of the failure distribution. This means for

- testing **properties systematically common to all products** (intrinsic properties / failure mechanisms) of the same kind: the sample size can be small, and
- testing for a **small fraction of defective products** (latent defects / weaknesses): the sample size should be large corresponding to the small fraction to be determined.

Traditional qualification plans with LTPD based sample sizes usually do not provide this differentiation for appropriate sample sizes*.

---

* Sample sizes with acceptance numbers given in traditional stress test qualification tests refer to LTPD (lot tolerance percent defectives) sampling plans, e.g., the acceptance number and sample size 0/77 refers to LPTD = 3, which defines an acceptance probability of 10% of a lot with 3% defects/failures or more.

4.5 Statistical Model Distributions and the Choice of Sample Sizes (cont'd)

Figure 9 shows schematically a distribution of times to failure caused by a mechanism. It is represented as a lognormal distribution together with the confidence range for a small sample size of n = 20. (The distribution is represented at use conditions using the specific acceleration model for the observed mechanism.)

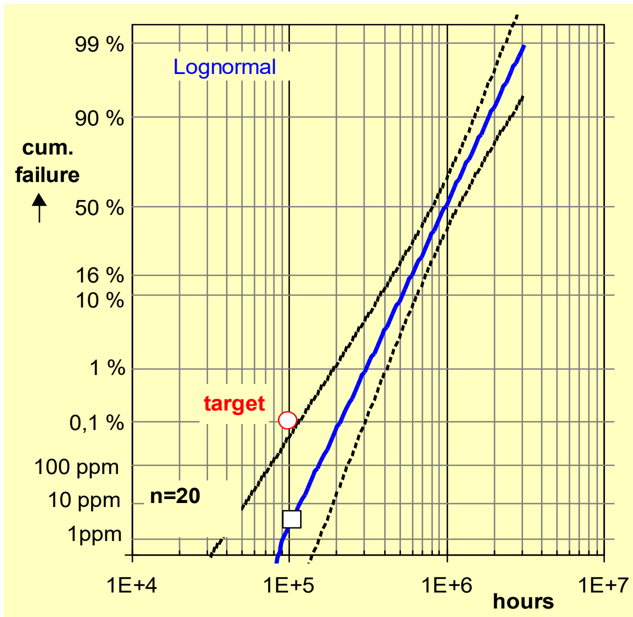


Figure 9 — Schematic Lognormal Failure Distribution with 90% Confidence Range for Sample Size n = 20

As long as a chosen target value of max. tolerable cumulative failures during useful life is greater than the upper confidence limit of a determined distribution, the useful life is confirmed for the effects of the mechanism under consideration.

The example also illustrates for which orders of magnitude the effects of systematic degrading mechanisms need to be checked in order to assure useful life. In the example the characteristic value of the failure distribution (here median value) would be 10^6 hours. This also explains why tests with high acceleration are required for investigation and demonstration.

The indicated target value of cumulative failure is 0.1% (1000 ppm) in 100,000 hours of operation (at 12 years). Averaging this over the passing life period would result in an average failure rate of 10 fit (10×10^{-9} h^{-1} or 10 ppm / 1000 hours).

Testing for defect related reliability means determination of small fractions of products affected by (extrinsically induced) weaknesses. These are outliers / mavericks in large volumes of defect-free products. Here, large sample sizes are required for adequate demonstration of a tolerable failure rate due to the fraction of weak products. This typically is performed using a representative product or monitor product of a technology.

Manufacturing variability with effect on reliability properties is an additional concern, which is taken into account by taking samples from lots produced in a reasonable time window.

Annex A (Informative) Examples for Application of the Risk and Opportunity Assessment Process (ROAP)

A.1 Example of Package Development

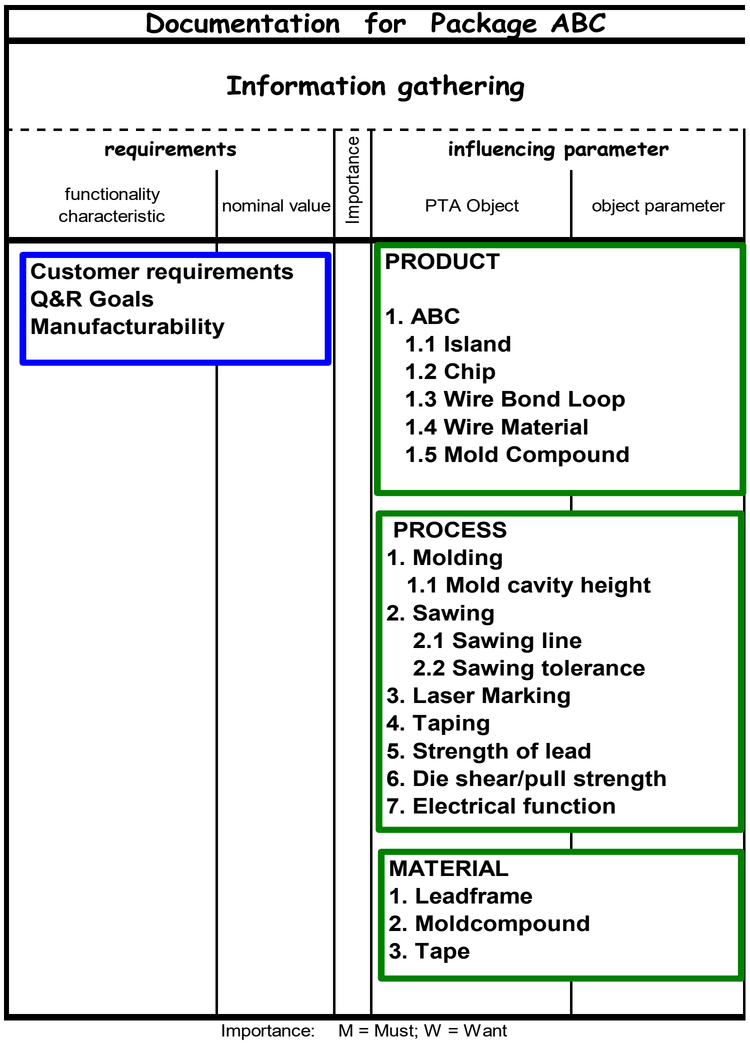


Figure A.1 — Breakdown of Requirements

Figure A.1 gives an overview of the breakdown of requirements to the set of influencing parameters of the development. In the first example the ROAP is used during the development of a new package called ABC starting with the assessment at project definition. The ROAP is then continuously updated towards the qualification. The example shows three stages of this development.

The requirements come from the customer and the Q&R goals of the company and should cover the specific manufacturing aspects of the planned production line. For cases with no one-end customer market segment or application segment specific requirements have to be taken into account. All requirements have to be specified with a nominal value. So this column also helps to highlight open topics between customer and manufacturer. In the third column it has to be specified whether the requirement is a “must”, which means it shall be fulfilled or whether it is a “want”, which could result in a performance or cost opportunity that improves the product for the customer or the manufacturer, but is no blocking point if not fulfilled.

A.1 Example of Package Development (cont'd)

The requirements of the product now have to be broken down into the elements of the package, in this case the product itself, the process to manufacture it and the materials to be used. The elements for the risk analysis are defined by a product/process tree analysis (see Figure A.2). They have to be chosen as an entity for which a requirement is derived from the overall product requirements could be defined for an object parameter which characterizes the relevant property.

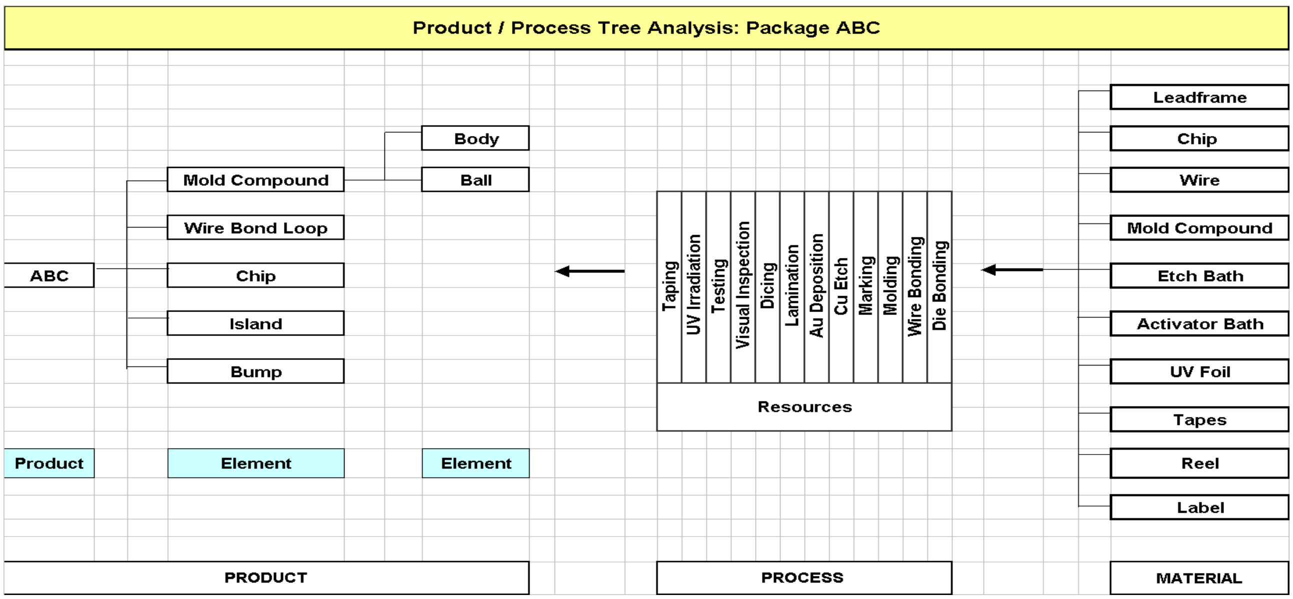


Figure A.2 — Product/Process Tree Analysis for Package ABC

Figure A.1 illustrates how the requirements are broken down into the specific requirements of the elements of the product, the related process and the supplied material or parts. For each element the target and actual ability for function and/or reliability based on existing knowledge is compared to evaluate the risk levels of certain areas of non-conformity. The information for the ability could come from data of former technologies or products, from simulation or even from the literature if the boundary conditions have been checked to fit to the assessed object. Depending on the risk level measures are defined for clarification, improvement or qualification.

One important requirement of the new package was the height. The following description will focus on this characteristic only, although all parameters of Figure A.2 are analyzed in the same way. The height is a manufacturability topic that should be stable over time. Therefore reliability risks are not discussed. Figure A.3 describes how the solution for this requirement evolved during the development. Numbers are arbitrary units.

At project definition before starting the development work it was clear after the first risk assessment that one of the targets, the package height, could not be met without significant effort (Figure A.3a). Because the alternatives to reach the target were very risky for costs and schedule of the project a discussion for a change of target started with the customer, which resulted in a new target value, with a lower risk for development (Figure A.3b). But there were still some unsolved issues about the release of a new mold tool and the ability of the lead frame supplier to guarantee the required dimensions. Ability and target for the wire bond loop were the same. Therefore this medium risk should be reduced by verification of the ability of the wire bond tool. At the qualification phase (Figure A.3c) all these topics had been solved, and the new package could be released without any further investigations with respect to the chip height.

A.1 Example of Package Development (cont'd)

The values of actual ability were then based on determined data and could be taken as granted. Because the statistical base for the island height was still low, only a guaranteed range could be given, a monitoring was started to improve the data set during ramp up and then check whether the assigned risk level "M" should go to "L".

"We-Know-Matrix"			ABC Development		ROAP at Project Definition													
Information gathering											Risk for function & reliability				Measures			
requirements		Importance	influencing parameter		type	function		reliability (stability)			customer	organisation	society	overall	plan next steps	who	when	completion
functionality characteristic	nominal value		PTA Object	object parameter		target value	actual ability	stressor	load	actual reliability								
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Device Heigth	**< 70**	M	ABC-23	device heigth	A	< 70	80				H	H	H	**H**	targets can not be met: change request	Miller	CW 19	
			Island	Island heigth	B	10+/-1	10+2/-1							**H**				
			Chip	Chip heigth	B	24+/-2	28+/-2							**H**				
a			WB Loop	WB Loop	B	20+/-2	24+/-2							**H**				
			Clearance	Loop - device top	B	> 10	14+/-2							**L**				

"We-Know-Matrix"			ABC Development		ROAP at Development Release													
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Device Heigth	**< 82**	M	ABC-23	device heigth	A	< 82	80				M	H	L	**H**	Release New Moldtool (delivery CW48 production equipment & tool) **Clarification of supplier ability** -New LF will be measured (release of leadframes)	Berger Holden	CW 50 CW 48	
			Island	Island heigth	B	10+2/-1	10+2/-1				H	H	L	**H**				
			Chip	Chip heigth	B	28+/-2	28+/-2				L	L	L	**L**				
b			WB Loop	WB Loop	B	24+/-2	24+/-2				M	M	L	**M**	Verification of ability at Wirebonder	Lang	CW 48	
			Clearance	Loop - device top	B	> 10	14+/-2				L	L	L	**L**				

"We-Know-Matrix"			ABC Development		ROAP at Qualification													
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Device Heigth	**< 82**	M	ABC-23	device heigth	A	< 82	80				L	L	L	**L**				
			Island	Island heigth	B	10+2/-1	9-12				M	M	L	**M**	Monitoring during Ramp Up	Fab	CW 52	
			Chip	Chip heigth	B	28+/-2	28+/-2				L	L	L	**L**				
c			WB Loop	WB Loop	B	24+/- 2	24+/-2				L	L	L	**L**				
			Clearance	Loop - device top	B	> 10	14+/-2				L	L	L	**L**				

Importance: M = Must; W = Want

type A: product parameter
type B:process parameter

Risk-Level:
L=low; M=medium; H=high; N=not relevant; U= unacceptable; ? = unknown

Figure A.3 — We-Know-Matrix (WKM) at Project Definition

A.2 Example of Process Change

The second example describes the application of the ROAP and the application of the WKM during the implementation and qualification of a process change. Due to the reduction of the number of different processes in a production line the thickness of the barrier layer in the third layer (M3) of a four layer copper metallization has to be reduced and the new process flow has to be qualified. As in the first example a product tree analysis of M3 is done first, but not shown here. The requirements for the M3-layer have been divided into requirements for the barrier layer, the Cu layer and the intermetal oxide (IMOX) isolating M3 from M2 and M4. The influencing parameters where the impermeability of the barrier for Cu diffusion measured as intra- and interlayer leakage current, the absolute value and allowed degradation of the resistance, which was a design parameter, and the isolation property of the IMOX. The first WKM done at the planning phase of the change (Figure A.4) shows that some information is already available or can be transferred from other investigations like the electromigration lifetime from M2 (②) and the qualification data of the isolation behavior (③), some information like the impermeability of the barrier layer against Cu diffusion required to show the ability is still unknown and is therefore an unknown risk (①) that should be evaluated. Therefore measures were planned to check the leakage current at V_m after temperature cycling and temperature storage, which seemed to be the most critical stresses with respect to the mechanical stability of a thinner barrier layer. It was not planned to do further EM investigations, because the existing data of the layer below having identical geometry showed a sufficient lifetime and the assessment criteria was such that the barrier layer had no influence on the measured lifetime distribution.

But the increased lateral leakage indicated a problem that could be caused. This result supported the above interpretation, because the enhanced temperature during EM test could enhance the diffusion of Cu. EM was chosen because data for correlation already existed. Temperature storage without current would have had the same effect for the problem.

"We-Know-Matrix"			Thickness Reduction M3-Barrier			1st Risk Assessment												
Information gathering											Risk for function & reliability				Measures			
requirements			influencing parameter			function		reliability (stability)										
functionality characteristic	nominal value	Importance	PTA Object	object parameter	type	target value	actual ability	stressor	load	actual reliability	customer	organisation	society	overall	plan next steps:	who	when	completion
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Reliability																		
useful life at OC	15y/10Fit	M	metal 3 stack+IMOX3	see below				Tm	125°C									
								Vm	2.5V									
M3+IMOX																		
Barrier layer	d=100nm	W	impermeability for Cu diffusion	I_{leak} (M3-M3)		<10nA/µ	?	Tm	125°C	?	?	?	M	?	Check lateral barrier impermeability for Cu after TC and Tm measured at Vm			
								TC	-40/125	?	?	?	M	?				
								Vm	2.5V	? (1)	?	?	M	?				
				I_{leak} (M3-M2/4)		<10nA/µ	?	Tm	125°C	?	?	?	M	?	Check vertical barrier imperm. after TC and TM at Vm			
								TC	-40/125	?	?	?	M	?				
								Vm	2.5V	?	?	?	M	?				
Cu layer M3	d=300nm	M	Resistance	spec. resistance		1 Ω/sq∓10%	1 Ω/sq∓8%	uncrit			L	L	L	L	calc Cpk of RSM3	Fab Q		
				stability		R0+20%(15y)	see M2	Tm	125°C	τ=15y (2)	L	L	L	L	take EM-data from M2	Q-Team		
IMOX	d=500nm	M	parasitic load	Capacitance		+-15%	+-10%				L	L	L	L	Calc Cpk of CapIM3	Fab Q		
			Isolation	I_{leak} (M3-M3)		<10nA/µ	<10nA/µ	see barrier layer			L	L	L	L	no measures, IMOX unchanged (3)			
				I_{leak} (M3-M2/4)		<10nA/µ	<10nA/µ	see barrier layer			L	L	L	L				

Importance: M = Must; W = Want

type A: product parameter
type B:process parameter

Risk-Level:
L=low; M=medium; H=high; N=not relevant; U= unacceptable; ? = unknown

Figure A.4 — 1st Risk Assessment as Feasibility Check

A.2 Example of Process Change (cont’d)

During development the reliability is checked as planned and shows sufficient reliability for most of the unknown topics but also for one critical parameter with a high reliability risk (Figure A.5). Storage at elevated temperatures was performed. Based on an acceleration model it confirmed a lifetime of 15 years at maximum operating temperature for the lateral and vertical leakage current (④). To address mechanical stability a temperature cycling test (TC) was applied. After the TC there was also no problem seen for the vertical but enhanced leakage for the lateral case (⑤). It was decided to do no further qualification tests for the vertical leakage (⑦). But the increased lateral leakage indicated a problem that could be caused by enhanced Cu diffusion along the liner interface resulting in increased leakage current. The problem for the lateral case is enhanced by electromigration in addition to TC (⑤). This result supported the above interpretation, because the enhanced temperature during EM test could enhance the diffusion of Cu. Failure analysis showed that barrier thinning at the corner of vias was the reason for the problem, which could also explain the reduced EM lifetime. It was decided to improve the step coverage and to use the sequence TC + EM as qualification test (⑥). EM was chosen because data for correlation already existed. Temperature storage without current would have had the same effect for the problem, which appeared to be the root cause of stress influenced leakage current.

"We-Know-Matrix"		Thickness Reduction M3-Barrier				2nd Risk Assessment												
Information gathering											Risk for function & reliability				Measures			
requirements			influencing parameter			function		reliability (stability)										
functionality characteristic	nominal value	Importance	PTA Object	object parameter	type	target value	actual ability	stressor	load	actual reliability	customer	organisation	society	overall	plan next steps:	who	when	completion
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
M3 + IMOX																		
Barrier layer	d=100nm	W		I_{leak} (M3-M3)		<10nA/µ	<1nA/µm	Tm	125°C	τ=15y ④	L	L	L	L				
								TC	-40/125	τ<15y ⑤	H	H	M	H	Improve step coverage, qualify with TC+EM-Test ⑥			
								EM after TC	jm, Tm	τ<<15y	H	H	M	H				
			impermeability for Cu diffusion					Vm	2.5V	τ<<15y	H	H	M	H				
				I_{leak} (M3-M2/4)		<10nA/µ	<1nA/µm	Tm	125°C	τ=15y	L	L	L	L	Vertical imperm. OK. No further qual tests ⑦			
								TC	-40/125	τ=15y	L	L	L	L				
								Vm	2.5V	τ=15y	L	L	L	L				

Importance: M = Must; W = Want

type A: product parameter
type B:process parameter

Risk-Level:
L=low; M=medium; H=high; N=not relevant; U= unacceptable; ? = unknown

Figure A.5 — 2nd Risk Assessment after First Reliability Data is Available

A.2 Example of Process Change (cont'd)

The measure to reduce this risk is defined and the correctness of this measure could be shown by a final qualification test (Figure A.6). To avoid barrier problems it was planned to monitor the critical step coverage, which appeared to be the root cause of stress influenced leakage current. Thus appropriate measures are taken to reduce and control residual risks.

"We-Know-Matrix"		Thickness Reduction M3-Barrier				ROAP at Qualification												
Information gathering											Risk for function & reliability				Measures			
requirements		Importance	influencing parameter		type	function		reliability (stability)			customer	organisation	society	overall	plan next steps:	who	when	completion
functionality characteristic	nominal value		PTA Object	object parameter		target value	actual ability	stressor	load	actual reliability								
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
M3 + IMOX																		
Barrier layer	d=100nm	W	density against Cu diffusion	I_{leak} (M3-M3)		<10nA/µ	<1nA/µm	Tm	125°C	τ=15y	L	L	L	L				
								TC	-40/125	τ=20y	L	L	L	L	Implement monitoring of step coverage			
								EM after TC	jm, Tm	τ=20y	L	L	L	L				
								Vm	2.5V		L	L	L	L				

Importance: M = Must; W = Want

type A: product parameter
type B:process parameter

Risk-Level:
L=low; M=medium; H=high; N=not relevant; U= unacceptable; ? = unknown

Figure A.6 — WKM at Qualification

A.3 Example of Product Development

This example shows the progress of the incremental product development and inherent qualification from planning through release of a complex large die in a standard package and how the Risk & Opportunity Assessment Process (ROAP) helped to create awareness of existing challenges together with listing and keeping track of achieved items and performance ready for exploitation of these identified opportunities (see ++ in the "We-Know-Matrix" risk logs) in the aimed at automotive market segment with its typical set of AEC (Automotive Engineering Council) defined requirements plus known customer or application specific add-ons (refer to #**1**# in Figure A.7, WKM of the INITIAL ROAP @ Planning).

"We-Know-Matrix" — **Large Die in Small SMD**xyz (**INITIAL** risk & opportunity assessment @ planning) — **Phase, rev., date**

Requirements: functionality characteristic	Requirements: nominal value	Importance	Influencing parameter: PTA Object	Influencing parameter: object parameter	type	Function: target value	Function: actual ability	Reliability (stability): stressor	Reliability (stability): load	Reliability (stability): actual reliability	Risk: customer	Risk: organisation	Risk: society	Risk: overall	Measures: plan next steps:	who	when	completion
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Application conditions																		
Automotive Body	AEC + custom	M	product	#1#	A	Similar product (die + package) does exist and is qualified								**?**	AEC baseline + custom confirmation			
Automotive Safety	AEC + custom	M	product		A	Similar product (die + package) does exist and is qualified								**?**	AEC baseline + custom confirmation			
Functionality																		
Mixed Signal	digital	M	process		B	Qualified by similarity				OK	L	**++**	L	**L**	No action: qualified			
	analog HV	M	voltage regulator	Vout	A	Vout +/-5%	+/-10%	Tj=125 °C	1008hrs	?	L	M	L	**M**	Characterize Vout: HTOL, HTRB			
		M	I/O periphery	latch-up robustness	A	>100mA@hot	100mA@room			?	H	H	H	**H**	Perform latch-up on first silicon			
Embedded Memory	ROM	M	program array	array size	A	qualified by identity				OK	**++**	**++**	L	**L**	No action: qualified,			
	NVM	M	data EE	array size	A	qualified by similarity				OK	L	**++**	L	**L**	functional parts ready-for-use			
		M	program EE	array size	A	Yield of N >> n array	n array				M	M	L	**M**	Model/evaluate yield			
#3#		M	program EE	program/erase and data retention	A		#4#	**T**use profile over 15 yrs	**T**use/time	?	M	H	L	**H**	Get **T**use profile from customer			
Manufacturability/Processability																		
Packaging #2#	SMDxyz	M	die / flag size	length	A	X > x	x	TC	-40/150 °C	?	L	M	L	**M**	Review assembly rules and l/f design			
				width	A	Y > y	y	TC	-40/150 °C	?	L	H	L	**H**	Review assembly rules and l/f design			
#3#	Tj=f(Ta, P, ...), Tj < 150 °C	M	SMDxyz	Tambient, Tjunction Tj = Ta + P x ThetaJA	A	Ta = 125 °C and Tj < 150 °C	?				H	H	H	**H**	Define thermal capabilities of **SMD**xyz and operating conditions of application(s)			
Board Assembly	245 °C Reflow	M	solder temperature resistance	package top surface temperature	B	245 °C	220 °C				H	H	H	**H**	In-depth MSL/PRT evaluation			
#5#	245 °C @ package top	M	package integrity	moisture sensitivity level	A	MSL3	MSL1 for smaller die	pre-conditioning per J-STD-020A but PRT @ 245 °C			H	H	H	**H**	In-depth MSL/PRT evaluation			
	245 °C @ package top	W	package integrity	moisture sensitivity level	A	MSL1	MSL1 for smaller die	pre-conditioning per J-STD-020A but PRT @ 245 °C			M	M	M	**M**	In-depth MSL/PRT evaluation			

Importance: M = Must; W = Want
type A: product parameter
type B: process parameter
Risk-Level: L = low; M = medium; H = high; N = not relevant;
U = unacceptable; ? = unknown;
++ = Opportunity

Figure A.7 — WKM at Product Planning

A cross-functional expert team including customer counterparts was built and contributed to an initial WKM at the begin of the product and qualification planning phase (Figure A.7). The customer had set tough boundary conditions requesting a specific small SMD package for the relatively large die (#**2**#). In addition there were some requirements going beyond package and cell design rules of already existing products of the same and already qualified mixed technology (#**3**#). Certain product features like the size of the EE Program Array and the stability of the Voltage Regulator needed attention from manufacturing yield point of view respectively for the electrical performance capability. The expected operation at elevated temperatures initiated detailed collection of working conditions for the applications. Customer input of the automotive systems' mission-profiles was mandatory at this point in time (#**4**#).

A.3 Example of Product Development (cont'd)

From begin on the main activities, however, resulted from requirements in the area of package manufacturability and processability. Assembly rules and leadframe design needed re-assessment for packaging that large die into the customer requested and relatively small plastic body. Related in-depth evaluations were undertaken to confirm compliance with customers' board soldering process needs of MSL3 / 245 °C and to prove market specific board-level processability and reliability requirements are fulfilled (#**5**#). Another WKM sheet is outlining the situation in course of development (Figure A.8) and includes NEW ITEMS that surfaced during day-to-day progress (#**7**#). First functional silicon was successfully characterized and found acceptable per a reduced customer specification (#**6**#). That enabled early use of new product taking account of existing and clearly documented limitations. New items of interest and concern surfaced during the development phase and were added to the WKM which is a living document reflecting status and changes all along the new product creation process. The power density issue was clarified together with the customer and limiting the maximum dissipation during device operation and excluding all power stages are ON at the same time. With this boundary condition T_j < 150 °C could be reliably achieved. The relationship of $T_j = T_a + P \times \theta_{Ja}$ was initiated to be detailed in an application note outlining these products' thermal limitations (#**8**#). "Glueability" needs made it necessary to bring the mold compound supplier into the team and have him perform development work to fulfill customer board assembly needs (#**10**#).

"We-Know-Matrix"			Large Die in Small SMDxyz (INTERIM risk & opportunity assessment during development												Phase, rev., date			
Information gathering											Risk for function & reliability				Measures			
requirements			influencing parameter			function		reliability (stability)										
functionality characteristic	nominal value	Importance	PTA Object	object parameter	type	target value	actual ability	stressor	load	actual reliability	customer	organisation	society	overall	plan next steps:	who	when	completion
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Application conditions																		
Automotive Body		M			A			passed AEC & custom						**L**	AEC baseline + custom qualification			
Automotive Safety		M			A			passed AEC						**?**	AEC OK, custom qual ongoing			
Functionality																		
Mixed Signal	digital	M	process		B	Qualified by similarity				OK	L	++	L	**L**	No action: qualified			
	analog HV	M	voltage regulator	Vout	A	Vout +/-5%	Vout +/-5%	Tj=125 °C	1008hrs	OK	L	L	L	**L**	Passed requirements			
		M	I/O periphery	latch-up robustness	A	>100mA@hot	>125mA@hot	+/- 125mA @ Tj=125 °C		OK	L	L	L	**L**	Passed requirements			
Embedded Memory	ROM	M	program array	array size	A	Qualified by identity				OK	++	++	L	**L**	No action: qualified			
	NVM	M	data EE	array size	A	Qualified by similarity				OK	L	++	L	**L**	(ROM + data EE) parts ready-for-use			
		M	program EE	EE array size	A	Yield of N >> n	n array				L	L	L	**L**	Meets targets and passes requirements			
		M	program EE	EE W/E and D/R	A			**T**use profile over 15 yrs	**T**use/time	W/E + D/R bake	M	M	L	**M**	Interim readouts show zero failures, finalize extended D/R bake			
#7# NEW ITEM	Development & early samples	M	product	functionality	A	reduced customer specification #6#				(OK)	++	++	L	**++**	"Reduced Spec" parts fit-for-use			
Manufacturability/Processability																		
Packaging	SMDxyz	M	die / flag size	length	A	X > x	x	TC	-40/150 °C	OK	L	L	L	**L**	Leadframe modifications successful			
				width	A	Y > y	y	TC	-40/150 °C	OK	L	L	L	**L**	Leadframe modifications successful			
#7# NEW ITEM		M	trim & form	lead/plastic adhesion	B	no delamination	?	THB, TC, lead pull, etc.		?	M	M	M	**M**	Review capabilities, do rel tests			
NEW ITEM		M	wire dressing	wire-to-edge clearance	B	> 1mil	?	bonder capability		?	H	H	L	**H**	Review capabilities, adjust tools			
NEW ITEM		M	2nd bond	heel integrity	B	no crack	?	wire pull	pull force	?	H	H	L	**H**	Review capabilites, adjust tools			
	Tj=f(Ta, P, ...), Tj < 150 °C	M	SMDxyz	Tambient, Tjunction Tj = Ta + P x ThetaJA	A	Ta=125 °C and Tj < 150 °C	Ta = 85 °C at limited load	operation	power dissipation	OK	H	L	L	**H**	Specify maximum Tj < 150 °C and outline thermal limitations in application note. #8#			
Board Assembly	SOIC Reflow	M	solder profile	package top surface temperature	B	245 °C	245 °C				M	++	L	**M**	Successfully processed MSL3/245 °C. Customer oven profile has to be monitored.			
	245 °C @ package top	M	package integrity	moisture sensitivity level	A	MSL3 @ 245 °C	MSL3 @ 245 °C	pre-conditioning per J-STD-020A but PRT @ 245 °C			L	++	L	**L**	Development work finalized @ MSL3/245 °C. #11#			
	245 °C @ package top	W	package integrity	moisture sensitivity level	A	MSL1 @ 245 °C	MSL3 @ 245 °C	pre-conditioning per J-STD-020A but PRT @ 245 °C			H	U	H	**U**	MSL1/245 °C requires material and process changes. #9#			
#7# NEW ITEM	Glueability	M	mold compound	surface cleanliness	A	higher shear force	too low shear force	shear force	F Newton	?	H	M	N	**H**	Bind mold compound supplier into development work, do experiments #10#			

Importance: M = Must; W = Want
type A: product parameter
type B: process parameter
Risk-Level: L = low; M = medium; H = high; N = not relevant; U = unacceptable; ? = unknown; ++ = Opportunity

Figure A.8 — WKM During Product Development

A.3 Example of Product Development

Effort for customer's WANT of MSL1 / 245 °C was abandoned and ranked "Unacceptable" after finding out that the actual material set was capable of only MSL3 / 245 °C (#**9**#). The customer took measures for MSL3 handling and measured/adjusted/monitored the oven profile of his convection line. Both the solder joint and the package top surface temperature are recorded for components using some volume of similarly populated printed circuit boards (#**11**#).

At product release the WKM (Figure A.9) shows all requirements completed (#**12**#). Notes indicate what monitoring is committed during ramp-up and what documents explain the proper use of the released product (#**13**#). The data sheet and application notes belong together; both reflect the final device specification. The device marking outlines the maximum T_j. An interim solution was established to maintain parts' glueability for the customers' SMD processing (#**14**#). Actual trend to Pb-free soldering is accounted for by goal setting of package top surface temperature of (260 °C +5 °C / -0 °C) and plans for looking into necessary assembly material and/or process changes for acceptable MSL as part of future development work (#**15**#).

"We-Know-Matrix"			Large Die in Small SMDxyz (FINAL risk & opportunity assessment @ release)												Phase, rev., date			
Information gathering											Risk for function & reliability				Measures			
requirements		Importance	influencing parameter		type	function		reliability (stability)			customer	organisation	society	overall	plan next steps:	who	when	completion
functionality characteristic	nominal value		PTA Object	object parameter		target value	actual ability	stressor	load	actual reliability								#12#
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Application conditions																		
Automotive Body		M			A			passed AEC & custom			L	L	L	**L**	product released			✓
Automotive Safety		M			A			passed AEC & custom			L	L	L	**L**	product released			✓
Functionality																		
Mixed Signal	digital	M	process		B	Qualified by similarity				OK	L	**++**	L	**L**	No action: qualified			✓
	analog HV	M	voltage regulator	Vout	B	Vout +/-5%	Vout +/-5%	Tj=125 °C	1008hrs	OK	L	L	L	**L**	Passes requirements			✓
		M	I/O periphery	latch-up robustness	B	>100mA@hot	>125mA@hot	+/- 125mA @ Tj=125 °C		OK	L	L	L	**L**	Passes requirements			✓
Embedded Memory	ROM	M	program array	array size	B	Qualified by identity				OK	L	**++**	L	**L**	No action: qualified			✓
	NVM	M	data EE	array size	B	Qualified by similarity				OK	L	**++**	L	**L**	(ROM + data EE) in field application			✓
		M	program EE	EE array size	B	Yield of N >> n	n array				L	L	L	**L**	Meets targets and passes requirements			✓
		M	program EE	EE W/E and D/R	B			**T**use profile over 15 yrs	**T**use/time	W/E + D/R bake	L	L	L	**L**	Passes requirements			✓
	Development & early samples	M	product	functionality	A	reduced customer specification				OK	**++**	**++**	L	**++**	Full qual plan completed			✓
Manufacturability/Processability																		
Packaging	SMDxyz	M	die / flag size	length	B	X > x	x	TC	-40/150 °C	OK	L	L	L	**L**	Leadframe modifications successful			✓
				width		Y > y	y	TC	-40/150 °C	OK	L	L	L	**L**	Leadframe modifications successful			✓
		M	trim & form	lead/plastic adhesion		no delam	no delam	THB, TC, lead pull, etc.		OK	L	L	L	**L**	Monitor during ramp-up			✓
		M	wire dressing	wire-to-edge clearance	B	> 1mil	> 1mil	bonder capability		OK	L	L	L	**L**	Monitor during ramp-up			✓
		M	2nd bond	heel integrity	B	no crack	no crack	wire pull	pull force	OK	L	L	L	**L**	Monitor during ramp-up			✓
	Tj=f(Ta, P, ...), Tj < 150 °C	M	SMDxyz	Tambient, Tjunction Tj = Ta + P x ThetaJA	B	Ta=125 °C and Tj < 150 °C	Ta = 125 °C at limited load	operation	power dissipation	OK	L	L	L	**L**	Maximum Tj < 150 °C specified and outlined in marking. Application note published and followed.		#13#	✓
Board Assembly	SOIC Reflow	M	solder profile	package top surface temperature	B	245 °C	245 °C				L	**++**	L	**L**	Parts successfully processed with MSL3/245 °C and passing reliability.			✓
	245 °C @ package top	M	package integrity	moisture sensitivity level	B	MSL3 @ 245 °C	MSL3 @ 245 °C	pre-conditioning per J-STD-020A but PRT @ 245 °C			L	**++**	L	**L**	Development work finalized @ MSL3/245 °C			✓
	245 °C @ package top	W	package integrity	moisture sensitivity level	B	MSL1 @ 245 °C	MSL3 @ 245 °C	pre-conditioning per J-STD-020A but PRT @ 245 °C			H	U	H	**U**	Development work heading for Pb-free with <260 °C at package top		#15#	✓
	Glueability	M	mold compound	surface cleanliness	B	higher shear force	too low shear force	shear force	F Newton	OK	**++**	**++**	N	**++**	Bottom lasering provides glueability. Plastic/mold release system in development with supplier.		#14#	✓

Importance: M = Must; W = Want

type A: product parameter
type B: process parameter

Risk-Level: L = low; M = medium; H = high; N = not relevant; U = unacceptable; ? = unknown; ++ = Opportunity

Figure A.9 — WKM at Product Release

Annex B (Informative) Bibliography

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JESD659, *Failure-Mechanism-Driven Reliability Monitoring*

Annex C (Informative) Differences between Revisions

This annex briefly describes most of the changes made to entries that appear in this publication, JEP148C, compared to its predecessors. If the change to a concept involves any words added or deleted (excluding deletion of accidentally repeated words), it is included. Some punctuation changes are not included.

C.1 Differences between JEP148C and JEP148B (January 2014)

Clause	Description of Change
All	This publication was brought into style/formatting compliance with the latest style standard, *Style Manual for Standards and Other Publications of JEDEC*, JM7A (July 2024). Minor editorial corrections were made, such as replacing the term section with clause.
2	Moved informative references to new Annex B, "Bibliography"; re-numbered this clause and subsequent clauses accordingly.
Annex B	New annex; Moved the informative references from clause 2 to the Bibliography. References 6 and 9 were removed, and remaining references were re-numbered accordingly.

C.2 Differences between JEP148B and JEP148A (December 2008)

Clause	Description of Change
2	Reference 13 and 14 added.
3	Definition added or changed for mission profile, safe operating area, service life, wafer level reliability, definition deleted for library.
4.4.1	Figure 2 and related text deleted. Additional explanation for new Figure 2B added in paragraph before Figure 2.
Figures	Old Figure 3 through Figure 11 renumbered as Figure 2 through Figure 9.
4.6	Description how risk pareto develops during project added after Figure 4.
5.4	Reference to Annex A changed to reference to JEP143.
Annex A	Removed; Subsequent annexes were re-numbered accordingly.

C.3 Differences between JEP148A and JEP148 (April 2004)

Clause	Description of Change
Intro	Editorial changes, introduction of the term "robustness".
2	Reference 5 changed, reference 11 and 12 added.
3	Definition of defect updated, definition of robustness added, definition of weakness deleted, introduction of the terms "mission profile" and "service life".
4.2 b	References 11 and 12 added.
4.4	Process description in 7 steps.
4.6	Steps in 4.6 deleted.
5.2	Replacement of term "weakness" by "latent defect"; in Table 4, "handling" added with processability (under Test intention); 5.2.1 below Table 5; model list deleted; 5.2.2 Figure 10, title corrected.
5.3	Description of models replaced by reference to JEP122; below Figure B.7, first paragraph replace (Fig. C.3.1) with (Figure 5.7); in second paragraph replaced (Figure C.3.2) with (Figure B.8); deleted Figure 11, Figure 12, Figure 13, and Figure 14.
5.4	Deleted Table 6: Reliability Test Scheme.
5.5	Renumbered Figure 15 to Figure 11; paragraph 2, introduction of failure distribution as stress test target; added first paragraph.

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