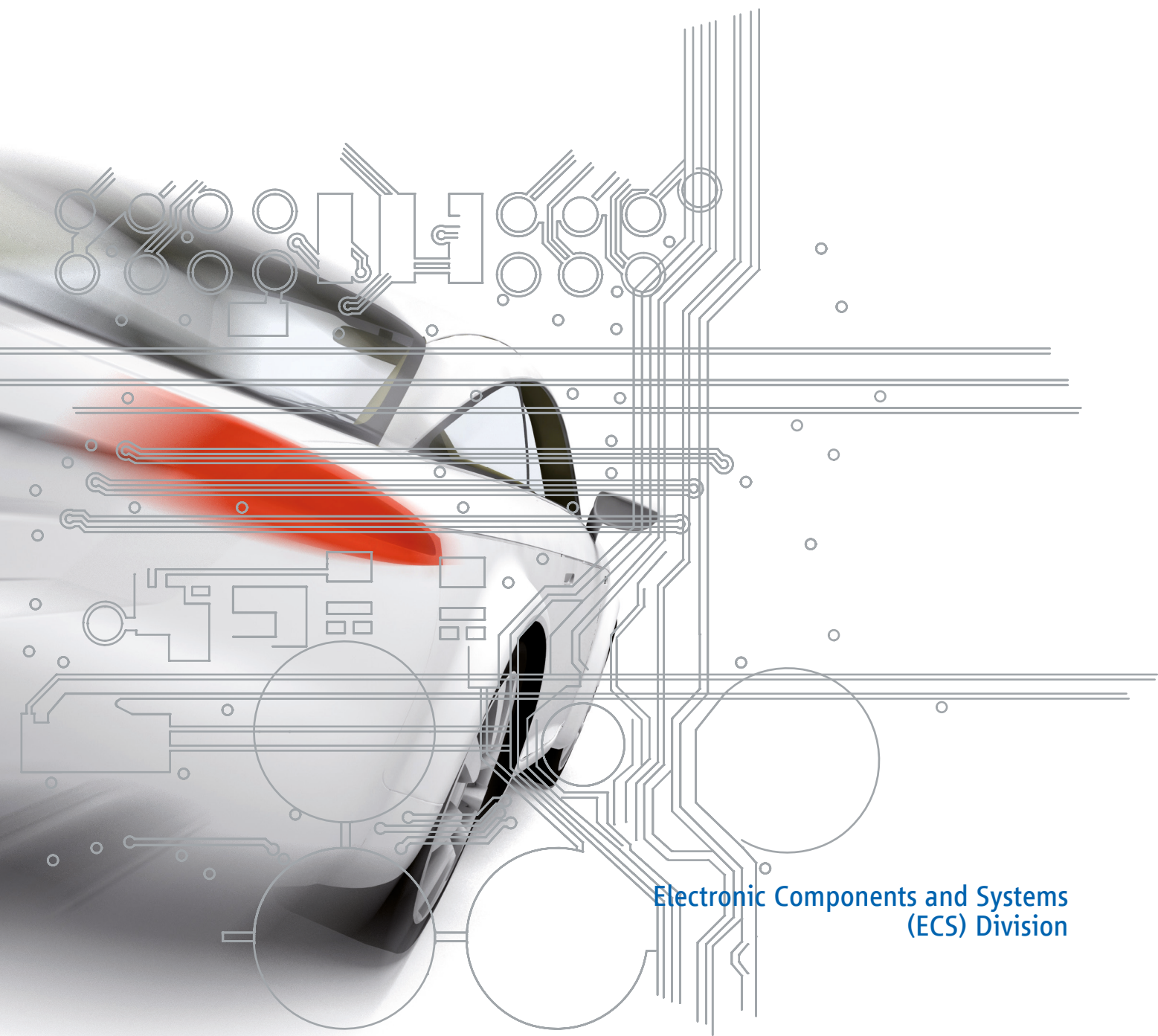


Handbook for Robustness Validation of Automotive Electrical/ Electronic Modules



**Electronic Components and Systems
(ECS) Division**

Handbook for Robustness Validation of Automotive Electrical/Electronic Modules

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ZVEI - Zentralverband Elektrotechnik- und
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(German Electrical and Electronic Manufacturers' Association)

Electronic Components and Systems Division

Lyoner Straße 9

60528 Frankfurt am Main, Germany

Telephone: +49 69 6302-402

Fax: +49 69 6302-407

E-mail: zvei-be@zvei.org

www.zvei.org

Contact: Dr.-Ing. Rolf Winter

Editor: ZVEI Robustness Validation Working Group

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Revision: June 2013



Foreword (second revised edition)

Since five years Robustness Validation has found its way into the daily business of EE-Modules product qualification. During that time several working groups of the ZVEI have published supporting documents:

- Handbook for Robustness Validation of Semiconductor Devices in Automotive Applications and content copy SAE Standard J1879 (first edition 2008, revised 2013)
- Knowledge Matrixes published on ZVEI and SAE homepages (yearly updated)

- Robustness Validation for MEMS - Appendix to the Handbook for Robustness Validation of Semiconductor Devices in Automotive Applications (2009).

- Automotive Application Questionnaire for Electronic Control Units and Sensors (2006, Daimler, Robert Bosch, Infineon).

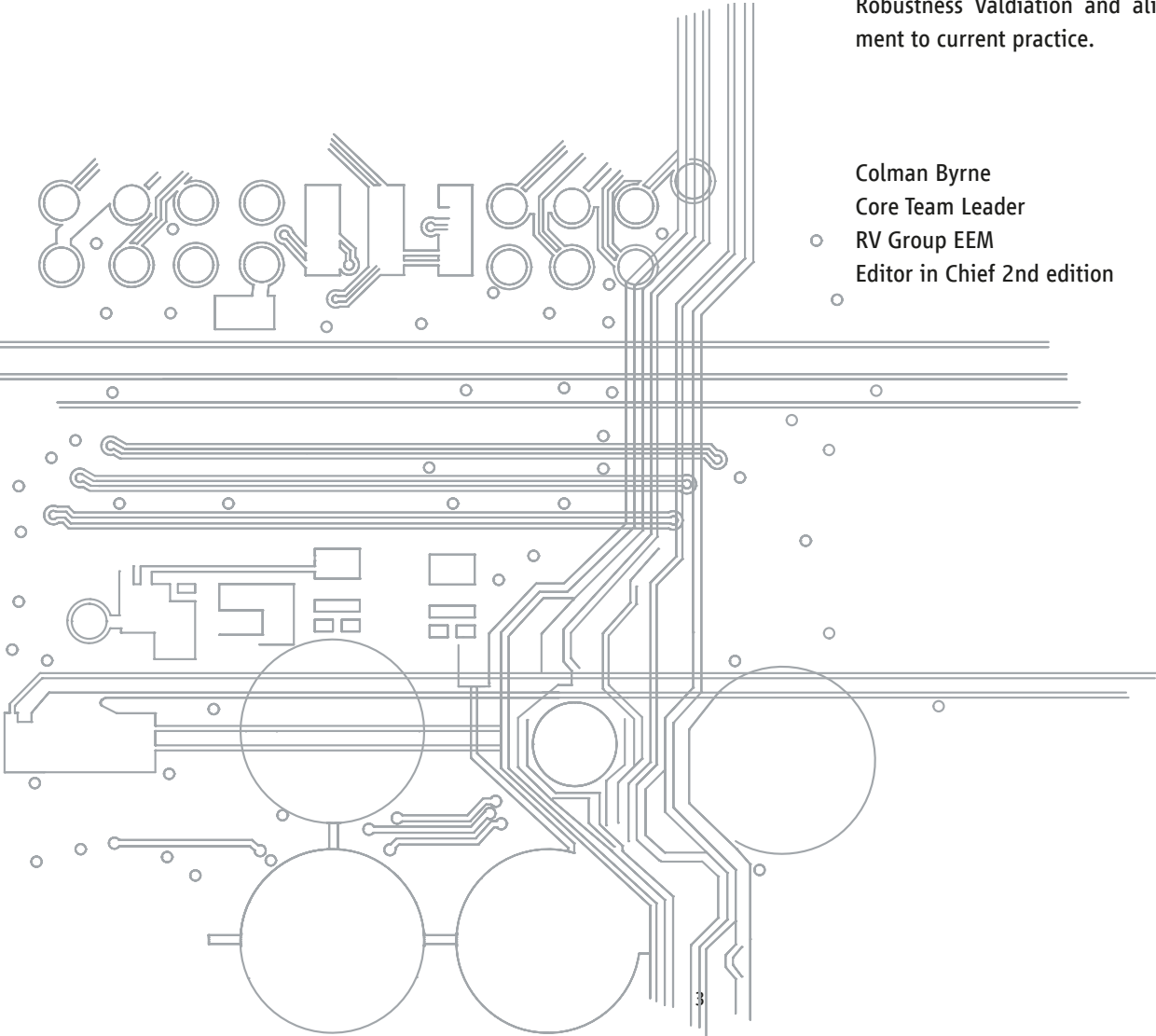
- Pressure Sensor Qualification beyond AEC Q 100 (2008, IFX: S. Vasquez-Borucki).

- Robustness Validation Manual - How to use the Handbook in product engineering (2009, RV Forum).

- How to Measure Lifetime - Robustness Validation Step by Step (November 2012).

Especially the Robustness Validation Manual gives guidance in how to apply RV in different scenarios. The 2nd revision contains topics the community learned during application of Robustness Validation and aligns the document to current practice.

Colman Byrne
Core Team Leader
RV Group EEM
Editor in Chief 2nd edition



Preface (first edition)

In late 2006 Members of the SAE International Automotive Electronic Systems Reliability Standards Committee and ZVEI (German Electrical and Electronic Manufacturers' Association) formed a joint task force to update SAE Recommended Practice J1211 November 1978 "Recommended Environmental Practices for Electronic Equipment Design". The 1978 version of J1211 was written in an era when electronics were first being introduced to the automobile. There was a high level of concern that the harsh environmental conditions experienced in locations in the vehicle could have a serious negative affect on the reliability of electronic components and systems. Some early engine control modules (ECMs) had failure rates in the 350 failures per million hours ($f/10^6$ hrs.) range, or expressed in the customer's terms, a 25% probability of failure in the first 12 months of vehicle ownership. At that time, warranty data was presented in R/100 (repairs per 100 vehicles) units, for example 25 R/100 at 12 months.

In these early years, when the automotive electronics industry was in its infancy, a large percentage of these were "hard" catastrophic and intermittent failures exacerbated by exposure to environmental extremes of temperature (-40°C to $+85^{\circ}\text{C}$); high mechanical loads from rough road vibration and rail shipment; mechanical shocks of up to 100g from handling and crash impact; severe electrical transients, electrostatic discharge and electromagnetic interference; large swings in electrical supply voltage; reverse electrical supply voltage; and exposure to highly corrosive chemicals (e.g. road salt and battery acid). The focus of the 1978 version of J1211 was on characterizing these harsh vehicle environment for areas of the vehicle (engine compartment, instrument panel, passenger compartment, truck, under body, etc.) and suggesting lab test methods which design engineers could use to evaluate the performance of their components and systems at or near the worst-case conditions expected in the area of the vehicle where their electrical/electronic components would be mounted. By testing their prototypes at the worst case conditions (i.e. at the product's specification limits) described

in the 1978 version of J1211 designers were able to detect and design out weaknesses and thereby reduce the likelihood of failure due to environmental factors.

By the mid-1980s, it became common practice to specify "test-to-pass" (zero failures allowed) environmental conditions-based reliability demonstration life tests with acceptance levels in the 90% to 95% reliability range (with confidence levels of 70% to 90%). This translates to approximately 5 to 20 $f/10^6$ hrs. The sample size for these tests was determined using binomial distribution statistical tables and this would result in a requirement to test 6 to 24 test units without experiencing a failure. If a failure occurred, the sample size would have to be increased and the testing continued without another failure till the "bogie" was reached. The environmental conditions during the test were typically defined such that the units under test were operated at specification limits based on J1211 recommended practices (e.g. -40°C and $+85^{\circ}\text{C}$) for at least some portion of the total test time. The "goal" of passing such a demonstration test was often very challenging and the "test-analyse-fix" programs that resulted, although very time-consuming and expensive, produced much-needed reliability growth. Reliability improved significantly in the late 1980s and early 1990s and vehicle manufactures and their suppliers began expressing warranty data in R/1,000 units instead of R/100 units.

By the turn of the century automobile warranty periods had increased from 12 months to 3, 4, 5 (and even 10 years for some systems) and most manufacturers had started specifying life expectancies for vehicle components of 10, 15 and sometimes 20 years. And by this time several vehicle manufacturers and their best electrical/electronic component suppliers had improved reliability to the point where warranty data was being expressed in parts-per-million (ppm) in the triple, double and even single-digit range. This translates to failure rates in the 0.05 $f/10^6$ hrs range and better! The achievement of such high reliability is not the result of test-to-pass reliability

demonstration testing based on binomial distribution statistical tables. With this method, reliability demonstration in the 99.99% to 99.9999% range would require thousands of test units! On the contrary, the methods and techniques used by engineering teams achieving such reliability excellence did not require increasingly large sample sizes, more expensive and lengthy testing, or more engineers. It is about working smarter, not harder; and about systems-level robust design and Robustness Validation thinking rather than component-level "test-to-pass" thinking.

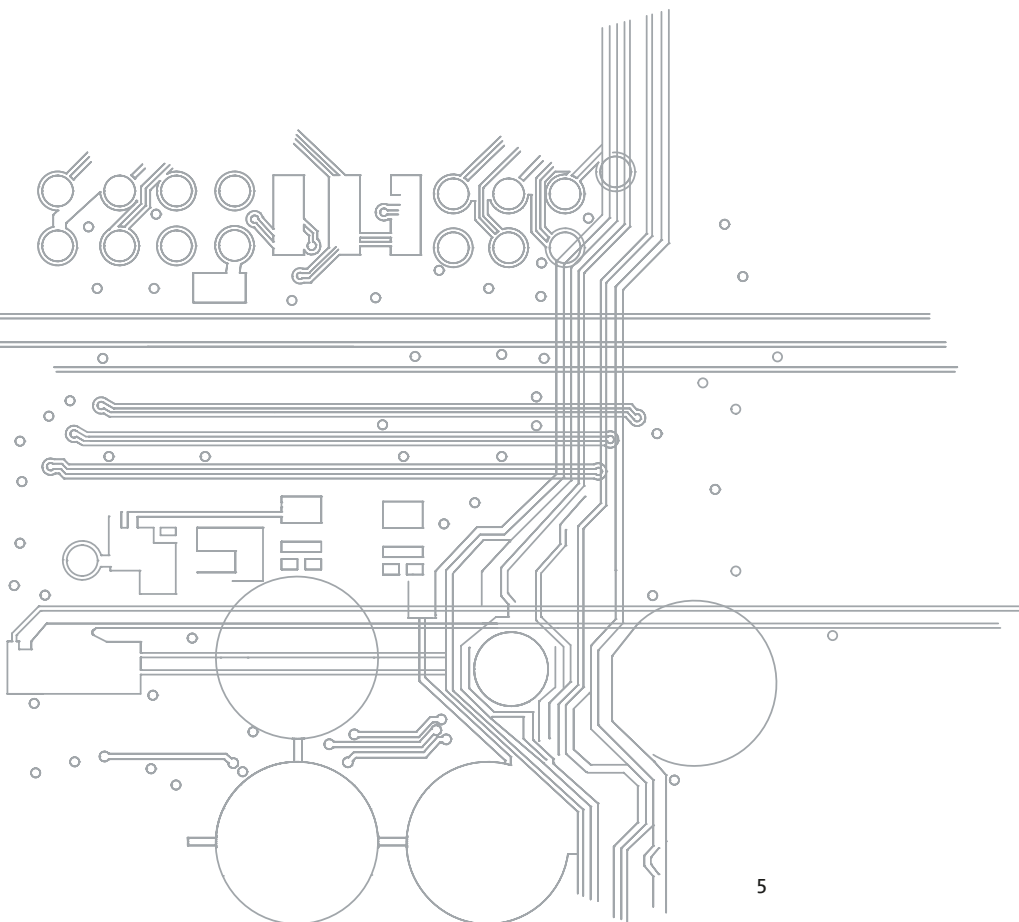
The task force leaders and members were of the strong opinion that the 2008 version of SAE J1211 should document the state-of-the-art

methods and techniques being used by leading companies and engineering teams to achieve ultra-high reliability while at the same time reducing overall cost life-cycle and shortening time-to-market. The SAE International Automotive Electronic Systems Reliability Standards Committee and ZVEI (German Electrical and Electronic Manufacturers' Association) are hopeful that this Handbook for Robustness Validation of Automotive Electrical/Electronic Modules will help many companies and engineering teams make the transition from the 1980s "cookbook" reliability demonstration approach to a more effective, economically feasible knowledge-based Robustness Validation approach.

Sincerely
Yours

Helmut Keller
Chairman ZVEI
Robustness Validation Committee

Jack Stein
Chairman SAE
Automotive Electronics Reliability Committee



Foreword (first edition)

The quality and reliability of the vehicles a manufacturer produces has become a deciding factor in determining competitiveness in the automotive industry. Achieving quality and reliability goals effectively and economically depends on fundamental knowledge of how to select and integrate materials, technologies and components into functionally capable and dependable vehicle systems and being able to assess whether acceptable levels of quality and reliability have been achieved as the design comes together, matures and transitions into a mass production environment.

Evaluation methods, whether physical or analytical, must produce useful and accurate data on a timely basis in order to provide added value. Increasingly, manufacturers of automotive electrical and electronic (E/E) equipment must be able to show that they are producing a product which performs reliably in applications having defined Mission Profiles.

Reliability is a measure of conditional probability that a product will perform in accordance with expectations for a predetermined period of time in a given environment under defined usage conditions. To efficiently meet any reliability objective requires comprehensive knowledge of the relationships between failure modes, failure mechanisms and Mission Profile. Gradual reliability growth by repeated test-analyse-fix cycles is no longer sufficient or competitive (see Rationale).

Ten years ago the prevailing philosophy was: "Qualification tests of production validation units must ensure that quality and reliability targets have been reached". This approach is no longer sufficient to guarantee robust electronic products and a failure free ownership experience for the life of the car, i.e. a philosophy of the Zero-Defect-Strategy. The emphasis has now shifted from the detection of

failures at the end of the development process to prevention of failures throughout the full life cycle, beginning with concept development and requirements specification.

In the past, screening methods were still required after the product had been manufactured and after the product had successfully passed a qualification program. In recent years the emphasis has shifted to reliability-by-design methodologies applied during development. The philosophy of Robust Design has been widely accepted and the number methods, tools and techniques to support the approach have been increasing steadily.

The fundamental philosophy of product qualification is also changing from the detection of defects based on predefined sample sizes to the generation and reuse of knowledge gained by studying specific data regarding the product's failure modes and mechanisms combined with existing knowledge in the field. Using these methods, known as "physics of failure" or "reliability physics" it is possible to generate highly useful knowledge on the robustness of products.

This handbook is intended to give guidance to engineers on how to apply a Robustness Validation Process (RV Process) during development and qualification of automotive electrical/electronic modules. It was made possible because many companies, including electronic/equipment manufacturers and vehicle manufacturers worked together in a joint working group to bring in the knowledge of the complete supply chain.

This handbook is synchronized with its American counterpart document: SAE J1221 "Handbook for Robustness Validation of Automotive Electrical/Electronic Modules" published by SAE International, Detroit, 2013.

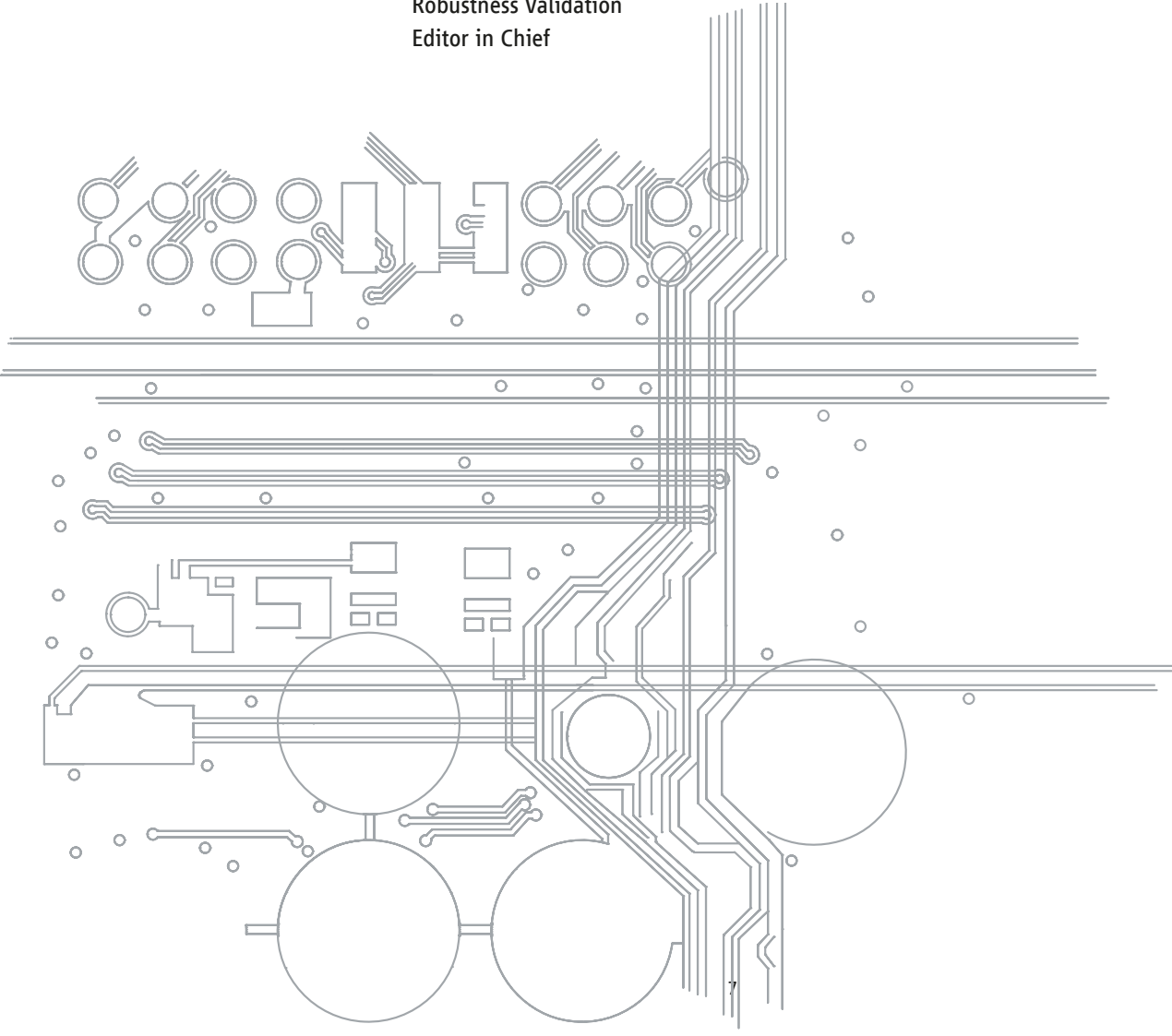
Software robustness is not specifically addressed in this document. However some degree of software evaluation is addressed by the test methods. Some examples are:

- Testing the module in a sub-system configuration if possible.
- Testing the module with realistic loads.
- Exercising the module in various modes during a test.

Also, although this handbook is directed primarily at electrical/electronic “modules” it may certainly be applied to other equipment such as sensors, actuators and mechatronics.

Sincerely
Yours

Colman Byrne
Core Team Leader
Robustness Validation
Editor in Chief



Acknowledgements (first edition)

We would like to thank all teams, organizations and colleagues for actively supporting the Robustness Validation approach.

EE Module Robustness Validation Joint International Task Force Team Leader (ZVEI)

Byrne, Colman - Kostal Ireland

EE Module Robustness Validation Joint International Task Force Team Leaders (SAE)

Craggs, Dennis - Chrysler

ZVEI Robustness Validation Committee Chair

Keller, Helmut - ZVEI and Co-Chairman SAE Reliability Committee Europe

SAE Automotive Electronic Systems Reliability Committee Chair

Stein, Jack - TCV System

We would specially like to thank the team members of various committees and their associates for their important contributions to the completion of this handbook. Without their commitment, enthusiasm, and dedication, the timely compilation of the handbook would not have been possible.

Team Members of Working Groups

Aldridge, Dustin - Delphi
Aubele, Peter - Behr
Berkenhoff, Niels - Kostal Kontakt Systeme
Butting, Reinhard -, Robert Seuffer
Duerr, Johannes - Robert Bosch
Edson, Larry - General Motors
Freytag, Juergen -, Daimler
Gehnen, Erwin - Hella
Getto, Ralf - Daimler
Girgsdies, Uwe - Audi
Guerlin, Thomas - Harman/Becker
Hodgson, Keith - Ford
Hrassky, Petr - STMicroelectronics Application
Jeutter, Roland - Agilent Technologies
Kamali, Dogan - Delphi Deutschland
Kanert, Werner - Infineon Technologies
Knoell, Bob - Visteon

ZVEI Robustness Validation Committee

Keller, Helmut - Keller Consulting Engineering Services and ZVEI

Winter, Rolf - ZVEI

SAE Automotive Electronic Systems Reliability Standards Committee

Stein, Jack - SAE Automotive Electronic Systems Reliability Standards Committee Chair

Robustness Validation Core Team WG Leaders

Menninger, Frank - Delphi Deutschland

Byrne, Colman - Kostal Ireland

Girgsdies, Uwe - Audi

Vogl, Günter - Continental/Siemens VDO

Enser, Bernd - Sanmina-SCI

Craggs, Dennis - Chrysler

Becker, Rolf - Robert Bosch

Stein, Jack - TCV Systems

McLeish, James - DfR Solutions

Representative of ZVEI

Winter, Rolf - ZVEI

Representative of SAE

Michaels, Caroline - SAE International

Koetter, Steffen - W. C. Heraeus

Krusch, Georg - Robert Seuffer

Liang, Zhongning - NXP Semiconductors

Lindenberg, Thomas - Preh

Lorenz, Lutz - Audi

Mende, Ralf - Delphi Deutschland

Nielsen, Arnie - Arnie Nielsen Consulting

Reindl, Klaus - On Semiconductor Germany

Richter, Stefan - Brose Fahrzeugteile

Ring, Hubertus - Robert Bosch

Roedel, Reinhold - Audi

Schackmann, Frank - Automotive Lighting

Schleifer, Alexander - VDO Automotive

Schmidt, Herman Josef - Leopold Kostal

Schneider, Konrad - Audi

Schneider, Stefan - Audi

Then, Alfons - Preh

Trageser, Hubert - Conti Temic
Unger, Walter - Daimler
Weikermann, Frank - Harman/Becker
Wiebe, Robert - Global Electronics
Wilbers, Hubert - Huntsman

Editorial Team (second revised edition)

Byrne, Colman - Kostal Ireland
Breibach, Joerg - Robert Bosch
López Villanueva, Pantaleón - Visteon Innovation & Technology
Preussger, Andreas - Infineon
Keller, Helmut - Keller Consulting Engineering Services and ZVEI

de Place Rimmen, Peter - Danfoss Power Electronics
Guenther, Oliver - Osram Opto Semiconductors
Kanert, Werner - Infineon Technologies
Kraus, Hubert - Zollner Elektronik
Lettner, Robert - TItech Computertechnik
Liang, Zhongning - NXP Semiconductors
Nebeling, Alexander - Delphi Deutschland
Richter, Stefan - Brose Fahrzeugteile
Rongen, René t.H. - NXP Semiconductors
Schackmann, Frank - Automotive Lighting
Stoll, Michael - Osram Opto Semiconductors
Wieser, Florian - STMicroelectronics Application
Wulfert, Friedrich-Wilhelm - Freescale Semiconductor

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1. Introduction

This Robustness Validation Handbook provides the international automotive electronics community with a common knowledge-based qualification methodology based on the philosophy of robust design. Robustness Validation activities begin in the product conceptualization phase and continue throughout the full life cycle of the product. By integrating robust design and Robustness Validation with systems engineering practices, project teams are able to design-in and demonstrate product reliability for the user's intended application(s).

This handbook defines a methodology to assess the Robustness Margin of an electrical/electronic module. Robustness Margin is defined as the margin between the outer limits of the modules specification and the actual performance capability of the mass-produced product considering all significant source of variation. The task of determining Robustness Margin is started during the design and development process and continues throughout the production life using monitoring mechanisms. It is in this manner that reliability is assured throughout the life cycle of the product.

This Robustness Validation Handbook defines a RV Process in which the user and the supplier of the electrical/electronic module establish requirements and acceptance criteria based on a defined Mission Profile and reliability performance requirements for the vehicle application(s). The objective of RV Process is to design-out susceptibility to failure mechanisms, assess whether the Robustness Margin is sufficient for the intended application(s), and develop inherently robust manufacturing and assembly processes capable of producing zero-defect product.

Robustness Validation relies first on knowledge-based modeling simulation and analysis methods to develop a highly capable design prior to building and testing physical parts; and then on test-to-failure (or acceptable degradation) and failure/defect susceptibility testing to confirm or identify Robustness Margins, to enable failure prediction and verify that manufacturing processes produce defect free parts. These techniques represent

advancement beyond "test-to-pass" qualification plans which usually provide very little useful engineering information about failure modes, failure mechanisms and failure points.

Robust design concepts provide an efficient way to optimize a product in light of the "real world" operating conditions it will experience. Validation is a process for evaluating a product's suitability for use in its intended use environment. Thus it is natural that robustness and validation go hand-in-hand. To achieve efficiency, robustness relies on up front use of "physics-of-failure" knowledge and tools, fundamental principles of statistical experimentation, and techniques and tools like FMEA, P-Diagrams, orthogonal arrays and Response Surface Methodology. However, the objective of robustness is not merely to complete a design of experiments (DOE), but to understand how the product or process performs its intended function within, and at the limits of, the user specifications.

2. Scope

This document addresses robustness of electrical/electronic modules for use in automotive applications. Where practical, methods of extrinsic reliability detection and prevention will also be addressed. This document primarily deals with electrical/electronic modules (EEMs), but can easily be adapted for use on mechatronics, sensors, actuators and switches. EEM qualification is the main scope of this document. Other procedures addressing random failures are specifically addressed in the CPI (Component Process Interaction) Section 10. This document is to be used within the context of the Zero Defect concept for component manufacturing and product use.

It is recommended that the robustness of semiconductor devices and other components used in the EEM be assured using ZVEI/SAE J1879 "Handbook for Robustness Validation of Semiconductor Devices in Automotive Applications".

The emphasis of this document is on hardware and manufacturing failure mechanisms, however, other contemporary issues as shown in Figure 1 need to be addressed for a thorough Robustness Validation. A pareto of contemporary issues is shown in Figure 1. Although this document addresses many of the issues shown, however some are outside the scope of this document and will need to be addressed for a thorough RV Process application. Examples of issues outside the scope of this document are system interactions, interfaces, functionality, HMI (Human-Machine Interface) and software. For further readings see References/ additional reading or www.zvei.org/RobustnessValidation.

FIGURE 1 - Relative Contributions of Issues with E/E Systems at Vehicle Level

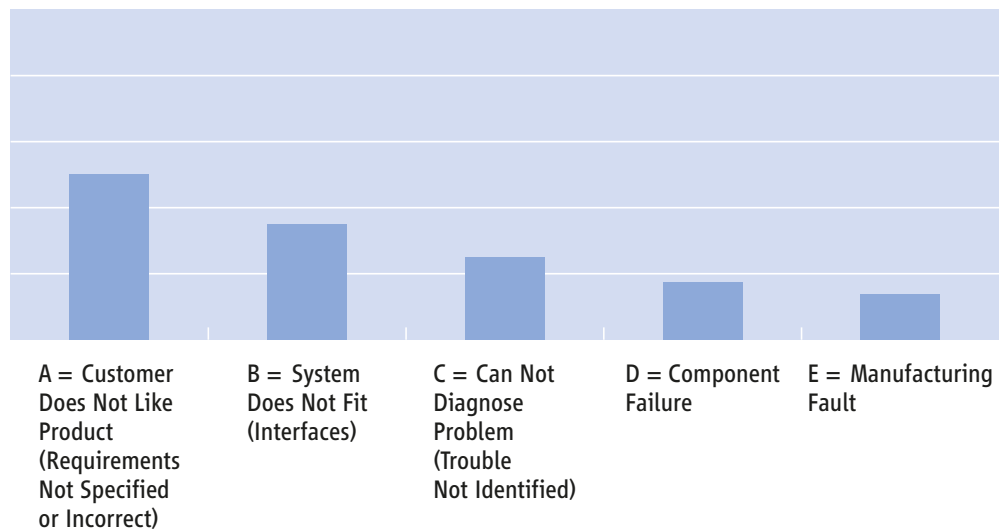


Figure according [9]

2.1 Purpose

This Robustness Validation Handbook provides the automotive electrical/electronic community with a common qualification methodology to demonstrate robustness levels necessary to achieve a desired reliability.

The Robustness Validation approach emphasizes knowledge based engineering analysis and testing a product to failure, or a predefined degradation level, without introducing invalid failure mechanisms. The approach focuses on the evaluation of the Robustness Margin between the outer limits of the customer specification and the actual performance of the component. These practices integrate robustness design methods (e.g. test-to-failure in lieu of test-to-pass) into the automotive electronics design and development process. With successful implementation of Robustness Validation practices, the producer and consumer can realize the objectives of improved quality, cost, and time-to-market.

The purpose of this Robustness Validation Handbook is to establish globally accepted concepts, processes, methods, techniques and tools for implementing the Robustness Validation qualification methodology for automotive electrical/electronic modules and systems.

3. Definitions

3.1 Definition of Terms

Accelerated Test

An accelerated test is designed to identify failures or produce degradation in a shortened period of time.

Acceleration Factor

Acceleration factor is the ratio between the times necessary to produce the same degradation or failure mechanism in an accelerated test compared to the use conditions.

Component

Component is a parts required for the function of an electrical/electronic module (EEM). Examples include capacitors, resistors, ASICs, power-MOSFET, connectors, fasteners and mechatronic assemblies.

Defect

A defect is a deviation in an item from some ideal state. The ideal state is usually given in a formal specification.

Degradation

Degradation is a gradual deterioration in performance as a function of time.

Derating

Derating is the intentional reduction of stress/strength ratio in the application of an item, usually for the purpose of reducing the occurrence of stress related failures.

Design Validation

Design validation is a set of tests or analyses performed to demonstrate that a component or systems is suitable for its intended use and meets known customer/application validation requirements.

Design Verification

Design verification is a set of tests or analyses performed to demonstrate that a component or system has the potential to meet its specified design requirements.

ECU (Electronic Control Unit)

The ECU is an electrical stand-alone module or modules with electrical and/or optical interface. The ECU typically consists of housing, connector, conductor boards and electrical components. An example is a motor management system.

EEM (Electrical/Electronic Module)

The EEM is an electrical alone module or modules with electrical and/or optical interface. The EEM typically consists of housing, connector, conductor boards and electrical components. An example is a motor management system. Mechatronics integrate mechanical and electrical functions into one unit. The Mission Profile of this solution has to take into account the requirements of both the mechanical and electrical parts. In vehicle applications typical mechatronic products cannot be exchanged independently from electronics. Typical examples include ABS, EPS (Anti-Lock Braking System, Electrical Power Steering).

Failure

Failure is the loss of ability of an EEM to meet the electrical or physical performance specifications that it was intended to meet.

Failure Mechanism

A failure mechanism is the process or sequence of processes (mechanical, chemical, electrical, thermal, etc.) that produces a condition that results in a failure or fault.

Failure Mode

A failure mode is the manner in which a failure, or fault condition is perceived or detected.

FMEA (Failure Mode and Effects Analysis)

An FMEA is a qualitative and consensus based disciplined analysis of possible failure modes on the basis of seriousness, probability of occurrence and likelihood of detection.

Load

A mechanical load is an externally applied and internally generated force that acts on a system or device. The application of loads results in stress and strain responses within the structures and materials of the system or device. Loads may be acoustic, fluid, mechanical, thermal, electrical, radiation or chemical in nature.

Load Distribution

A load distribution is a statistically described load level over time, cycles, temperature, voltage, climatic conditions, or other load types.

Mechatronic Module

A mechatronic module integrates mechanical and electrical/electronic functions.

Mission Profile

A Mission Profile is a simplified representation of relevant conditions to which the EEM production population will be exposed in all of their intended application throughout the full life cycle of the component.

Model

A model is a simplified scientific representation of a system or phenomenon, in which a hypothesis (often mathematical in nature) is used to describe the system to explain behaviour.

Operating Conditions

Operating conditions are environmental parameters such as voltage bias, and other electrical parameters whose limits are defined in the datasheet and within which the device is expected to operate reliably.

Product Life Cycle

The product life cycle is the time period from the beginning of the manufacturing process of the EEM to the end of life of the vehicle.

Qualification

A qualification is a defined process by which a product or production technology is examined and tested, and then identified as qualified.

Random Failure

A random failure or fault which occurs in a statistically random fashion.

Reliability

Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time.

Robustness

Robustness is insensitivity to noise (i.e. variation in operating environment, manufacture, distribution, etc., and all factors and stresses in the product life cycle).

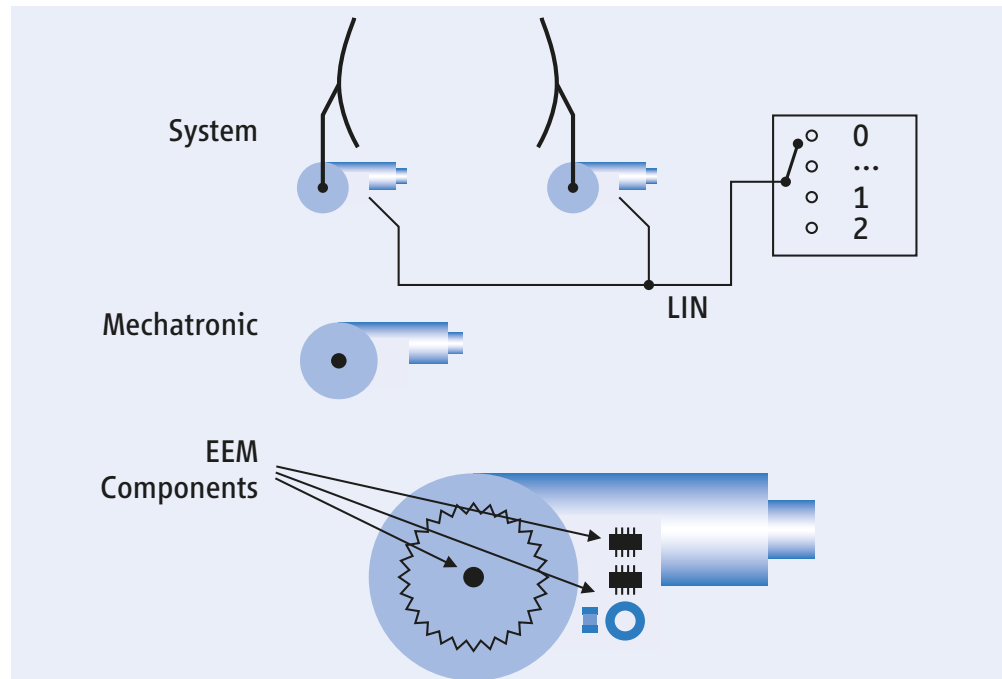
Robustness Validation

A RV Process demonstrates that a product performs its intended function(s) with sufficient margin under a defined Mission Profile for its specified lifetime. It requires specification of requirements based on a Mission Profile, FMEA to identify the potential risks associated with significant failure mechanisms, and testing to failure, "end-of-life" or acceptable degradation to determine Robustness Margins. The process is based on measuring and maximizing the difference between known application requirements and product capability within timing and economic constraints. It encompasses the activities of verification, legal validation, and producer risk margin validation.

Simulation

Simulation is the representation of the behaviour or characteristics of one system through the use of another system, especially with a computer program designed for the purpose of simulating an event or phenomenon. The technique of representing the real world by a computer program, such that the internal processes of a system, are emulated as accurately as is possible or practical and not merely mimicking the results of the thing being simulated.

FIGURE 2 - Example of System, Mechatronic and Components



Stress Factor

A stress or combination of stresses triggering a failure mechanism.

System

A set/combination of several EEMs/Mechatronics or sensors/actuators, connected to perform a distributed functionality is shown in Figure 2.

Systemic Failure

A systematic failure is a non-random failure caused by an error in any activity which, under some particular combination of inputs or environmental conditions, will cause failure. For example, an incorrectly rated resistor may result in systematic failure.

Temperatures

To describe the thermal conditions in the EEM/mechatronic and the semiconductor components inside the EEM, the temperatures at the points defined in Figure 3 can be used. The definitions of these temperatures are:

$T_{\text{Vehicle Mounting Location Ambient}}$: Temperature at 1 cm distance from the EEM package.

$T_{\text{EEM Package}}$: Temperature at the EEM package.

$T_{\text{EEM internal}}$: Temperature of the free air inside the EEM.

$T_{\text{Comp., Package}}$: Temperature at the component package.

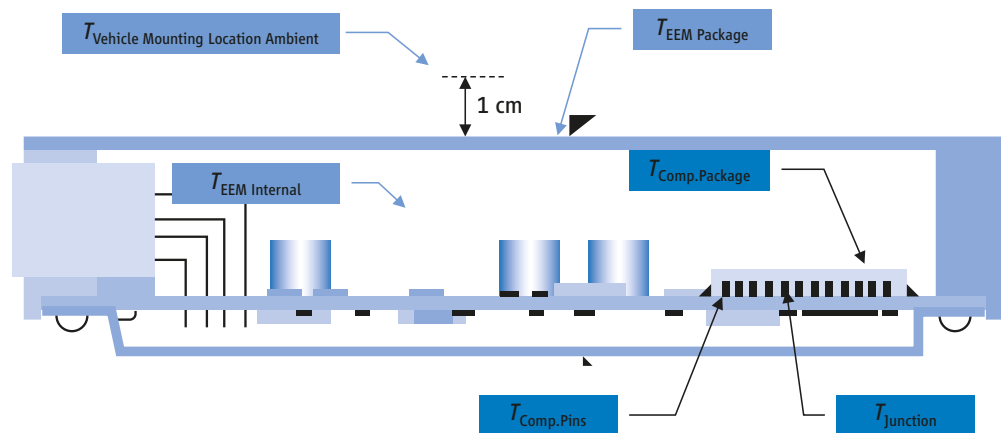
$T_{\text{Comp., Pins}}$: Temperature at the component pins.

T_{Junction} : Junction temperature of the component chip (or substrate).

The OEM relevant temperature for mission profiling is: $T_{\text{Vehicle Mounting Location Ambient}}$

In mechatronic systems additional heat sources or sinks have to be considered (e.g. coolant, engine block...).

FIGURE 3 - EEM Temperature Measurement Points



Trouble Not Identified (TNI)

The Customer Declared Failure could not be duplicated or identified.

Vehicle

The vehicle is the automobile.

Vehicle System

A system on a vehicle is made up of several interconnecting modules or mechanics.

Verification

The conclusion of the primary product development learning process supporting progress to the legal validation phase that the product has a high probability for meeting all known application requirements. There are no legal ramifications in verification. Learning may occur with test to failure for capability measurement beyond the established requirements and reliability demonstration.

Validation

The process of accumulating evidence to support a declaration with legal force that a system/module/component meets the known application requirements. Validation culminates in producing a formal declaration with legal weight that a product has been confirmed supported by objective evidence that the requirement for a specific intended use have been fulfilled. Tests have a defined success point that becomes the base measurement for the "Robust Validation" phase.

Virtual Entity

An item that is not physically real, but displays the qualities of reality or exists in a potential state that could become realized and is often represented in a simulation model.

Wear-Out Failure

A wear-out failure caused by accumulation of damage due to loads (stresses) applied over an extended period of time.

Zero Defect Strategy

Zero Defect is a management approach (also described as a fashion, mindset or culture), which does not mean Zero Defects in a literal of statistical sense. Rather, it is a value chain activity which makes attempts in its approach and methods to achieve Zero Defects with the design goal to manufacture a product with the minimum defects possible.

3.2 Acronyms

| | | | |
|------------------|--------------------------------------|--------------------|--------------------------------------------|
| AMS | Analysis Modeling and Simulation | IEC | International Electro Technical Commission |
| AOI | Automatic Optical Inspection | I/O | Input/Output |
| AVL | Approved Vendor List | M&S | Modeling and Simulation |
| BOM | Bill of Material | OEM | Original Equipment Manufactura |
| CAD | Computer Aided Design | PCB | Printed Circuit Board |
| CAE | Computer Aided Engineering | PPT | Package Peak Temperature |
| CD | Continuous Duty | PoF | Physics of Failure |
| Cm | Capability Maschine | PTH | Pin Through-hole |
| Cmk | Machine Capability Index | PV | Production Validation |
| CPI | Component-Process Interaction | QFP | Quality Function Deployment |
| CPIM | Component Process Interaction Matrix | QRD | Quality, Reliability and Durability |
| Cpk | Process Capability Index | R | Reliability |
| CTE | Coefficient of Thermal Expansion | RFA | Remote Function Actuation |
| DBTF | Design - Build - Test - Fix | RIF | Robustness Indication Figure |
| DFM/DFT | Failure Mode and Effects Analysis | RKE | Remote Keyless Entry |
| DPMO | Defects per Million Operations | RPN | Risk Priority Number |
| DUT | Device Under Test | RV | Robustness Validation |
| DV | Development | SAC solders | SnAgCu solder |
| D&V | Development and Validation | SFDC | Shop Floor Data Collection System |
| DVP&R | Design Validation Plan and Report | SMD | Suface Mounted Device |
| ECU | Electronic Control Unit | SOR | Statement of Requirements |
| E/E | Electrical/Electronic | SPC | Statistical Process Control |
| EEM | Electrical/Electronic Module | SS | Steady State |
| EMC | Electro Magnetic Compatibility | Tg | Glass Transition Temperature |
| ESD | Electrostatic | Tmax | Temperature Maximum |
| FCT | Functional Test | Tmin | Temperature Minimum |
| FMAE | Failure Mode and Effects Analysis | TNI | Trouble Not Identified |
| HALT | Highly Accelerated Limit Testing | TTF | Test-to-failure |
| ICT | Incircuit Test | | |

4. Definition and Description of Robustness Validation

4.1 Definition of Robustness Validation

Robustness Validation is a process to demonstrate that a product performs its intended function(s) with sufficient Robustness Margin under a defined Mission Profile for its specified lifetime. It should be used to communicate, analyse, design, simulate, produce and to test an EEM in such a manner, that the influence of noise (or an unforeseeable event) on an EEM is minimized.

Robustness Validation can and should be applied for developments of different types, completely new, incremental change or modifications when evaluating the different types of development projects account should be taken of previous knowledge and lessons learned.

4.2 Robustness Validation Process

A robust product is one that is sufficiently capable of functioning correctly and not failing under varying application and production conditions. The Robustness Validation Process (RV Process) defined in this handbook relies heavily on team expertise and knowledge, and therefore requires detailed explanation and intensive communication between the user and supplier.

The Robustness Validation flow shown in Figure 4 is an essential part across the development process. This method is based on three key components:

- Knowledge of the conditions of use (Mission Profile).
- Knowledge of the failure mechanisms and failure modes and the possible interactions between different failure mechanisms.
- Knowledge of acceleration models for the failure mechanisms needed to define and assess accelerated tests.

Robustness Validation is a knowledge-based approach [1, 2] that uses analytical methods and stress tests that are defined to address specific failure mechanisms using suitable models, test and stress conditions. This approach results in a product being qualified as “fit for use”, not “fit for standard”.

It is important to note, that as Robustness Validation is a knowledge based approach it must not be applied blindly, or in a standardized default manner as current verification approaches, but with appropriate experience and training of the people applying the process and of the failure mechanisms. The Robustness Validation Users own Knowledge Matrix (see Section 7) must be a central part of the RV Process within an organization.

When considering the RV Process the standard V-model concept should be applied at each level/stage of the Robustness Validation process from the top (System) level to the bottom (Component) and back up again with repeated iterations and feedback up and down the process chain.

The V-model in Figure 5 shows the concept of requirement flowing from the customer, to the vehicle, to the system, to the module, and to components. The sources of requirements should be documented. Module design concepts need verification which involves sharing and documenting information between the OEM and suppliers at all levels. Once a requirement is accepted, it needs validation to determine if the requirement is satisfied.

FIGURE 4 - The Robustness Validation Process Flow

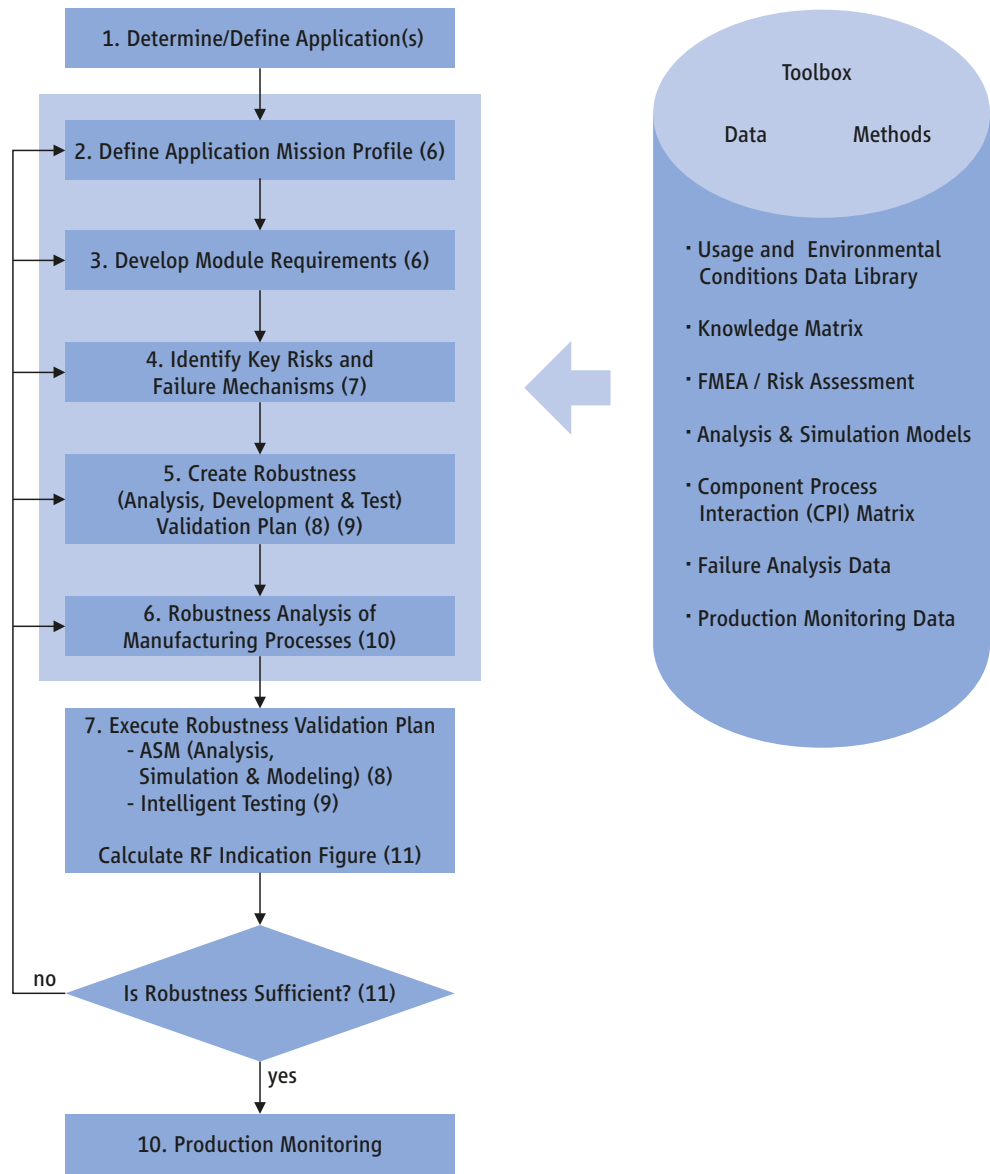
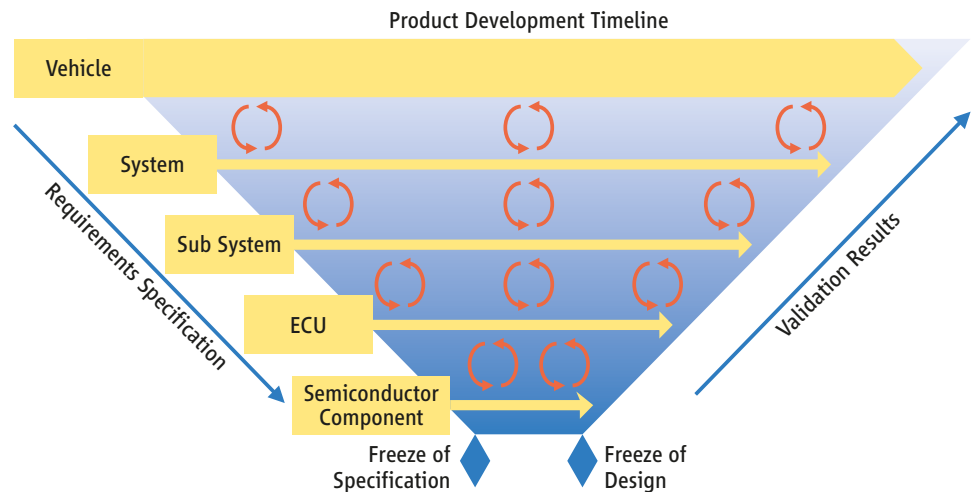


FIGURE 5 - The Agile Product Development Process

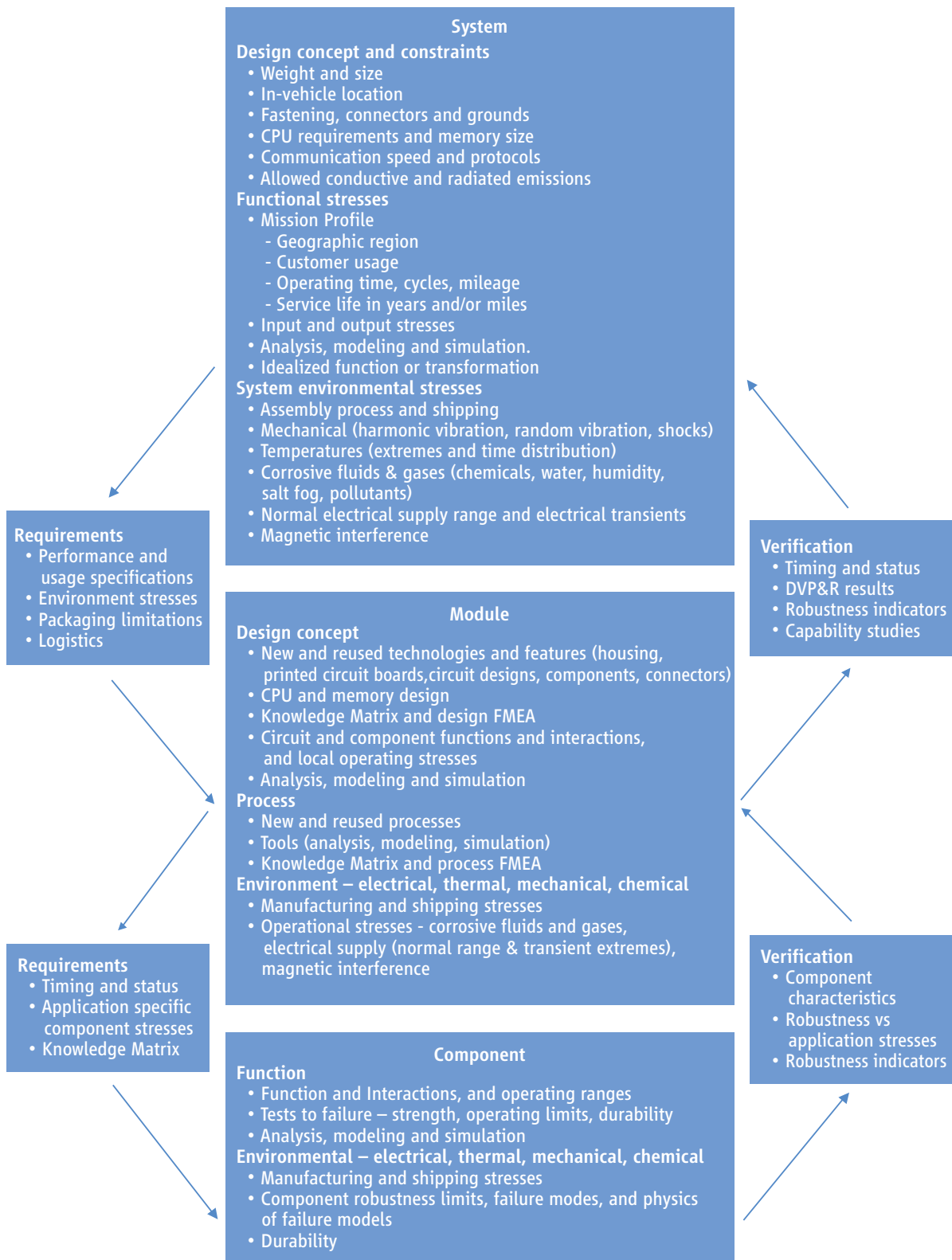


5. Information and Communication Flow

The efficiency and effectiveness of Robustness Validation largely depends on communication of previous and on-going learning that takes place between the individuals, teams

and organizations involved in the module's design, development, validation, production and use, as seen in Figure 6.

FIGURE 6 - Robustness Validation Informationen Flow



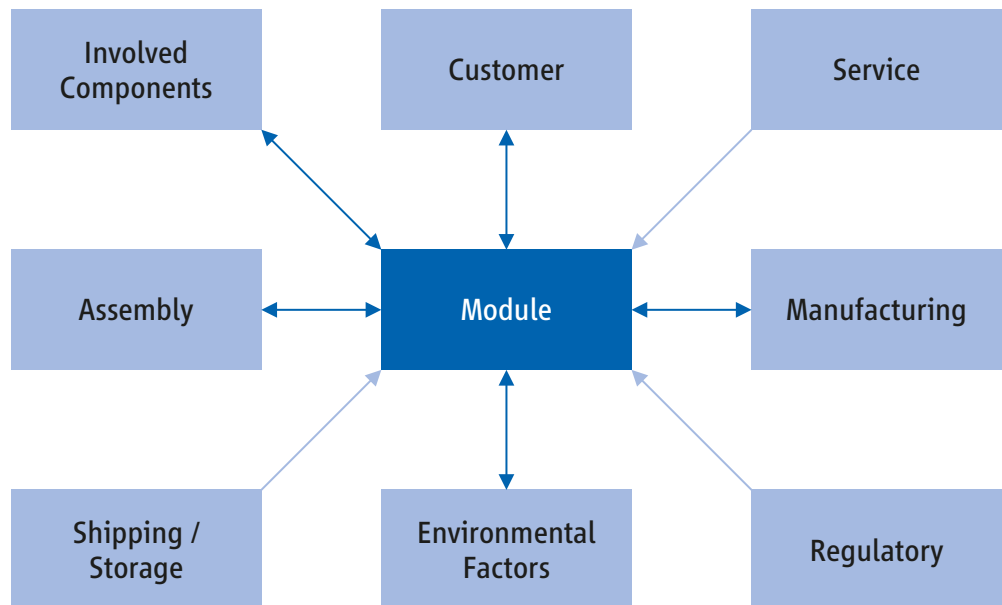
5.1 Product Requirements

Modules are expected to support requirements that are developed from the Mission Profile which considers different aspects of the module's intended function, environments, and service life targets. There are different sources of these requirements, i.e. the vehicle user, regulatory agencies, market consideration, local environments, dealer service, vehicle and parts shipping and storage, vehicle assembly, mounting location in the vehicle, and other OEM requirements. The require-

ments flow from these sources to the vehicle, to the system, and finally to the module.

A boundary diagram shows as inputs to the module customer, regulatory, and assembly requirements plus "involved" modules that interface to the device. Some requirements are subjective and difficult to capture as a measurement parameter. The boundary diagram in Figure 7 is a useful tool to assure these requirements are captured.

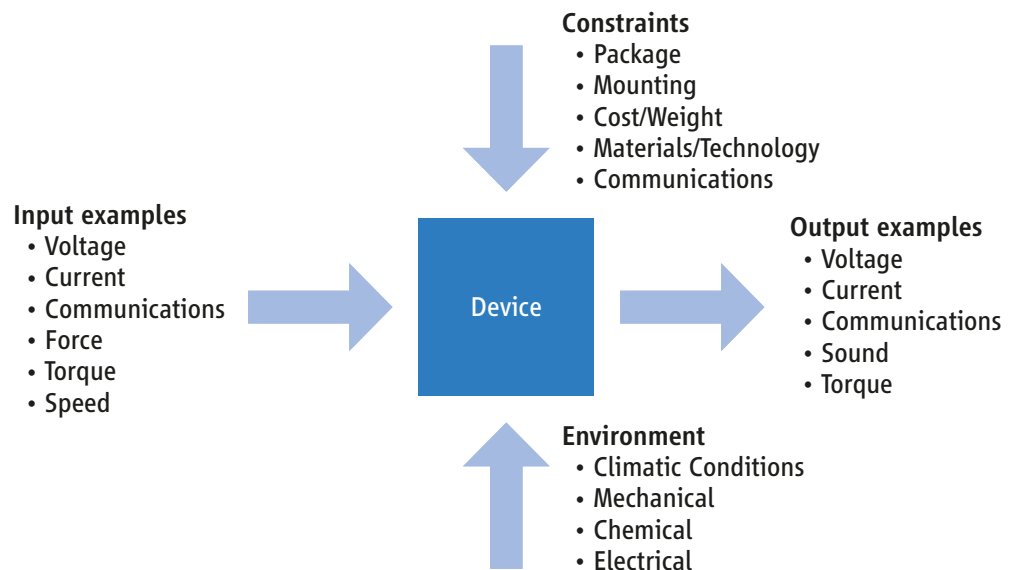
FIGURE 7 - Boundary Diagram



The Parameter Diagram (P-Diagram) in Figure 8 captures and summarizes inputs, outputs, environmental stresses, and design constraints for products. A device, represented by a box at the centre of the diagram, may be a component, module, system, or vehicle. By

convention, inputs are listed on the left with arrows leading into the box; outputs, on the right with arrows leading from the box; environmental stresses, on the bottom with arrows leading to the box; and design constraints, above the box with arrows leading to the box.

FIGURE 8 - Module Parameter Diagram (P-Diagram)



5.2 Use of Available Knowledge

Most electronic modules are evolutionary development of past modules and use similar design and manufacturing concepts. There is a high level of reuse of individual components, circuit designs, connectors and housing concepts. In vehicles, the modules perform similar functions and share similar locations. Around 90% of a new module design is similar to some predecessor module. However, the changes that occur may include the addition of functions to a module, some new circuits, new board layouts to accommodate the new circuits, and technology changes of components. Also, the vehicle environment may become more severe.

Traditionally, module verification and validation focused on repeating a standard suite of tests with the addition or deletion of functional tests. Similarly, environmental stress tests were repeated with every new module. As electronic modules become more complex, the potential number of combinations and permutations of operating modes and

associated functional tests becomes very large with associated very expensive long duration tests. A more efficient process is required that focuses verification and validation on changes and potential interactions of the changes with other module functions.

How does one manage this process? The design and process reviews are appropriate forums. The first topic should be the predecessor design. What were the problems and lessons learned? Are their symptomatic warranty, vehicle assembly, manufacturing, and shipping/storage issues? The new design should include changes to correct these issues, i.e. support continuous improvement. The new features need to be reviewed. The new features, old module improvements, and technology changes constitute the scope of the change verification. The risk associated with these changes should be addressed in Design and Process FMEAs. High risk items and functional validation need to be included in a test plan. The Robustness Validation Plan (RV Plan) should be integrated in the DVP&R.

6. Mission Profile

The Mission Profile is a representation of all relevant conditions an EEM will be exposed to in all of its intended applications throughout its entire life cycle. It is therefore important that the Mission Profile for each individual EEM be developed and communicated to the engineers designing the module as soon as possible. With a good description of the Mission Profile, engineers can begin to estimate reliability and quality levels and start to work toward achieving "Zero Defects" and robust design at all levels of the supply chain.

This section provides an overview of the various conditions and stress factors (loads) an EEM may experience during its life cycle. This information is intended to be used as a starting point in developing Mission Profiles for individual EEMs. Stress factors may be mechanical, climatic, chemical and electrical loads during manufacturing, operation, stand by operation, transport and car assembly. As shown in Figure 9, the stress factors may be due to environmental loads, functional loads or both simultaneously.

FIGURE 9 - Environmental and Functional Load Stress Factors

| | | |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Environmental Loads <ul style="list-style-type: none"> ✓ Thermal ✓ Mechanical ✓ Radiation ✓ Dust ✓ Humidity ✓ Water ✓ Chemical ✓ Electromagnetical (EMC) | Interaction | Functional Loads <ul style="list-style-type: none"> ✓ Usage profiles ✓ Mechanical operation ✓ Emitted radiation ✓ Electrical operation |
| Assembly Requirements | | Shipping and Service |

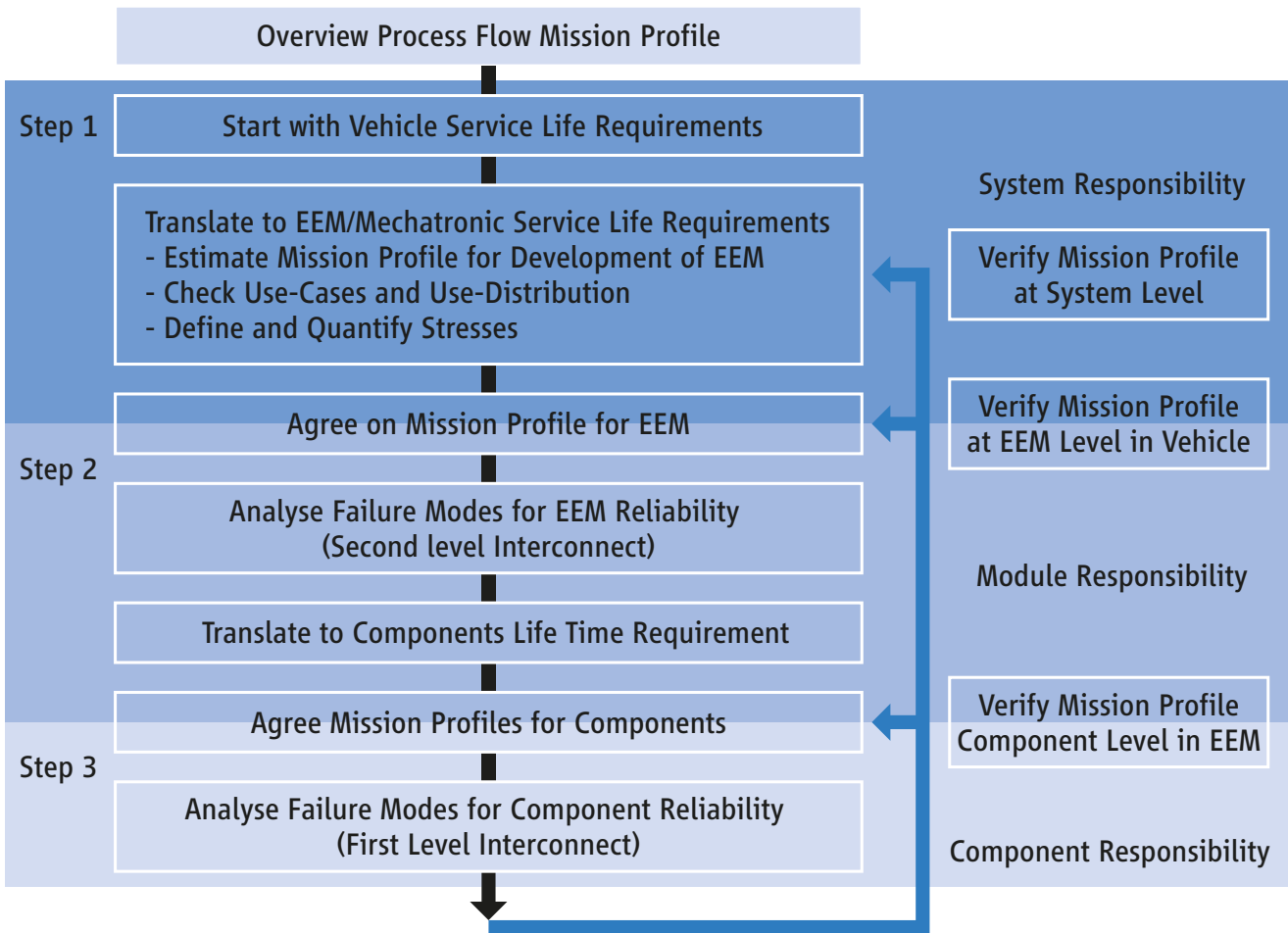
As the product development process progresses, Mission Profiles and functional loads will be defined more precisely. Therefore changes and revisions to loads or load distributions shall be agreed upon between the parties.

The Mission Profile is not a test description. It is the basis for material selection, design, test engineering, parameterization, analysis, modeling and simulation, and robustness evaluation.

6.1 Process to Derive a Mission Profile

When developing a Mission Profile, using the process flow defined in Figure 10 it is likely that multiple sources of data will be utilized. In most cases a combination of publicly available [3, 22], private historical data and freshly generated data will be used. Knowledge of the conditions of use in the vehicle application(s) and the possible effects on the module and components is required. Because some factors may have little effect while other may have a strong effect, it is also necessary to judge the relevance of each factor.

FIGURE 10 - Overview of a Process Flow for Generating a Mission Profile



STEP 1:

Start with vehicle service life requirements. The most general data concern is the required vehicle service life. This comprises information for example:

- Service lifetime: The total lifetime of the car.
- Mileage: The total amount of miles/kilometres that the car is assumed to drive during its service life.
- Engine on time: The amount of time that the engine is switched on (key-on time) and operational during the service lifetime (if product is active during this time).

An example of this kind of data is given in Table 1 next page.

TABLE 1 - Example of Vehicle Mission Profile Parameters at the Vehicle Level

| | | |
|-----------------------------|---------------------------|------------------------------------------------------------------------------------------------------------------------------|
| Service lifetime | 15 years (= 131,400 h) | |
| Mileage | 600,000 km | High level high mileage request for stand alone EEM (no for mechatronics). |
| Engine on time | 12,000 h | Engine on time is directly proportional to mileage. Operating time of single component may be different than engine on time. |
| Engine on/off cycles | 54,000 | Without additional start/stop functions. |

STEP 2:

Translate to EEM/Mechatronic life time requirements (OEM).

The above definitions are valid for the whole vehicle. However, depending on the function-

ality required, the active and passive periods may be very different for the vehicle versus the EEM. Their different service life requirements are exemplified in Table 2 below.

TABLE 2 - Different Service Life Requirements for Vehicle and EEM

| Vehicle | EEM |
|---------------------------------|--------------------------------------------------|
| Engine on time | EEM on time (operating, active) |
| Engine off (non-operating time) | EEM off time (non-operating) EEM standby time |
| Engine on/off cycles | EEM on/off cycles |

Furthermore, for the Mission Profile of the EEM, the mounting location and specific use cases have to be considered. Therefore, for each EEM/Mechatronics, the active, stand-by, sleep and non-operating time must be determined individually.

Step 2.1:

Collect possible operating modes (active, stand-by, special loads, sleep, power supply interrupted, cyclically reoccurring operation, and operating mode changes)

Each relevant function must be completely covered.

Step 2.2:

Assign operating modes to the defined vehicle lifetime requirements.

Step 2.3:

Describe mounting locations, conditions and related loads:

- Temperature (Distribution)
- Temperature cycling (Distribution)
- Vibration (Distribution)
- Water, salt, dust, humidity, chemical agents
- Detail load profiles (e.g. electrical/thermal/mechanical loads) of the EEM/Mechatronic (experience from present projects).

Result:

Basis for Mission Profile for EEM/Mechatronic

Consider:

Misuse, safety requirements, transport, storage, service (EOS/ESD), processing/assembly, testing.

An example of this kind of data for EEM level is given in Table 3 below.

TABLE 3 - Example of OEM EEM Operating Life Time Requirements

| | Operating on Time (active) (h) | Non Operating Time (h) | EEM Active on/off Cycles | EEM Specific Operating Load Cycles |
|-----------------------------|--------------------------------|------------------------|--------------------------------------------------------|------------------------------------|
| Motor-management | 12,000 + 3,000 Standby time | 116,400 | 54,000 Without additional start/stop functions | Engine on/off... |
| Transmission control module | 6,000 | 125,400 | | Gear shift... |
| Door Module | 8,000 | 79,800 | 36,000 + operating cycles + window + mirror activation | Window lift... |

Estimation of Mission Profile for Development of EEM.

A first set of Mission Profiles is necessary to derive requirements for use in the development process (temperature limits for component selection, etc.). It is likely that there is little or no data available at that time. However, an approximation can be given by:

- Use standard Mission Profiles for defined mounting location.
- Use measurements from previous developments.
- Use measurements from similar applications/vehicles.
- Estimate usage, generated by thinking possible use-cases through.

To make sure that all parameters of any adopted Mission Profile cover the requirement for the specific mounting location, a validation of the chosen Mission Profile for the specific application is necessary.

These estimates should be verified by actual measurements as parts/installations become available during the development process.

Check Use-Cases and Use-Distribution (Refinement and Validation)

Define Use-Cases - Use-Cases can help identify sources of loads and provide operation parameters. By thinking through several use-cases, choices of descriptive parameters, their distribution of values and severity of effect of failure can be outlined. Usually several relevant use-cases can be combined into one enveloping Mission Profile thus enabling validation with the same plan.

Analyse Use-Distribution - Often EEM/Component stress is significantly higher when operated close to the design limits (e.g. max. load). Also there are use-cases that may result in unusually high load cycle numbers (e.g. taxi driver).

Due to this, considering only possible limits/extremes may not be sufficient, additionally a use distribution is necessary. It shall describe the occurrence likelihood of loads with regard to the operation parameter range.

However, in the case that extreme distributions are ruled out from design considerations or test coverage, failures that may result there from these extreme distributions must still be evaluated for safety and customer satisfaction consequences. Furthermore it should

be checked by thinking through use cases, if a combination of different loads can occur simultaneously or sequentially. For certain parts or materials these combinations may provoke different failure modes or accelerate others. Therefore a definition of combined loads may be necessary.

Example:

Use-Case Brake application Stop and Go in the city, breaking every 200 m (high number of cycles, low load).

Highway singular power braking from 200 to 80 km/h (low number of cycles, high load).

6.2 Agree Mission Profile for EEM (System Level with Module Level)

First, possible uses must be collected and be evaluated for relevance. An OEM should supply typical vehicle-oriented descriptions for use scenarios and operating conditions.

- Generate environmental Mission Profile (e.g. complete ZVEI Application Questionnaire [8]).
- Describe electrical/functional loads (e.g. fill in functional requirements in specification).

6.3 Analyse Failure Modes for Reliability of EEM

With knowledge of the planned design of the EEM, the 1st (... nth) Tier suppliers must check the given Mission Profile (ZVEI Application Questionnaire) and the resulting loads for completeness with regard to failure modes:

- All potential failure modes have to be traced from component level to module up to system level.
- Critical components have to be identified from system down to component level, which in turn can generate need for an additional/different Mission Profile.

The collected information on source/effect interaction then should be used for a qualitative analysis to identify parameters of the Mission Profile which do affect reliability of the system and rank them by assumed impact.

This clarifies the significance of each parameter and helps in choosing an appropriate precision in its specification (e.g. requiring use-studies, measurements, a fine-grained distribution or allowing rough estimation).

6.4 Translate to Components Life Time Requirements

The translation to the component level must contain applicable environmental electrical and mechanical loads of the EEM design, especially power losses and active pulse loadings. The loads have to be analysed for each critical component.

The Steps are similar to 6.1.

Step 1:

Collect possible operating modes (active, stand-by, special loads, sleep, power supply interrupted, cyclically reoccurring operation, operating mode changes).

Each relevant functionality must be completely covered.

Step 2:

Assign operating modes to the defined vehicle lifetime requirements.

Step 3:

Describe related loads for each critical component:

- Temperature (distribution, including power loss)
- Temperature Cycling (distribution, including active pulse loading)
- Vibration (of the component in the EEM)
- Humidity in the EEM
- Service (ESD)
- Testing
- Processing Assembly
- Electrical

Result:

Basis for Mission Profiles for critical components.

Consider:

Misuse, safety requirements, transport and storage.

6.5 Agree on Mission Profile for Components (Module Level with Component Level)

An "application questionnaire" by the module level supplier shifts the focus to components and technologies intended for implementation and their critical conditions. The Module level supplier provides typical component oriented descriptions for environmental and operating conditions.

- Generate the electrical/mechanical loads as a function of the environmental condition.
- Discuss Mission Profiles for all critical components with suppliers.

6.6 Analyse Failure Modes for Reliability of Component

All potential failure modes have to be traced from component level to module up to system level. Critical loads have to be identified at the component level.

Result:

Sensitivity of system availability to parameters of Mission Profiles is evaluated, which gives indications on parameter significance and need for dimensioning precision.

6.7 Verify Mission Profile at Component Level in EEM (Module Level to Component Level)

Assumptions used in choosing Mission Profiles should be verified by measurements in the actual application as the EEM becomes available (e.g. temperatures in EEM package areas, temperatures of component in EEMs, load distributions, software driving behaviour).

Deviations can be assessed using results from analysing failure modes for reliability of components. In case of significant deviation there may arise the need for additional testing or even changes in construction.

6.8 Verify Mission Profile at EEM Level in Vehicle (Module Level and System Level)

A similar procedure to Section 6.7, but in vehicle.

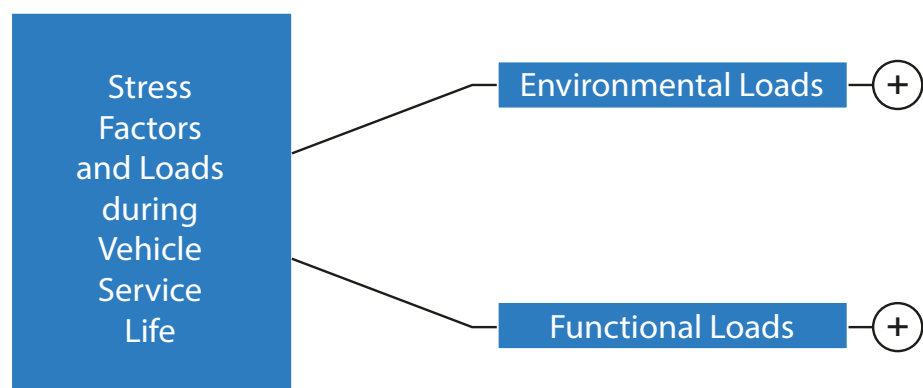
6.9 Verify Mission Profile at System Level

A similar procedure to Section 6.7, but with emphasis on distributed or combined functionalities of EEM/sensors in systems.

6.10 Stress Factors and Loads for EEMs/ Mechatronics

Stress Factors and loads during vehicle service life include environmental and functional loads as illustrated in Figure 11 and detailed in Section 6.12 and 6.13.

FIGURE 11 - Stress Factors and Loads During Service Life Overview



6.11 Vehicle Service Life

Service Life of the vehicle can be for example:

- Expected life time (e.g. 10 years, 15 years).
- Expected mileage (200,000 km to 600,000 km).
- Expected operating hours (4,000 h to 12,000 h).

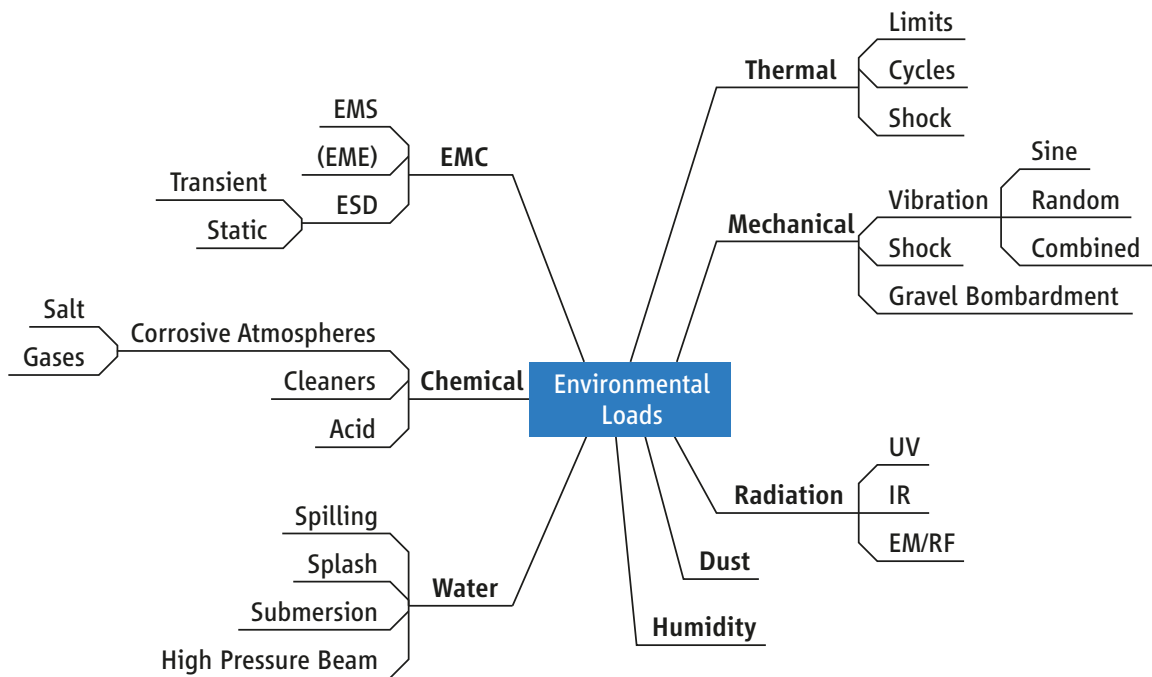
As defined in Section 6.1 and considering vehicle type (passenger or commercial vehicle).

6.12 Environmental Loads in Vehicle

The EEM reliability can be influenced by the environmental loads as shown in tree analysis of Figure 12. Environmental Loads are external stress factors caused by certain environmental conditions, such as temperature, humidity etc..

Environmental loads have to be selected from the tree and/or added when necessary for a specific mounting location. Describe and quantify conditions of the relevant loads.

FIGURE 12 - Tree Analysis of Environmental Loads

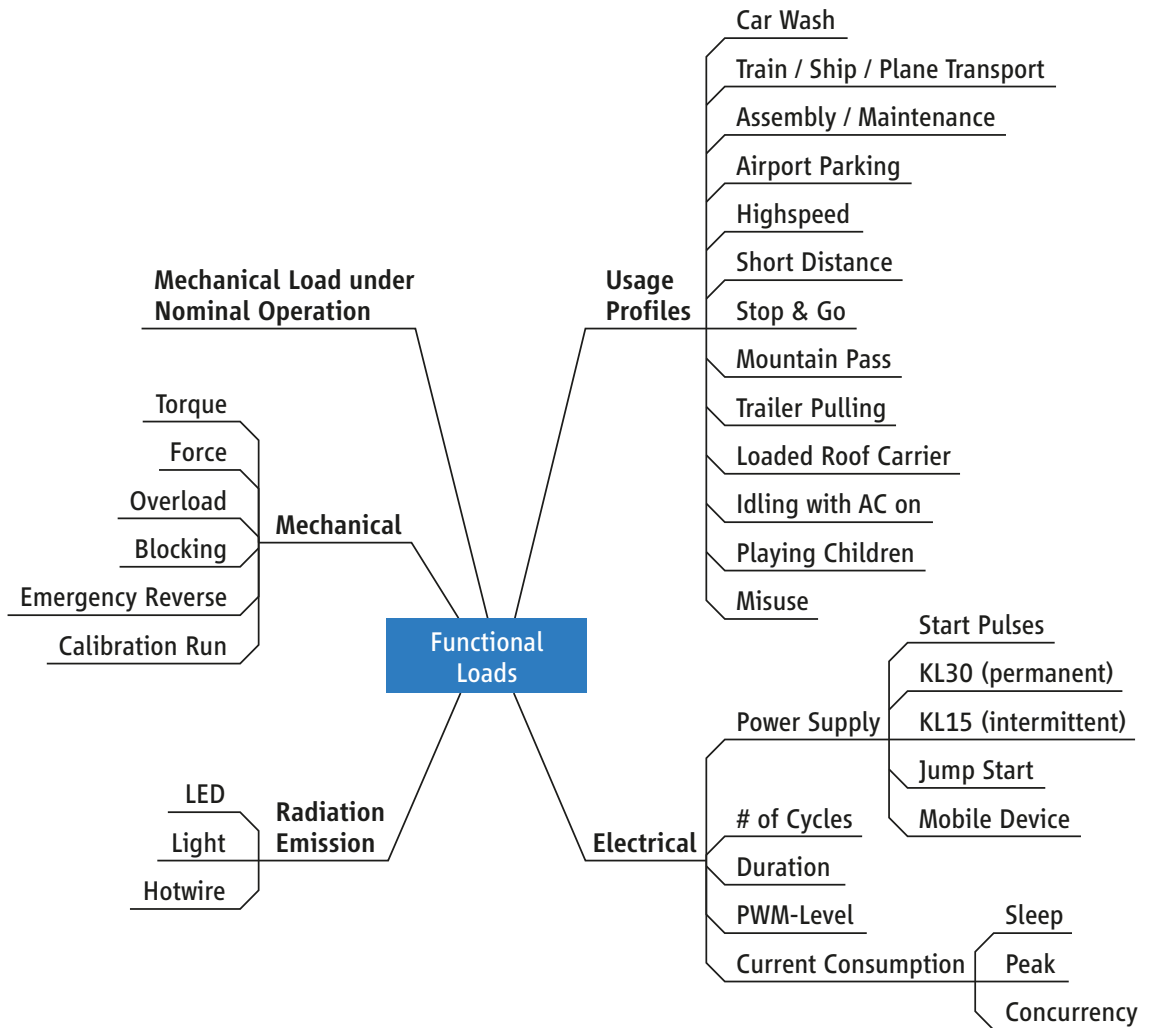


6.13 Functional Loads in Vehicle

The EEM reliability can be influenced by the functional loads as shown in tree analysis of Figure 13. Functional loads are stress factors caused by EEM operation, usage profiles etc..

Functional Loads for a specific EEM have to be selected from the tree and/or added when necessary. Describe and quantify conditions of the relevant loads.

FIGURE 13 - Tree Analysis of Functional Loads



6.14 Examples for Mission Profiles / Loads

The Mission Profiles in this section are simplified 'typical' loads for different mounting locations. Note, that these profiles are estimations, which represents typical operational profiles of different drivers in a passenger cars and have to be validated.

However, 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.

See Appendix A.1 and A.2 for examples of typical Missions profiles.

7. Knowledge Matrix for Systemic Failures

7.1 Knowledge Matrix Definition

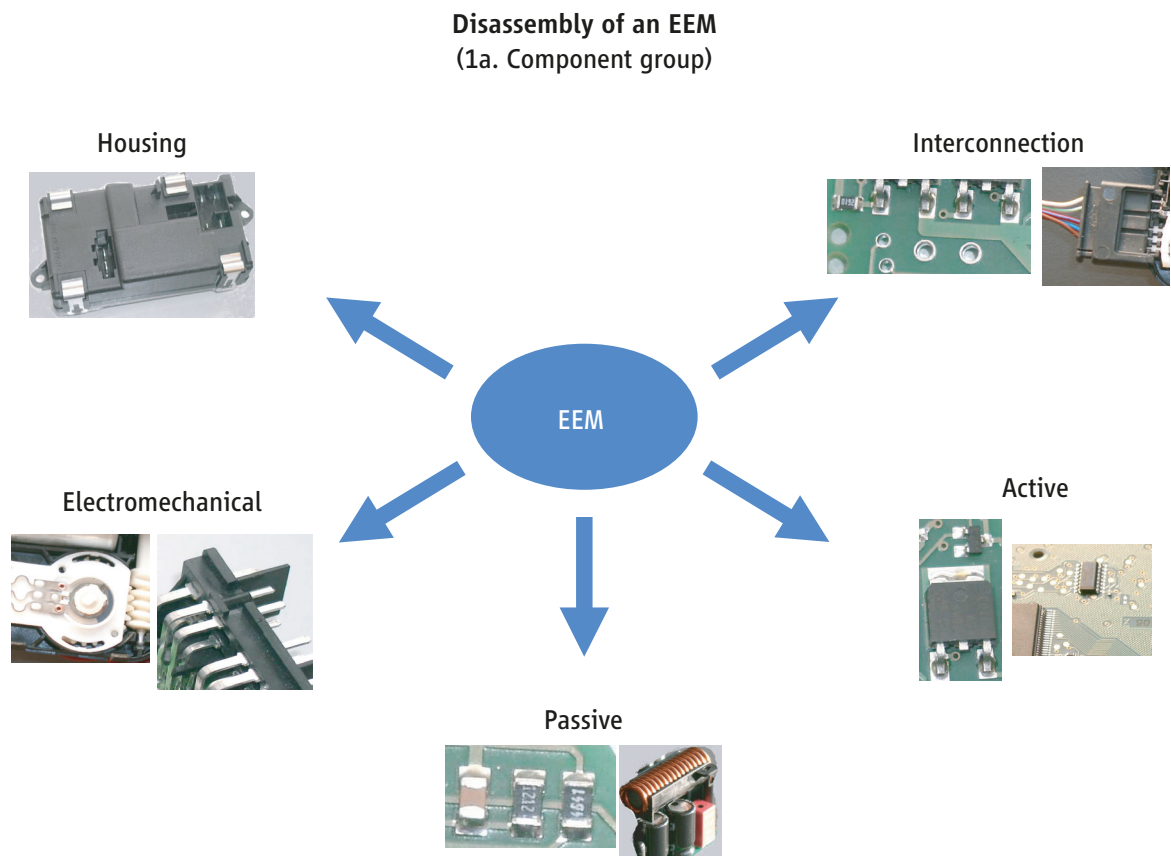
A Knowledge Matrix is a repository for systematic failures, i.e. failures that are systemic or inherent in the product by design or technology. The Knowledge Matrix is a collection of the lessons learned by the organization using the RV Process. Extrinsic failures, i.e. failures that are random in nature and predominantly generated by manufacturing processes, are covered in Section 10.

In order to apply and interpret the results of the RV Process, knowledge of the basic failure mechanisms of the EEM is required. The root causes of the failure mechanisms and the effects on the module

must be known in order to relate the failure mechanisms to the product's performance and the conditions of use. A Knowledge Matrix can be very useful in identifying potential failure mechanisms and their causes.

To make the development and use of the Knowledge Matrix easier to understand the Knowledge Matrix is divided into several logical groups with the first level being the Component Group. An example of this process is illustrated in Figure 14.

FIGURE 14 - Decomposition of an Electronic Control Unit (EEM)



7.2 Knowledge Matrix Structure

The following example Knowledge Matrix shown in Table 4 is defined with a structure to enable easy navigation of the possible failure modes and causes. This is received by taking a

module in combination with the intended customer use and breaking it down to the components and technology used to assemble it.

TABLE 4 - Knowledge Matrix Structure

| Field No | Field/Column Name | Field/Column Required | Field/Column Description | Field/Column Content/Example |
|----------|----------------------|-----------------------|---------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1a | Main Component Group | Mandatory | Top Level Main Component group | Housing Interconnection Passive Active Electromechanical |
| 1b | Component Sub Group | Mandatory | Components broken down to the next level | Resistor Diode PCB IC Inductor Capacitor Crystal etc. |
| 2 | Product Life Phase | Mandatory | The Product life phase that impacts on the Robustness Characteristics | <p>Design/Development Phase Robustness aspects that are determined during the Initial Design & Development phase of a product life (e.g. wrong material chosen).</p> <p>Manufacturing Phase Robustness aspects that are determined during the serial production phase of a product life (e.g. too high process temperature).</p> <p>OEM Assembly Phase Robustness aspects that are determined during the assembly of the product into the vehicle (e.g. mounting force too high).</p> <p>Customer Use Phase Robustness aspects that are determined at 0 km & Field (e.g. incorrect specified operation conditions; misuse).</p> |
| 3 | Robustness Aspect | Mandatory | The Characteristic that defines the robustness of the product | Cleanlines (e.g. production process), Resistance, Mechanical stability, Material; operational conditions etc.. |
| 4a | Failure Mode | Mandatory | The effect by which a failure is observed to occur. | EEM-Level: incorrect function Component-Level: Open circuit PCB Track. |
| 4b | Failure Cause | Mandatory | The specific process, design and/or environmental condition that initiated the failure, and whose removal will eliminate the failure. | i.e. Excessive Current in PCB track. |

TABLE 4 - Knowledge Matrix Structure (Continued)

| | | | | |
|----|-------------------|-----------|-----------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 4c | Failure Mechanism | Mandatory | The specific process, by which physical, electrical, chemical and mechanical stresses act on materials to induce a failure. | I.e. track overheating from excessive current to point of failure. |
| 4d | Failure Type | Mandatory | Systemic or Random | |
| 5 | Failure Stressor | Mandatory | The Type of Stress or combination of stress's required to trigger the failure mechanism. | Temperature Cycle + Vibration, Temperature + Humidity + Vibration |
| 6a | Test Methodology | Optional | If available the test methodology to be used to trigger the failure. | This field is intended as a reference guide to assist the user in finding an appropriate test methodology and does not constitute a specific test definition. The Robustness Validation User has the responsibility to understand the failure mechanism and to determine the appropriate test methodology. |
| 6b | Test Reference | Optional | If available the standard reference used to trigger the failure. | This field is intended as a reference guide to assist the user in finding an appropriate test methodology and does not constitute a specific test definition. The Robustness Validation User has the responsibility to understand the failure mechanism and to determine the appropriate test methodology. |

7.3 Knowledge Matrix Use

There are two distinct versions of the Knowledge Matrix - the publicly available example version defined in this document and a company-specific version.

The failure data in the publicly available Knowledge Matrix should be considered a starting point and guide for any user of the RV Process as it contains only the generic state of current knowledge information.

Users of the RV Process should generate their own Knowledge Matrix based on their own specific product types, and their own personal experience and lessons learned. A format and structure similar to the example Knowledge Matrix illustrated here is suggested. The data contained in the sample publicly available Knowledge Matrix can be used as a guide and a starting point.

There are many ways to use the Knowledge Matrix, and the way to use it depends on what information is already known and what information is needed. The Knowledge Matrix can be used in a reactive manner when there is a failure mode requiring root cause analysis, and an acceleration model. Likewise, the Knowledge Matrix may be used in a proactive preventative manner to identify potential failure modes in a design during the design phase of a product development, particularly as part of an FMEA. Knowledge Matrix Use in Failure Prevention (Proactive).

As part of the RV Process there should be a review of the user's existing Knowledge Matrix against the Mission Profile and product-specific requirements. The user should also be able to demonstrate the completeness of the review during discussions with the customer.

The user should be able to demonstrate lessons learned that are in the Knowledge Matrix and are included in the product design, for example a design review report.

One of the outputs of the review might be the FMEA, which includes the lessons learned.

See Appendix A for examples of using the Knowledge Matrix. (Knowledge Matrix Use in Failure Analysis Reactive).

During a failure incident and as part of the user's failure analysis process the Knowledge Matrix can be used to identify the potential root cause of the failure. When a new failure mode and causes are identified during the analysis, processes that are not currently in the user's Knowledge Matrix should be updated to add the new failure mode.

One use of the Knowledge Matrix is when a failure mode has been observed and there is a need to identify the potential failure causes and/or stress factors (stressors). This may be done as follows:

Step 1:

Filter on the component group (column 1a) and component sub group (column 1b) involved.

Step 2:

Find the potential Failure modes in column 4a.

Step 3:

Find the potential failure cause in column 4b.

Note:

It is possible that the specific failure cause does not exist in the matrix. Therefore a new entry would be required to describe the failure.

Step 4:

Find the failure mechanism in column 4c.

Step 5:

Review the potential stressors in column 4d.

The list of potential failure modes, causes and stressors may then be used to plan an investigation to confirm which one is the correct one for the particular failure.

See Appendix A for examples of using the Knowledge Matrix.

7.4 Knowledge Matrix Change Control

The users Knowledge Matrix must be a controlled document within the users organization subject to change control and regularly updated with lessons learned from each product life cycle.

7.5 Lessons Learned

The Knowledge Matrix is intended to be the main repository for all lessons learned within the organization so users of Robustness Validation must have in place a process to collect and review lessons learned from their Robustness Validation activities and update their own Knowledge Matrix from all sources of experience with EEM failures.

7.6 Knowledge Matrix Availability

The example Knowledge Matrix is freely available from the SAE/ZVEI website and will be updated on a regular basis by a team of experts.

Suggestions to update or modify the example Knowledge Matrix are actively encouraged and such suggestions should be sent to CustomerService@sae.org.

The users' company specific version of the Knowledge Matrix should be available for review by the customer, but is not required to be given to the customer.

8. Analysis, Modeling and Simulation (AMS)

8.1 Introduction to the Use of Analysis, Modeling and Simulation

Analysis is the process of studying the nature or operation of an issue, item or substance by sorting out and investigating the component parts so that the relationships of how something is made and why it functions the way it does can be understood. Engineering analysis can focus on either of two objectives:

- 1) Learning how and why things work or do not work in order to resolve an issue or
- 2) Using the knowledge and lessons learned from past endeavors to predict how new designs or processes will perform.

Many different types of analysis techniques have been developed to deal with different technologies, materials and issues, and which are essentially either a physical, intellectual or mathematical and sometimes statistical process.

It is not the intent of this handbook to go into detail regarding the many established and emerging analysis techniques available today. Engineers not familiar with such techniques are encouraged to seek out, study and apply them as needed. Internationally accepted standards and guides which provide an overview of proven techniques are readily available [10, 11, 12]. Detailed information, whether basic or state-of-the-art, on specific techniques, such as Sneak Circuit Analysis [13], FMEA and Fault Tree Analysis [14, 15, 16], and Worst Case Circuit Design and Analysis [17, 18, 19, 20] are also easily obtained through SAE International, Inc., national and international standards organizations, professional societies and journals, and bookstores.

Modeling is the creation of a representation of a process, device or system, used in predictive analysis to evaluate the behaviour of new systems. Engineering models are typically math based and are often incorporated into computer programs. The models can be either empirical (i.e. based on observation of a results or an outcome) or phenomenal (i.e. a model of the actual phenomenon and processes that produce the outcome). Phenomenal models are typically more detailed and therefore more complicated to use. However

this results in greater accuracy and makes them more applicable to a wider range of circumstances than empirical models. Care must be applied when using empirical models since they are typically accurate only under a limit range of conditions. These models give birth to the term cook book equations and the common modeler saying that “all models are wrong, however some models are useful if you know how and when to use them”. Therefore it is essential that modeling activities first require diligent development and validation of the foundation mode that includes understanding the limitations and ranges of linearity or nonlinearity of the model and how accurately it represents real world conditions.

Simulation refers to the use of one system or media to represent the behavior or characteristics of a real world system. Sophisticated engineering computer program are increasingly required and used to bring life to engineering models by simulating complex events and functions. True simulations attempt to emulate the sequence of deterministic (i.e. cause and effect) internal processes that produce a result by using phenomenal models and not merely predict an outcome or results of an item being simulated. Simulations may also provide a visual representation of the fundamental processes and the results in addition to mathematical and graphical results.

Advancements in computing power, simulation software and modeling algorithms are fuelling rapid progress in automotive Analysis, Modeling and Simulation (AMS) methods especially when performed in an integrated Computer Aided Design (CAD), and Computer Aided Engineering (CAE) environment. The skilled, up-front use of CAE analysis improves the optimization of product performance, quality and reliability while reducing the overall time and costs of design, development and validation.

In a modeling and simulation environment, design and analytical Development and Validation (D&V) become essentially one task. The

role of AMS in a product development process starts as virtual prototyping tasks for evaluating and (when needed) optimizing features and functions of a new design. The design evolves under this analyse and revise process until the designer and analyst (or designer/analyst) develops and demonstrates a design that can operate in accordance with the requirements and under expected variation and noise factors. The virtual D&V Process is completed when it can be demonstrated analytically with accepted and proven models and validation assumptions that the virtual (paper or CAD) design's theoretical capabilities are acceptable to the projects requirements

Sometimes, the opposite may be proven, i.e. that a specific design approach is not capable of meeting requirements. In this case an organization may save a significant amount of time and resources by not pursuing a design path that is incapable of acceptable performance. However, generally the objective of AMS activities is to grow the capabilities of the design to the point where it is found to be theoretically capable of consistently achieving its requirements and goals while operating in its intended environment. The pre-optimized design can then advance to physical build and test evaluations. The benefits of AMS virtual development and validation processes are:

- Performance, durability and reliability robustness issues can be developed and optimized without the time and cost of physically building and testing prototype parts.
- Designs move in to physical testing pre-optimized by analysis activities that have already screened out many defects and discrepancies.
- Physical testing can be smoother and faster without as many interruptions for fault detection, root cause trouble shooting and corrective action events.
- Physical testing can be optimized [4].

- Physical testing then does not need to be totally comprehensive; it can be reduced to a series of spot checks of critical features and refocused to criteria that cannot be evaluated by analysis.

This rapid combined virtual D&V approach is possible in an integrated CAD-CAE environment because the results of an evaluation can be used to immediately make informed, feedback guided revisions of design features as needed. The virtually revised design can then be rapidly re-evaluated in the AMS environment in order to gauge the degree of improvement until acceptable performance is achieved. The analyst then moves on to the next design criteria until all aspects of the design have achieved the desired level of robust performance, durability and reliability.

In the physical world the pace of D&V activities are limited by the time and cost required to physically Design, Build, Test and Fix (DBTF) successive generations of prototype parts. These real world limitations require the creation and coordination of a series of sophisticated, complete build and test cycles that must cover all aspects of the new design in each round of testing. Formal product validation is intended to be the final physical test series in this process. However, rarely does physical testing identify and resolve all discrepancies to result in a final robust product. Usually the rounds of physical DBTF activities conclude with the design being deemed "good enough" to advance into production launch activities where reliability and capability growth continues via warranty events and customer dissatisfaction feedback.

AMS Scope

This section provides an introduction to CAE Analysis, Modeling and Simulation evaluations and how they can be applied to evaluate, optimize and ensure robustness of Automotive Electrical/ Electronic (E/E) devices and defines recommended practices on how to integrate AMS procedures into development and validation procedures for E/E devices but it does not define the detailed requirements of each modeling or simulation method which are covered in SAE J2820.

This section is a summary of general-purpose math based evaluation techniques and CAE analysis tools that can be applied to calculate a wide range of product characteristics and capabilities common to many E/E devices. These methods can be applied individually or in groups during any product phase to:

3. Calculate capabilities of early design concepts.
4. Perform robustness optimization and virtual validation of a CAD or paper design of a product.
5. Perform test planning, test optimization and extrapolation of test results to field conditions.
6. Investigate and resolve discrepancies.

Four categories of proven AMS tools and modeling methods are defined that can be applied to assess a wide range of E/E product requirements during early product development.

These are:

1. E/E Circuit and systems analysis for evaluating performance, power issues and how performance is affected by variation.
2. Electromagnetic Compatibility (EMC) and signal integrity analysis.
3. Stress analysis for determining thermal and mechanical loads, peak stresses, stress distribution and stress transmission paths and evaluating if the design is strong enough to support the stresses.

4. Physics of Failure based failure mechanism susceptibility analysis for evaluating the durability and reliability capabilities of a design.

When properly applied AMS methods are capable of determining the theoretical performance and durability of a proposed new design. However, modeling and simulation methods are unable to predict what kind of manufacturing errors or variation issues could be inflicted on a design and what their outcome might be.

AMS Mission

It is the mission of this section to foster the development and use of efficiency enhancing E/E AMS CAE techniques by providing a reference resource of Models, CAE tools, methods and a structure for integrating CAE techniques into E/E product development processes and A/D/V plans.

It is the responsibility of the product engineer or team to determine which AMS objectives and procedures are relevant for a specific device, technology or application and how to interpret the results and define application specific acceptance (pass/fail) criteria when appropriate. However, general guidelines for interpretation and acceptance criteria are provided. It is up to product teams to balance the selection of analysis objectives and tasks for mitigating design risk factors against constraints factors such as: availability of CAE resources, component models, expertise of analysts, manpower, and budget etc..

The techniques defined in this document are not all-inclusive due to the dynamic rate of development of new AMS techniques and CAE tools; teams are encouraged to consider the use of other applicable analytical methods as they become available.

8.2 Integration of Design Analysis into the Product Development Process

Analysis Template for Automotive EEMs

A template of analysis objectives for supporting the development of highly reliable automotive electrical and electronic (E/E) devices is provided in Figure 15. The template is based upon analytical techniques that can be performed with currently available (CAE) software. The following four evaluation areas are:

1. E/E Circuit and Systems Analysis for Evaluating Performance and Power Issues.
2. EMC and Signal Integrity.
3. Stress Analysis for Thermal and Mechanical Stress Distribution and Transmission.
4. Durability and Reliability.

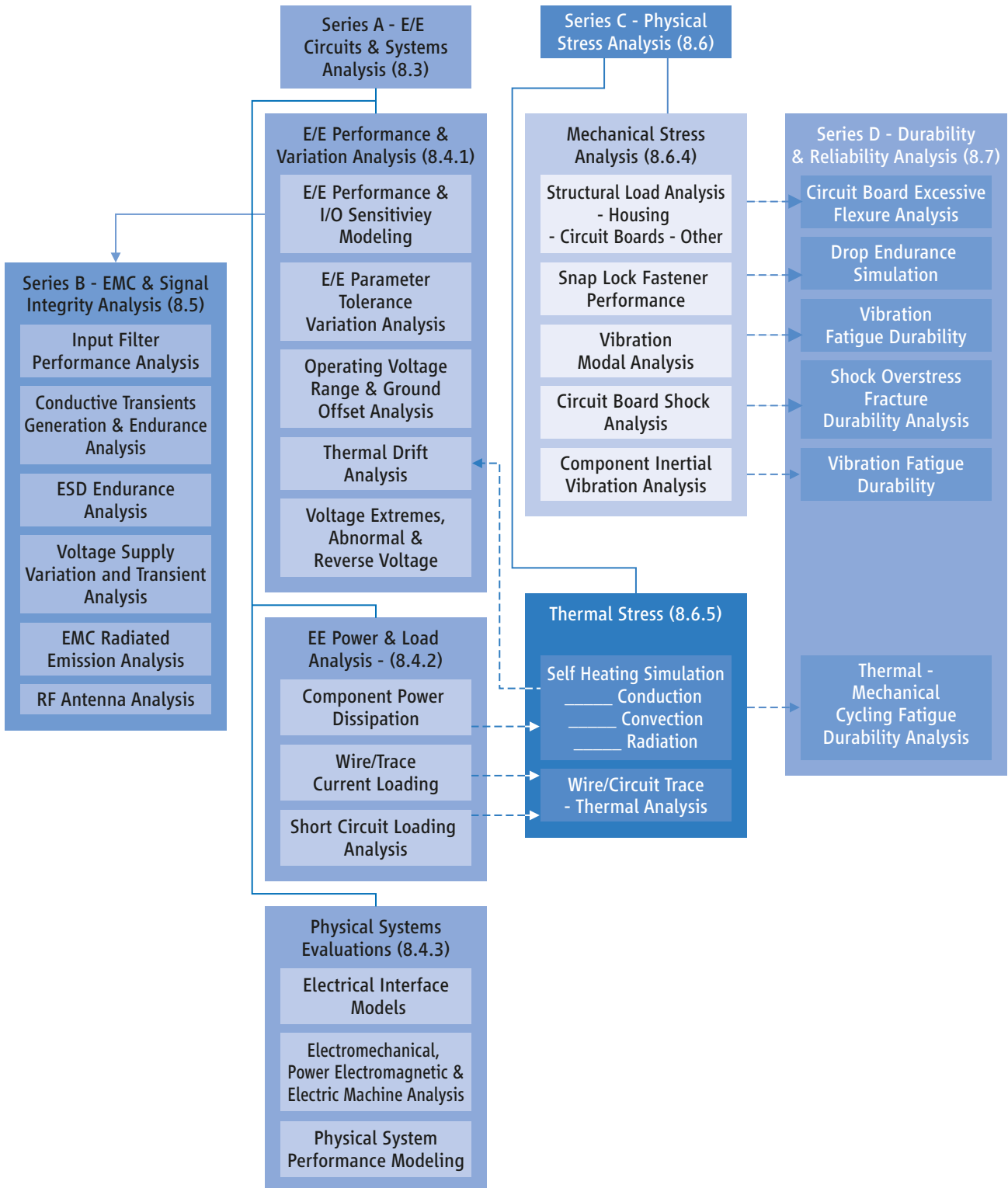
Some of the analytical objectives are independent which enables scheduling flexibility; others are related and may be combined into a single model or simulation to maximize efficiency. Others are dependent as denoted by the dotted arrows where the results of one analysis is used to as an input to another evaluation. Dependent analysis sequences may require scheduling to ensure a timely flow of data especially when analysts from different technical disciplines or departments are involved.

The template is not all-inclusive, due to the dynamic rate of development of new analytical techniques and CAE tools; teams are encouraged to consider the use of other applicable analytical objective or methods not included in the template. The template is not intended to be a mandatory list of tasks to be routinely applied to every program. Nor is it intended to mandate sophisticated high-end CAE simulations for situations when more basic calculation techniques will suffice.

The template Figure 15 is intended to be used as a planning tool to guide a product team through existing analytical methods for evaluating design objectives for automotive E/E devices. The objectives are then combined to determine the specific AMS tasks appropriated to a project to be performed as part of the component's D&V Plan. It is up to the team to balance the selection of analysis objectives and tasks for mitigating design risk factors such as: complexity, new technology, aggressive schedules... etc., against constraints factors such as: availability of CAE Resources, component models, analyst expertise, manpower, budget, etc..

When CAE analysis identifies potential design deficiencies, there may be a need for additional physical tests for further evaluation of the concern. Discussions on the four analysis objective categories start at Section 8.3.

FIGURE 15 - Analysis, Modeling and Simulation Objectives Template



The template (Figure 15) combines multiple technical disciplines into an overall virtual engineering prototyping process. Each column contains objectives, which require similar

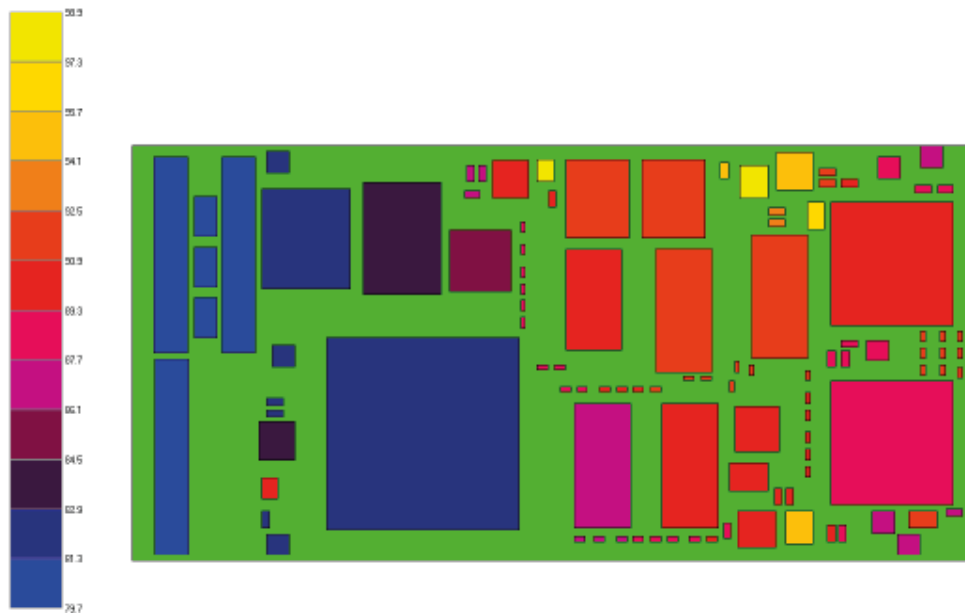
analytical skills and tools that are the primary interest of different members of the product team. The dotted arrows indicate when an analytical object requires the results of another.

EXAMPLE:

The results of the electrical power dissipation analysis is required to perform a thermal analysis to determine the local heating characteristics and thermal gradients across a circuit board under various power loading and climate conditions (see Figure 16 below). The thermal results are then supplied back to

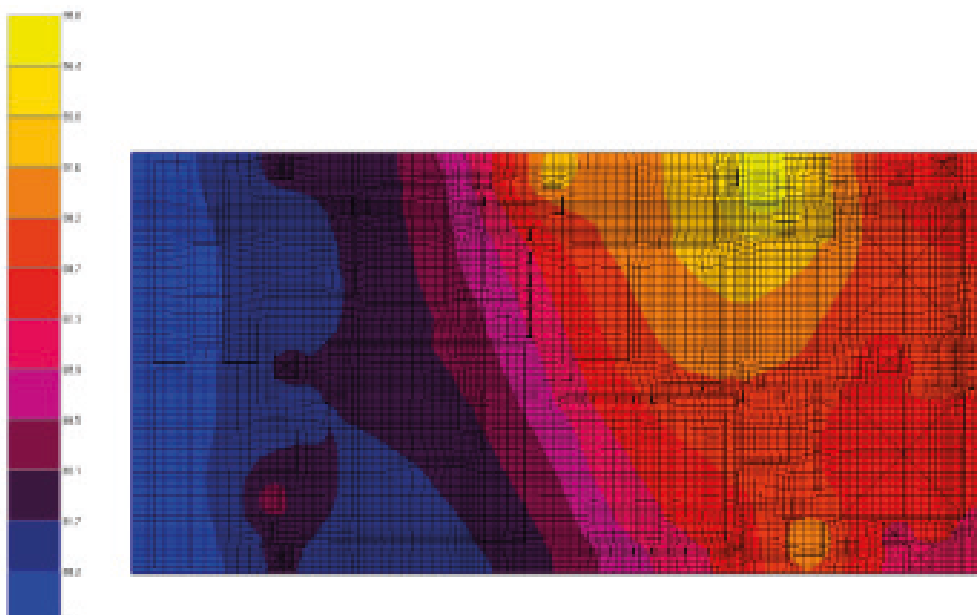
the circuit analyst and used to evaluate the effects of thermal and electrical drift on critical circuits as the device heats up. Thermal performance results are also used for thermal-mechanical (heating expansion-cooling contraction) fatigue durability analysis.

FIGURE 16 - Example Simulation PCB Radiated Heat Gradients



Above - CAE simulation of component power dissipation to determine case temperatures at a 60°C ambient.

Below - CAE simulation of circuit board radiated heat temperature gradients for the same situation.



CAE Analysis Reports and Documentation

As AMS analysis shares the burden or replaces physical tests in product development and validation, it is essential that analysis results, conclusions and recommendations be formally documented and archived. The need for analysis records is driven by requirements for product development communication, corrective action tracking and documentation of engineering due diligence.

8.2.1 Evaluation Report

All AMS evaluation results and conclusions should be documented in Analytical Evaluation Reports. These reports should document the evaluation objectives and procedures that were selected by the product team and performed on the device. The product engineer should present a summary of the report to the product team. A complete copy of the report should be delivered to the lead product engineer and a copy should be included and maintained as part of the products documentation.

8.2.2 Corrective Action Documentation

Issues and design features that did not meet the acceptance criteria shall be documented in a close loop tracking system. When appropriate the analysis should include corrective action recommendations in these analytical evaluation reports.

8.2.3 Simulation Aided Testing and the Integration of Simulation and Tests

CAE Analysis is not envisioned to totally replace physical testing. However it is expected to greatly reduce the need for testing and enable a switch to more effective and focused testing that compliments CAE capability.

When requirements can be confirmed by means of CAE virtual validation techniques, physical testing portions of the D&V Plan may be reduced to cover:

- Only the requirements that cannot be evaluated by analysis.

- Simplified tests to confirm that CAE models were accurate and based upon valid assumptions.
- Tests to confirm that parts were correctly manufactured and assembled in accordance with design expectations.

When CAE analysis identifies potential design deficiencies, there may be a need for additional physical tests for further evaluation of the concern.

8.3 Circuit and Systems Analysis

The circuits and systems analysis series is related to the operating performance objectives of EEM. The objectives are organized into three groupings for

- E/E Circuit Performance and Variation Optimization,
- Power and Loading Analysis and
- Physical System Performance Modeling purpose.

Circuit and systems analysis is performed to evaluate the static and dynamic electrical performance of a proposed circuit design in order to identify and resolve performance, tolerance and stability discrepancies during the initial early design stage. When an E/E device is part of a physical system comprised of mechanical, hydraulic, pneumatic or other elements, system level multi-physics modeling can be used to identify and resolve overall performance and interaction discrepancies.

Recommended Coverage

Challenge/Risk Related Circuits as identified by the product team, examples include:

- Circuits with new or complex designs, or new components.
- Circuits that require a high degree of accuracy, stability or timing synchronization.
- Circuits that perform essential vehicle control or safety related functions.
- Other Circuits Identified by the product development team as challenge/risk related.
- General Analysis Information Input Requirements.

- Circuit or system schematics: Device(s) internal and vehicle level as appropriate to analysis goals.
- Library of circuit element models or ability to create element models for the analysis.
- Definition of excitation signals or interface inputs to the circuit or system.
- Definition of power, grounding and circuit protection conditions for the circuit or system.

8.4 Categories of E/E Circuits and Systems Modeling and Simulations

E/E Performance and Variation Modeling

This category of AMS objectives are used to determine electrical performance objectives for a proposed circuit design such as static and dynamic voltage, current frequency responses, impedance characteristics, etc.. The evaluations are performed under the expected excitation, interface, loading, power and ground conditions of the intended application. The method may be applied to analogue, digital and mixed electrical signals.

These AMS objectives are intended to involve and promote communication for effective designs among product engineers, circuit designers and circuit analysts. This effort supports early design optimization and verification that the selected circuit configurations and component values perform stably throughout the range of tolerance stack-up, I/O loading, environmental variation and other noise conditions in accordance with design intent and product requirements. Design deficiencies identified by the analysis are to be resolved or flagged and tracked for further evaluation by the product team until corrective actions can be implemented.

The maximum analysis benefits are typically achieved by focusing on higher risk circuits. The types of typical models and simulations tasks that can be performed for E/E Circuit Performance and Variation Optimization are:

- Performance Simulations and Input/Output (I/O) Sensitivity Analysis
- E/E Property Tolerance, Variation Analysis
- Operating Voltage Range and Ground Offset Drift Analysis
- Circuit Electrical Performance Thermal Drift Analysis
- Voltage Extremes, Abnormal and Reverse Voltage Analysis

E/E Power and Load Analysis

Power and load analysis is used on the high power circuits of a device to determine the amounts of electrical current and power that must be carried by individual components and circuit connections. This information is used to properly size components and circuit connections for their loads. The results are also used by the self-heating thermal analysis task.

The maximum benefits are typically achieved by focusing power analysis resources to identify surge, and sustained maximum electrical current conditions and to quantify the power dissipation conditions for circuits and components that are expected to self-heat which will raise the overall internal temperature of the device. Typically, components expected to dissipate more than 0.25 W or expected to self-heat by more than 10°C under sustained duration conditions (i.e. continuous on or active for more than 5 minutes) should be considered for power analysis. Power analysis is typically applied to high power and heavily loaded input, output, power feed, voltage regulation and ground return circuits.

The power analysis tasks are related to the electrical performance analysis since electrical engineering skills and analysis tools are needed to determine electrical power and current flow. Packaging engineers and thermal analysts use the power analysis results to evaluate and optimize the device's thermal design. The tasks in this series are organized to involve and promote effective design communication among product engineers, circuit designers, circuit analysts packaging engineers and thermal analysts.

The types of AMS tasks that can be used to perform power and load analysis are:

- Component Power Dissipation Analysis
 - Wire/Trace Current Loading Analysis
 - Short Circuit Loading Analysis
- Physical System Evaluations

This category contains AMS techniques for analysis of how an EEM interfaces with other E/E components and systems in the vehicle as well as with electro-mechanical and mechanical systems.

8.4.1 Electrical Interface Models

Electrical interface circuit models of devices are used in vehicle and subsystem level modeling tasks. Unless otherwise specified the models are to be created in the customer's modeling language in order to be compatible with the customer's internal E/E modeling capabilities. This should be dynamic and account for the effects of vehicle supply and ground voltage variation conditions and support electrical parameter variation modeling across the full range of temperature conditions the circuit is expected to be exposed to (i.e. operating environment temperature plus power dissipation self-heating effects). Interface models shall also support modeling of component parameter tolerances to support variation effects modeling.

Interface models should include documentation of the model's relative accuracy, limitations and any modeling assumptions used in their creation. Detailed requirements for the interface model or required procedures shall be defined by a design team of design responsible engineers.

Examples of the typical types of interface models are:

- Power/Voltage Supply Loading - Models for typical, worst case and parasitic load conditions for battery, ignition and other power feeds for use in vehicle energy management analysis and wiring system design. Typically, load models are required to represent the device's electrical loading characteristics or equivalent resistance and should be accurate over the device's specified voltage and temperature ranges.
- Signal Interface Models - Models of input and output characteristics.
- Transfer Function - Use in evaluating control system performance and system interactions.

8.4.2 Electromechanical, Power Electromagnetic and Electric Machine Analysis

There are two categories of electromagnetic (EM) modeling and simulation tools. One deals with High Frequency EM (HF-EM) waves and radiation issues for wireless radio frequency signals and EMC. HF EM will be discussed in the EMC CAE section. This section will deal with CAE tools for Low Frequency Electromagnetic (LF-EM) issues involving power induction for electric machines.

The magnetic and electromagnetic aspects of electric machines cannot be modeled E/E analysis techniques (i.e. theories and equations of Coulombs, Ohm's, Kirchoff's etc.). At best E/E analysis can only estimate E/E circuit performance of EM elements by using equivalent circuit approximations to account for some of the electrical aspects of electric motors, generators, relays, solenoids, transformers, inductive sensors etc.. These estimates are usually sufficient for general E/E circuit interface calculations, but they are inadequate for

design evaluation and optimization of electric machines and any precision control circuits to the electric machine.

For example, a simple linear solenoid actuator is modeled electrically as a pure resistive-inductive (RL) circuit. But an electrical model cannot account for variations in the actuation force and response time due to voltage changes and the circuit analysis cannot respond to the change in inductance related to the motion of the solenoid's armature. Another example is that electric circuit analysis cannot model the electromagnetic fields, transients and noise characteristics of electric machines. This is a frequent source of electromagnetic interference (EMI) noise problems in vehicle programs.

Highly effective electromagnetic (EM-CAE) AMS programs for performing multi-domain (electricalmagnetic) modeling exists. They are based upon Maxwell's equations of electromagnetic induction. EM-CAE tools are more challenging to use since they require expertise in magnetic and electromagnetic circuit physics in addition to E/E circuit and electric machine skills. Furthermore, magnetic and EM circuit modeling requires physical layout, geometries and magnetic material property parameters in additions to electrical components and connection schematics. Despite the added complexities, the design improvement and time to market value added by these tools is resulting in the increased use of EM-CAE modeling techniques.

8.4.2.1 Purpose

This analysis is meant to evaluate the performance of electromechanical devices and their interfaces and interactions with EEM in order to identify and resolve performance, control, stability and EMI discrepancies during the initial early design stages. M&S tasks may include evaluation of magnetic, electromagnetic, mechanical and thermal performance criteria for electric machines such as motors, generators, transformers, inductors, solenoids, relays, inductive and reluctance sensors.

8.4.2.2 Recommended Coverage

Coverage is recommended for design, performance and control analysis of all electromagnetic and electro-mechanical mechanics.

8.4.2.3 General Analysis Information Input Requirements

- Circuit Schematics of the device and the as appropriate to the analysis objectives.
- Library of circuit element models and magnetic material properties.
- Definition of power, grounding, and excitation signals and circuit interfaces.
- Definition and geometries of mechanical layout and interfaces.
- Definition of required output characteristics and/or output loading conditions.
- Definition of the environment temperature range where device is required to operate.

8.4.3 Physical System Performance Modeling

These AMS tasks included multi-physics modeling techniques which are used when systems are comprised of element from different engineering disciplines or electrical energy is required to be transfer across physics domains or transformed into different physical forms. These modeling techniques allow the EEM interactions with various automotive mechanical elements to be analyzed in order to perform analysis of complete, sometimes complex systems that are comprised of E/E, electro-mechanical and mechanical elements.

8.5 EMC and Signal Integrity Analysis

The Electromagnetic Compatibility (EMC) and Signal Integrity M&S objectives are to evaluate and optimize the ability of an E/E component or system to correctly function in its environment, without responding to or generating electromagnetic interference (EMI) i.e. stray or misdirected electromagnetic energy.

Signal Integrity (SI) analysis relates to the propensity of higher frequency signals to be degraded by EM wave propagation effects, sig-

nal reflections and line impedance mismatch conditions. Evaluating these criteria requires transmission line analysis techniques.

When the functions of a system includes receiving or transmitting signals for radio frequency communication, telematics and wireless remote control, EMC analysis should also include antenna performance evaluation.

EMI energy can take the form of radiated waves that can be coupled into signal and power lines or conducted transients superimposed onto signal and power lines. Sometimes, both conditions are involved as a radiated wave is converted into a conducted transient or vice versa.

Every form of EMI requires a configuration or system consisting of:

- A noise generating interference source,
- An energy coupling mechanism,
- A susceptible receiver.

EMI can be prevented by the use of proven, well-documented design features and practices that:

- Suppress or contain noise at the source
- Disrupt or degrade the effectiveness of energy coupling mechanism,
- Protect or reducing the sensitivity of receivers.

Electromagnetic compatibility is essential for safety and reliability in today's high tech vehicles and society.

EXAMPLES:

Vehicles cannot afford engine stalls or brake malfunctions because a controller was disrupted by the ringing of a passenger's cell phone. Likewise, the heart pacemaker in a driver cannot be allowed to malfunction by activating a car's horn or air conditioning system.

For these reasons automotive OEM's, the SAE, Governments and other industries all have requirements for ensuring EMC by specifying maximum emission and minimum susceptibility levels for products and systems.

Despite these regulations and requirements, designers typically employ only minimal level of EMI control features into initial designs. This practice is based on valid "Over Design" concerns of incurring size, weight and cost penalties due to unnecessary components. Therefore, EMC features and components are often not used until a need is absolutely proven usually by means of EMC testing. Automotive EMC testing is typically comprised of 10-15 different evaluation procedures. These EMC tests require expensive, room size test cells and sophisticated monitoring equipment. EMC optimization usually requires several rounds of building, testing and fixing prototype parts, first on the component level then at the vehicle level. This process needs to be performed on dozens of E/E components and systems on every vehicle. This makes EMC testing the highest cost and most time-consuming activities in automotive E/E product development and validation.

To address this situation, many automotive OEM's have instituted a detailed EMC design review process which includes a design review checklist and EMC design guidelines based on the lesson learned experiences of the OEM's technical staff. This manual, labor-intensive review of component schematics and layout is used to ensure that an adequate level of EMC capability has been designed in prior to EMC testing, so that test resources, time and money are not wasted on basic easily prevented issues. The use of EMC-CAE AMS analysis methods during the initial design phase to optimize and verify the EMC capability of a design as it is created is the next logical step.

The types of typical AMS tasks that can be performed for EMC and Signal Integrity Analysis are:

- Circuit Input Filter Analysis.
- Conductive Transient Generation and Endurance Analysis.
- ESD Endurance Analysis.
- Voltage Supply Variation and Transient Analysis.
- EMC Radiated Emission Analysis.
- RF Antenna Analysis.

CAE Programs for EMC and SI Analysis

There are a number of EMI related analysis evaluations that can be performed with E/E circuit analysis methods. Filter performance and transient suppression are two basic procedures that should be incorporated into the design evaluation of every new circuit. Circuit analysis methods are of course limited to only the electrical components involved in an EMI threat. EMI/EMC multi domain electrical and magnetic analysis is one of the newer categories of CAE techniques to move out of the tools research labs and into the commercial realm. Much of this advancement is due to research efforts that have created math models and tools of EMI transmission and coupling mechanisms by groups such as the Electromagnetic Compatibility Research Consortium at the University of Missouri - Rolla.

EMC-CAE is also one of the most complex CAE areas due to the many different EMI coupling mechanisms that have to be considered and have produced many different specialized modeling tools and approaches. However, some of the newer EMC-CAE tools combine several analysis techniques. This allows them to model a wide range of EMC conditions for specific applications in a suite of interactive analysis tools there are four basic analysis approaches defined in the following list.

1. **Analytical Equations Solvers:** The easiest tools to use but have limited scope and are applicable only to simple shapes and structures. They have some use as part of specific application evaluation templates. However, they provide little practical value for most real world modeling situations.
2. **Numerical Simulations:** Perform any type of full field simulation for the full range of Maxwell's EM equations. Various types of numerical analysis methods are used such as: Finite Element Model (FEM), Method of Moment (MoM), Finite Difference Time Domain (FDTM), Frequency Domain Finite Difference (FDFD) etc. These programs are the most flexible and challenging tools to use. They require highly skilled analysts to set up the problem and interpret the results in term of how design will respond

to the field conditions predicted by the program.

3. **Design Rules Checkers:** CAE programs that rapidly scan designs and layouts to identify violations of rules contained in user-defined libraries. Good for accurate, automated detection of errors and enforcement of best practices guidelines. Usually an EMC expert is required to define and set up the rules.
4. **Expert Systems:** CAE programs that evaluate or ask questions about the design in order to suggest the type of EMI control features the design requires or to define and run a sequence of virtual evaluations that interpret the results in term of risk severity and recommend possible solutions.

EMC-CAE tools are then further divided into general and application specific sub groupings.

8.5.1 Purpose

The modeling and simulation of EMI/EMC characteristics and modeling of electromagnetic waves and fields is performed to determine their effect on EMI/EMC characteristics. The Results are used to evaluate and optimize the ability of E/E components and systems to correctly function in their environment without responding to or generating disruptive levels of stray electromagnetic energy.

8.5.2 Recommended Coverage

The Recommended Coverage depends on the type of devices being analyzed and the capabilities of the modeling tool. As a minimum circuit analysis tools should be used to verify filter performance and transient noise suppression capabilities of new, high risk, high performance and critical electronic circuits. When available radiated EM and design rule verification analysis is recommended on all new circuit board assemblies. Signal integrity analysis is recommended to be performed on high frequency circuits operating in and above the gigahertz range. Antenna performance analysis is recommended on wireless

communication systems and wireless remote control systems.

8.5.3 General Analysis Information Input and Requirements

Circuit Schematics - vehicle and internal device level as appropriate to analysis objectives.

- Library of circuit element models and magnetic material properties.
- Definition of power, grounding, excitation signals and circuit interfaces.
- Definition and geometries of mechanical layout and interfaces.
- Definition of required signal Input/Output characteristics and signal strength loading conditions.
- Definition of the environment temperature range where device is required to operate.

8.6 Physical Stress Analysis

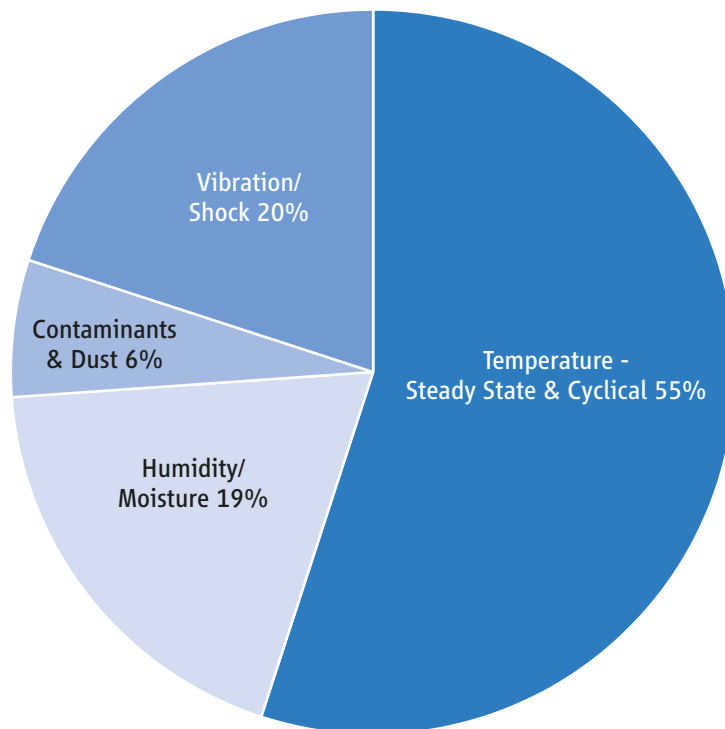
Physical stress analysis can be used to assess the effectiveness of an E/E device's physical packaging to maintain structural and circuit interconnection integrity and a suitable environment for E/E circuits to reliability function. (Note, electrical stress evaluations were previously discussed in the E/E analysis sections). Physical packaging involves the ergonomic, mechanical support, electrical connections, and power, thermal and environmental management features that sustain the E/E components assemble in an E/E device or module.

Analytical evaluations of these physical aspects transform the discipline of electronics packaging from a subjective art into an objective science. The following overview discusses how Reliability Physics and Physics of Failure principles can be used to analytically evaluate a design's ability to reliably endure operating stresses.

Stress is the effect usage and environmental loads place on a device and its materials. Every loading force applied to or generated in a device triggers either a resulting motion and/or a stress distribution built up within a device's materials and structures to balance the applied forces. The amount of strain experienced is a factor of a device's size, shape and material properties that determine strength.

Sources of stress experienced in electronic equipment are displayed in the pie chart in Figure 17.

FIGURE 17 - Sources of Stress for Electronic Equipment



The percentages vary for different applications and packaging locations.
(ref. "The handbook of electronic package design" 1.4.2).

Stress can produce four possible outcomes that must be accounted for to achieve a reliable product:

- The strain from an applied stress will be so small as to be inconsequential (i.e. the desired state).
- Electrical properties may shift (i.e. resistance and capacitance drift, piezoelectric effect, etc.) this can alter circuit performance during stress conditions. The amount of drift that can be tolerated without degrading system performance then becomes a key issue.
- The stress may exceed a yield point to trigger an imminent overstress failure mechanism in the materials (i.e. fracture, buckling, excessive deformation, melting or other thermal event, etc.).
- Enduring a steady stress or series of stress cycles, causes incremental damage accumulation in materials. Gradual molecular breakdown eventually produces wear out failures mechanisms (i.e. fatigue, delamination, creep, corrosion, etc.). Determining the durability time period during which required performance is maintained until wear out failures occur then becomes a key issue which is discussed further in the durability/reliability modeling section.

Typically, these effects are identified by means of physical performance and life testing that evaluates performance under applied loads over time in a pass/fail format. Such tests do not directly determine stress transfer or strain effects, so information on design margin (i.e. safety factor) that could be used for design optimization is not known. However, M&S methods can also perform stress analysis and optimization as the design is created. The objectives of stress analysis are:

- Identify the loading factors that will stress the device in its intended application.
- Calculate the device strength and the stress - strain relationship transferred throughout the device.
- Verify that the strain doesn't exceed material yield points which could cause imminent failure.
- Identify items that may be highly or frequently stressed. These items are at risk for damage accumulation wear out types of failure mechanisms and will also require long term durability analysis.

A Physics of Failure stress, strain and strength engineering analysis as the initial design is created provides an opportunity to adapt a "Right Design" engineering philosophy. This approach takes a neither takes a minimal or "Under Design" approach, to strength, robustness and reliability features to avoid excess costs, size and mass are minimized unless their need is proven by testing or an over design approach is needed to ensure high quality and reliability.

Physics of Failure based M&S stress analysis offers opportunities to 1.) improve product Quality, Reliability and Durability (QRD), 2.) reduce development-validation cost and time, and 3) perform M&S based design optimization that allows product to be "Right Designed" (i.e. right sized) for the stress load and the intended service life of the application.

Electrical, mechanical and thermal stress analyses are the types of stress M&S methods most applicable to automotive EEM. Electrical Stress analysis had been previously covered under the Circuit and System analysis sections. The following sections will address mechanical and thermal stress analysis.

Purpose

Physical stress analysis is performed to understand and use the static and dynamic physical, mechanical and thermal stress profiles that the E/E device is required to endure under usage and environmental conditions. It is also performed to evaluate the modules inherent strength, stress transfer mechanisms, stress distribution patterns and stress endurance capabilities in order to optimize and verify that the strength of a design. This is needed to show that it can endure the usage stresses that cause "Over-Stress" failure mechanisms such as yield, fracture, buckling, thermal melt down, etc.. Finally it is used to evaluate structural integrity or circuit interconnection and the suitability of the modules internal environment for E/E circuits to reliably function.

Recommended Coverage

EEM with:

- More than 50 components or components larger than 2" (~5 cm) per side.
- IC components larger the 64 pins or 1" (2.54 cm) per side.
- Discrete surface mount components of EIA package size 2010 or larger.
- Leadless Integrated Circuit component.
- Self-heat capabilities that are more than 10°C.
- Mounting locations in an under hood or other high temperature or high vibration environment or integrated into a mechanical component.

General Analysis Information and Input Requirements:

- Circuit Schematics: Device(s) internal and vehicle level as appropriate to analysis objectives.
- Circuit Board Component Assembly layout and dimensions.
- Circuit board housing and packaging support dimensions.
- Library of E/E part models of dimension and material or ability to create models for the analysis.
- Library of E/E part materials, their mechanical and thermal stress transfer and strength properties.
- Library of E/E parts Failure Mechanism Models.
- Definition of intended operating and off state - vibration, shock and thermal environmental profiles.
- Definition of operating usage profile and related power dissipation in E/E parts.

Mechanical Stress Analysis

Mechanical stress analysis (also known as structural analysis) calculates the stress-strain conditions that can occur in parts and materials due to the load, shock and vibration conditions a device is expected to endure. The results are evaluated against the material properties and strength capabilities of the device (i.e. yield strength, creep resistance etc.) to determine the loading factors that can

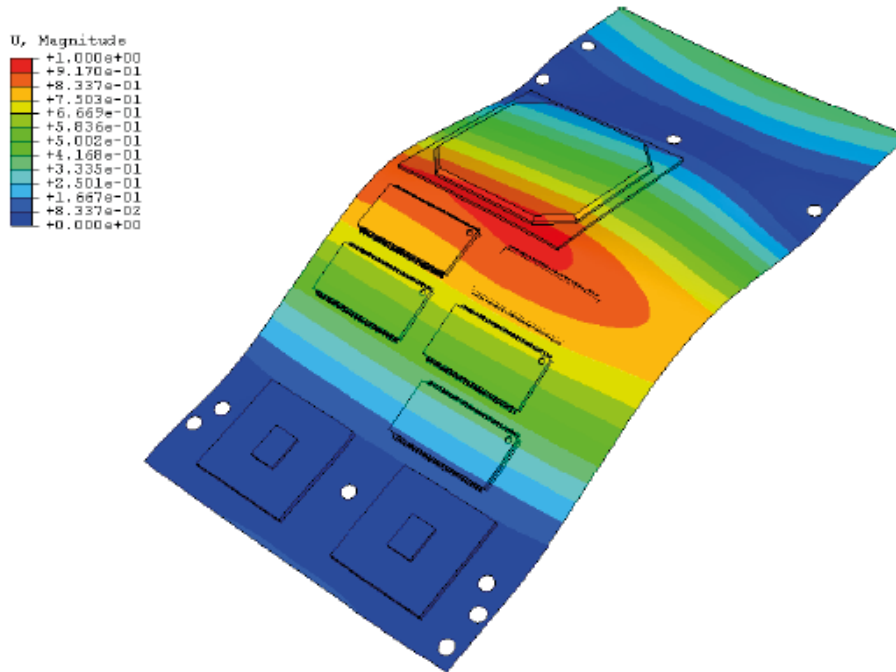
overstress the design to cause a failure. After the destructive stress conditions are known, the design can be optimized and analytically validated as able to support the loads. Finite Element AMS tools are used to determine structural stress, strength and behavior. Stress analysis and management is a vital cost, mass and QRD optimization skill as competition and rapidly changing technology results in smaller and lighter parts that must perform at higher stress and power levels.

Mechanical stress analysis is intended to involve and promote communication for effective mechanical packaging design among product engineers, circuit board E-CAD layout designers, packaging engineers/designers and mechanical test engineers and mechanical analysts.

Mechanical stress models and simulations analysis tasks are:

- Structural Load Analysis of Housings, Circuit Board Assemblies (CBAs) and other components.
- Snap Lock Fasteners Performance Analysis.
- CBA Vibration Modal Analysis (see example next page).
- CBA Shock Response Analysis.
- Component Inertial Vibration Analysis.

FIGURE 18 - Example PCB Assembly Vibration Simulation



Example of a Circuit Board Assembly Vibration Modal Simulation

Used to determine the first harmonic resonant frequency modal shape to identify the locations of peak bending stress (highlighted in red) and the stresses transmitted to components at those locations.

Thermal Stress Analysis

The purpose of the thermal analytical stress AMS tasks is to determine the effects of power dissipation self-heating on the E/E module. The results of these analyses can then be used as inputs to the durability models and simulations see Figure 15. Combining the results of the durability analyses with experience gives an early indication of the suitability of the initial design to environmental conditions.

Thermal models and simulations are used to predict the maximum temperature of the module and the temperature of its individual components, due to internal heating, when subject to various electrical power and usage loading conditions combined with the external environment heating conditions in the locating where the module is mounted in the vehicle. Thermal AMS is recommended to be performed under the following conditions: Nominal Operation, Heavily Loaded, Worst

Case Operation, and Short Circuit. The results of the electrical power modeling can be used as inputs to the thermal stress models.

Thermal stress models and simulations analysis tasks are:

- Power Dissipation Self Heating Simulations.
- Wire/Circuit Trace Thermal Analysis.

8.7 Durability and Reliability Analysis

After the stress conditions are known, the long-term effects of stress endurance that causes gradual degradation or wear out conditions in the materials of a device can be modeled to evaluate the wear out related durability and reliability of the design. Models of wear out failure mechanisms are based on the Physics of Failure concepts of stress driven damage accumulation in materials that continuous or cyclical exposure to stress/strain cycles causes incremental amounts of damage

accumulation in the material that endured these stresses. Gradually molecular breakdown eventually produces wear out failures mechanisms' (such as fatigue, delamination, creep, corrosion etc.).

Determining the durability time period until wear out failures occur becomes a function of calculating the ability of the strength-strain relationship of the materials in design features to resist degradation due to the strength and frequency of exposure to stress loading conditions via the use of Physics of Failure models and simulations. Often stress, strength and durability evaluations may be combined into a single modeling tasks. The primary concern is calculating the time to first failure for the weakest part or material (due to variation effects) that is exposed to the highest or most frequent stress loading conditions. This worst case time to first failure in modeling the failure rate for a theoretical variation profile of a population of parts can be modeled via Monte Carlo simulation to determine reliability performance of the design.

Note:

Manufacturing and fabrication quality errors can weaken a product; this can degrade the durability and reliability capabilities of even a highly optimized design. Durability and reliability modeling of a proposed virtual design is performed with the assumption that the parts will be correctly built and fabricated in accordance with the expectation of the designer. The PoF Durability Simulation Models are unable to predict what kind of manufacturing errors could be inflicted on a design as it is built and what their outcome might be.

Therefore total product robustness also requires that after a capable, robust design had been developed and validated an equal effort needs to be applied to developing a capable and consistent manufacturing and assembly processes. Issues of manufacturing robustness and quality are covered in Section 10.

The physics of durability/reliability models that can be performed in conjunction with stress modeling tasks are:

- Circuit Board Excessive Flexure Analysis.
- Drop Endurance Simulations.
- Circuit board Assembly Vibration Modal Fatigue Analysis.
- Shock Fracture Durability Analysis.
- E/E Component Vibration Fatigue.
- Thermal-Mechanical of Thermal Shock Cycling Fatigue Durability Analysis.

8.8 Physical Analysis Methods

In additions to math based AMS methods, there are also a number of physical material analysis techniques that can be applied later in the product development process to verify that the physical realization of a new device meet the design expectation for materials and assemblies quality and to verify that the devices are being produced without defects or susceptibilities to certain failure mechanism. These direct quality assessment (DQA) methods can be performed rapidly and without the need for environmental stress testing.

They are:

- Metallographic Analysis of Soldering Quality.
- Ion Chromatography of Evaluation of Circuit Board Cleanliness.
- Modal Characterization of Circuit Board Vibration Responses.
- Thermal Evaluation by Infrared Imaging.
- Acoustic imaging for delamination and cracking inside of encapsulated components or ceramic multilayer components.
- Chemical analysis of materials using traditional chemical analysis and newer methods such as laser ablation inductively coupled plasma mass spectroscopy (LA-ICP-MS), especially for new materials that may be introduced due to „green“ initiatives, for compliance with new standards and as a source of unanticipated failure mechanisms.
- Circuit verification by methods such as time domain reflectometry (TDR).

9. Intelligent Testing

9.1 Introduction and Motivation for Intelligent Testing

Intelligent Testing is a new testing approach for EEMs. It is implemented considering the RV Process philosophy from start of development till the end of production. The aim of Intelligent Testing beyond basic validation of the EEM for automotive suitability is to identify the Robustness Margin early in the development phase. The results of Intelligent Testing activities are used to calculate the Robustness Indication Figure (RIF) defined in Section 11 of this handbook. In addition, the results of Intelligent Testing may be used for the production ramp up and the control of the production process (control plan, SPC, etc.) and for the definition of any periodic and/or change driven re-validation activities.

See Appendix B for examples of test methods and approaches.

The new Intelligent Testing approach is knowledge based and

- Considers the application specific Mission Profile (see Section, 6 Mission Profile),
- Considers application, product and process technology specific failure modes (see Section 7, Knowledge Matrix),
- Is implemented by an EEM specific RV Plan and
- Uses Test to Failure (accelerated testing potentially exceeding specification limits) with final analysis and assessment of results.

The Intelligent Testing approach requires a change of mindset as well as strong communication throughout the complete value chain. It defines not another “cook book” style test specification, but instead gives a general guideline on how to get comprehensive robustness information about the product.

Not all information and knowledge related to the application of different acceleration models, or their calculation will be contained in this section. Topics of this complexity are beyond the scope of this handbook. Detailed information on these topics can be found in existing public literature (see Section 2, References).

Table 5 summarizes some key attributes of the Intelligent Testing Process versus a traditional approach. The Intelligent Testing process has the potential in many programs to save validation cost-time while also being more effective at finding real issues in a time frame that allows sufficient reaction time. For example in some cases 50% reduction in test costs has been achieved. However, the most significant savings have been achieved in terms of total lifecycle costs (warranty costs, engineering redesign costs, liability risk etc.) through the use of the Intelligent Testing process versus the traditional approach in which these future costs are avoided.

TABLE 5 - Goals Comparison of Traditional vs. Intelligent Testing

| Item | Description | Traditional Process | Intelligent Testing Process |
|------|----------------------------------|--------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1 | Approach | Cookbook | Tailored test plan utilizing historical data, analysis and development testing to focus on potential product weaknesses and changes. |
| 2 | Surrogate Data | Varies | Maximize to reduce non value testing. |
| 3 | Cost, Test Time | Expensive, Long | Potential to reduce by 50% or more. |
| 4 | Effectiveness | Minimal | More effective. Aimed at contemporary issues. Focused on what is unknown. |
| 5 | Test for Success | Majority of tests | Some but also generates variable data (test to failure or measuring degradation). |
| 6 | Sample Size | Large | Smaller, reduced facilities with the focus on what's needed to verify the unknown. |
| 7 | Monitoring | Limited | Continuous monitoring (allowed by smaller sample size). |
| 8 | Test Configuration | Artificial loads, minimal interfaces | Sub-system with realistic loads and interfaces (allowed by reduced sample size). |
| 9 | Time Compression, where Possible | Not applied sufficiently | Example: Reduce dwell times on thermal cycling/shock. Measure DUT board temp and set dwells to stabilization +5 minutes. Use surrogate data to only run the test required to verify the unknown. |
| 10 | EMC Testing | Done separately at room temp. | Supplemented by more realistic Conducted Immunity testing in Development Stage. Reference SAE J2628 |

9.2 Intelligent Testing Temple

In this section a temple as shown in Figure 19 is used as a visual aid to convey the concepts of Intelligent Testing. The three pillars of the Intelligent Testing Temple represent the three basic categories of tests in the RV Process:

- Capability Testing
- Durability Testing
- Technology Specific Testing

In general all three categories of tests are performed during all phases of development:

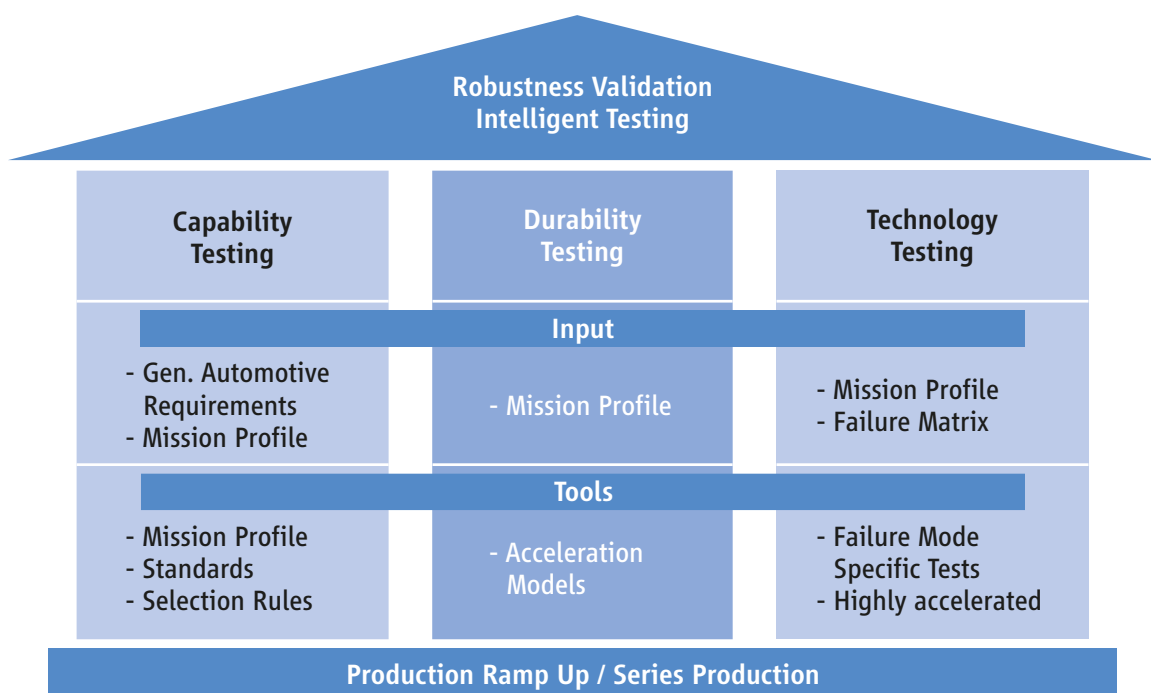
- Prototype Phase
- Design Validation Phase
- Product Validation Phase

The scope of tests is allocated to the three development phases, depending on the maturity of the product. Testing in the production ramp up and series production phase is an integrated part of Intelligent Testing, since the results of testing during the development phases are used to optimize the production control parameters. On the other hand the statistical information out of this phase is used to confirm Robustness Validation test results,

which have minimal statistical evidence due to limited samples quantities.

The implementation of the “state of the art” Capability Testing and Durability Testing, combined with failure mode and technology-specific testing, at the right time is the key for “Intelligent Testing” in the RV Process.

FIGURE 19 - Robustness Validation Intelligent Testing Temple



Capability Testing

Capability Testing confirms the ability of the product to withstand specific stresses, thus verifying that the product is capable for such stress factors which are not related to any life time or durability factors.

These capability tests are typically defined in the vehicle manufacturer’s requirements specification (based on Mission Profile) and should be performed as soon as possible for any new technologies, depending on the availability of test samples and maturity of the product related to this specific stress factor and failure mechanism. Design changes potentially affecting these capabilities may require that some tests be repeated (based on structured

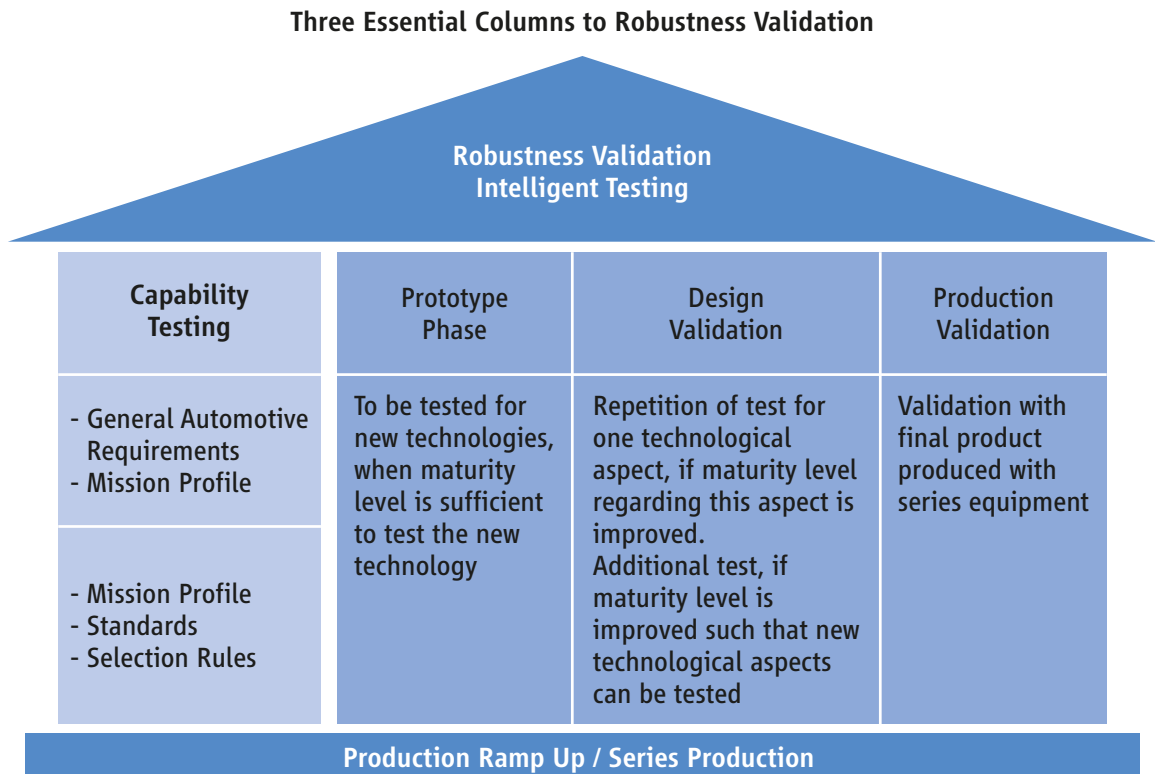
risk assessment). The scope of capability testing during any of the three development phases is shown in the temple of Figure 20.

For any well-known product and process technologies, these capability tests should be performed with final product configuration during the product validation phase for final confirmation.

Some examples for capability testing are:

- Flammability testing
- Water/Dust protection
- Electrical testing (Over Voltage, Reverse Polarity)
- Drop test

FIGURE 20 - Intelligent Testing Temple: Capability Testing



Durability Testing

Durability Testing assesses how long the product is able to perform to specification when subjected to various stress factors. Durability tests can be performed using either a test-to-failure or a “success run” approach against specified end-of-test criteria. To make such durability tests possible within a reasonable time frame, the stress factors can be set at accelerated stress levels which are based on mathematical models. For the most part, current test standards (definition of stress level and duration) utilize the success run approach, which means the target is to pass the tests without any failure.

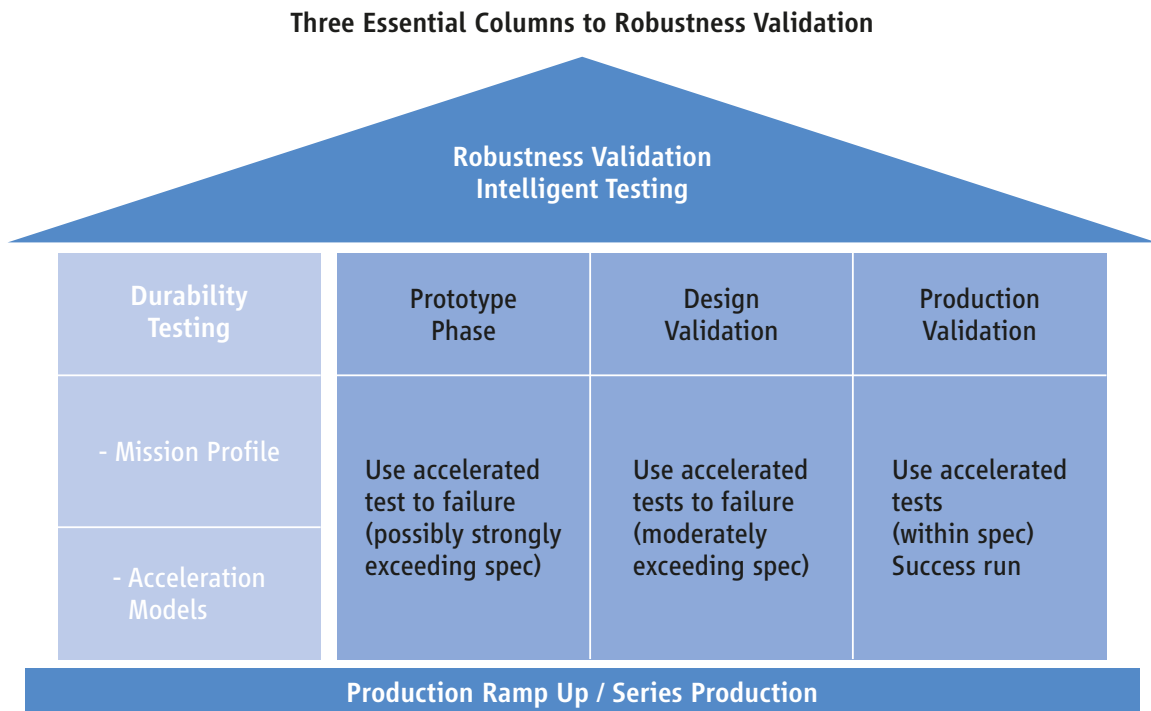
The Robustness Validation approach emphasizes obtaining test-to-failure results during Prototype and Design Validation phases to identify the Robustness Margin of the product compared to the expected life. Despite this the success run test approach is still part of the Intelligent Testing process as final validation of conformance to Mission Profile conditions which is performed during the Production Validation phase to confirm the production (pro-

duct/process) conformity and produceability and is the success point from which margin is measured. During the Prototype Phase the existing acceleration models are enhanced to reduce the time for testing to get earlier and faster results for a robustness assessment. See Ref [2]. The applicability and accuracy of the acceleration models depends on many parameters and may only be valid for a limited stress level range. There is therefore a need for strong communication through the value chain to define test cases with high acceleration while avoiding the generation of failure mechanisms, which are caused by the acceleration factors having no relevance to the field. Test results from the Design Validation phase are used for the calculation of the RIF. The scope of durability testing during any of the three development phases is shown in the temple of Figure 21.

Some examples for Durability Testing are:

- High Temperature Durability Testing
- Power Thermal Cycling Testing
- Mechanical Endurance Test

FIGURE 21 - Intelligent Testing Temple: Durability Testing



Technology-Specific Testing

The aim of Technology-Specific Testing is to activate specific failure modes by applying specific highly accelerated test conditions. It is quite suitable to assess new product and process technologies regarding these specific failure modes in a short time. The technology specific tests are based on the Mission Profile and the Knowledge Matrix and should be performed as soon as possible in the prototype phase when the maturity of the product is given for the specific technology.

Test-to-failure (TTF), or testing to determine levels of degradation, is necessary to establish the suitability of a product for usage. During the product design phase, engineers rely on published data that identifies material and subcomponent limitations. However, the published data frequently includes undocumented safety margins. A module is a composite of many components and materials, each

with their own safety margins. The only way to understand the strength and durability of a module is to increase stresses to determine what levels produce failures or unexpected operating modes. When these events occur, the recommended practice is to perform a root cause analysis to determine if there exists avoidable design or manufacturing issues.

Some stresses that can be used for TTF are:

- High and low steady DC voltage and current levels.
- Transient voltages and currents.
- High and low steady state temperature operation.
- Thermal cycles and shock.
- Humidity.
- Mechanical random vibration, sine vibration, and shocks.
- Exposure to environmental pollutants.
- Customer usage cycles.

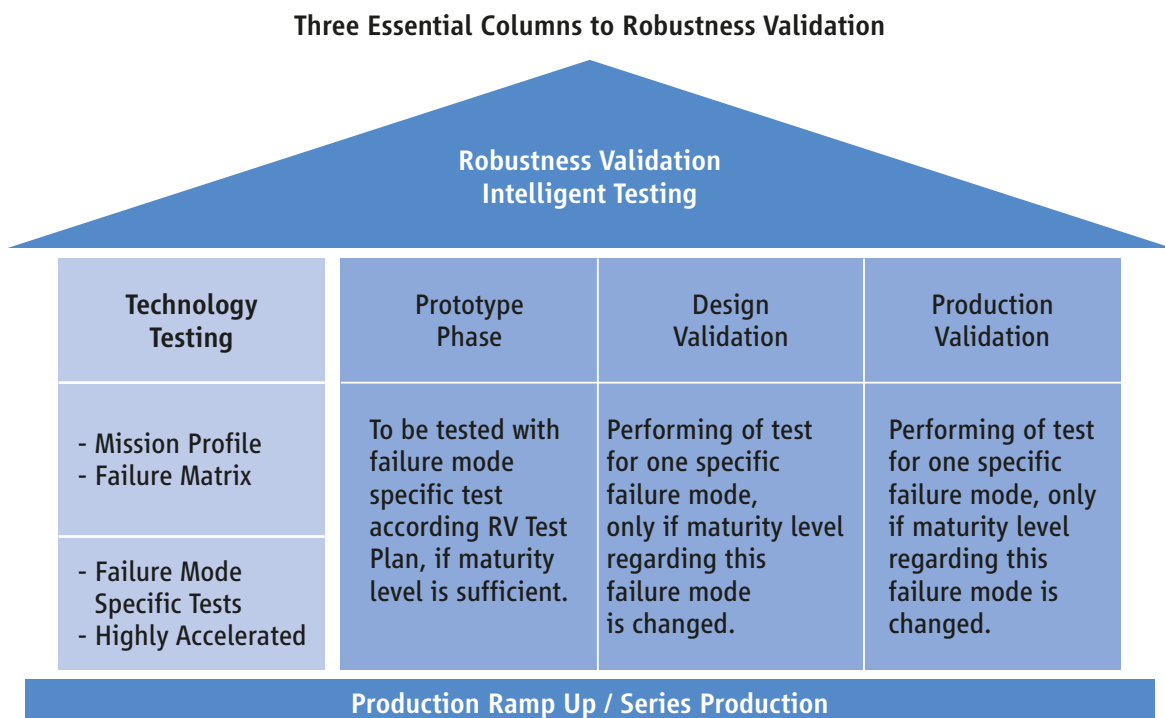
During the Prototype Phase such Technology-Specific Tests are performed with very high acceleration factors in order to generate very fast, technology-specific failure mechanisms which are expected or which are critical based on the RV Test Plan. These tests results show weaknesses of the product for specific technologies and failure mechanisms, with limited correlation to the field due to less accuracy or lack of the models for such acceleration factors. The HALT test method is an adequate test method for such robustness analysis during prototype phase. During the Design and Production Validation phases such Technology-Specific Tests shall be performed if the maturity level of these specific failure modes is changed. The scope of technology-

specific testing during any of the three development phases is shown in the temple of Figure 22.

Production Ramp-up and Mass Production

During the production ramp-up phase shown as the base of the temple in Figure 19 through Figure 22 the results and experience gained from the robustness assessments in the development phase are used to define production control plan parameters. In addition data gathered during ramp-up and mass production allows the engineering team to validate the development results of robustness assessments with statistical evidence.

FIGURE 22 - Intelligent Testing Temple: Durability Testing



9.3 Assessment of Product Robustness in the Development Phase

Robustness Validation Plan Development

The first step during the RV Process is the creation of the RV Plan during the concept phase. The RV Plan defines all stress tests necessary to assess the suitability of the robustness of the product during development with respect to the Mission Profile. An overview of the RV Plan development flow is shown in Figure 23.

The requirements are defined in the Mission Profile, normally described in the specification of the OEM. OEM and 1st tier supplier shall develop the RV Plan together to find a common understanding of the requirements in detail and to share their experiences.

The following sources of information can be used to help find the potential weaknesses of the product and can therefore be used for the creation of the RV Plan:

1. **Mission Profile** (see Section 6)
2. **Knowledge Matrix** (see Section 7)
3. **Assessment of New Sub Components:** Special interest should be given to new (sub) components (e.g. microcontrollers or sensors). Criteria for (sub) components are similar to the above mentioned for the comparison of existing products.
4. **Assessment of New Process:** For new processes similar criteria apply as for existing products.
5. **Comparison with existing products:** If a product with a comparable technology in design, process and fused in a comparable Mission Profile is available, then experiences with this product shall be considered to reduce the effort for testing in the Robustness Validation Test Plan (RV Test Plan). To assess the comparability between two products, the following criteria have to be considered in detail:
 - Product design (Materials, components, solders, adhesives, layout, etc.)

- Production Process (location, production line, tooling, handling, process materials, etc.)
- Mission Profile for the Comparable Products
- Quality Level (requirements)
- Load Conditions (Thermal, current, mechanical, etc.)
- Test Results
- Maturity and Release Status

Such comparison is also applicable on sub systems (e.g. the voltage supply part of a control unit). Comparative tests have to run under identical conditions. The repeatability of test procedures is a fundamental characteristic.

6. **FMEA:** The identified critical results of the Design, Process and System FMEA also provide input to the RV Test Plan.
7. **Analysis, Modeling and Simulation:** Results of any simulations shall be considered for the creation of the RV Test Plan.

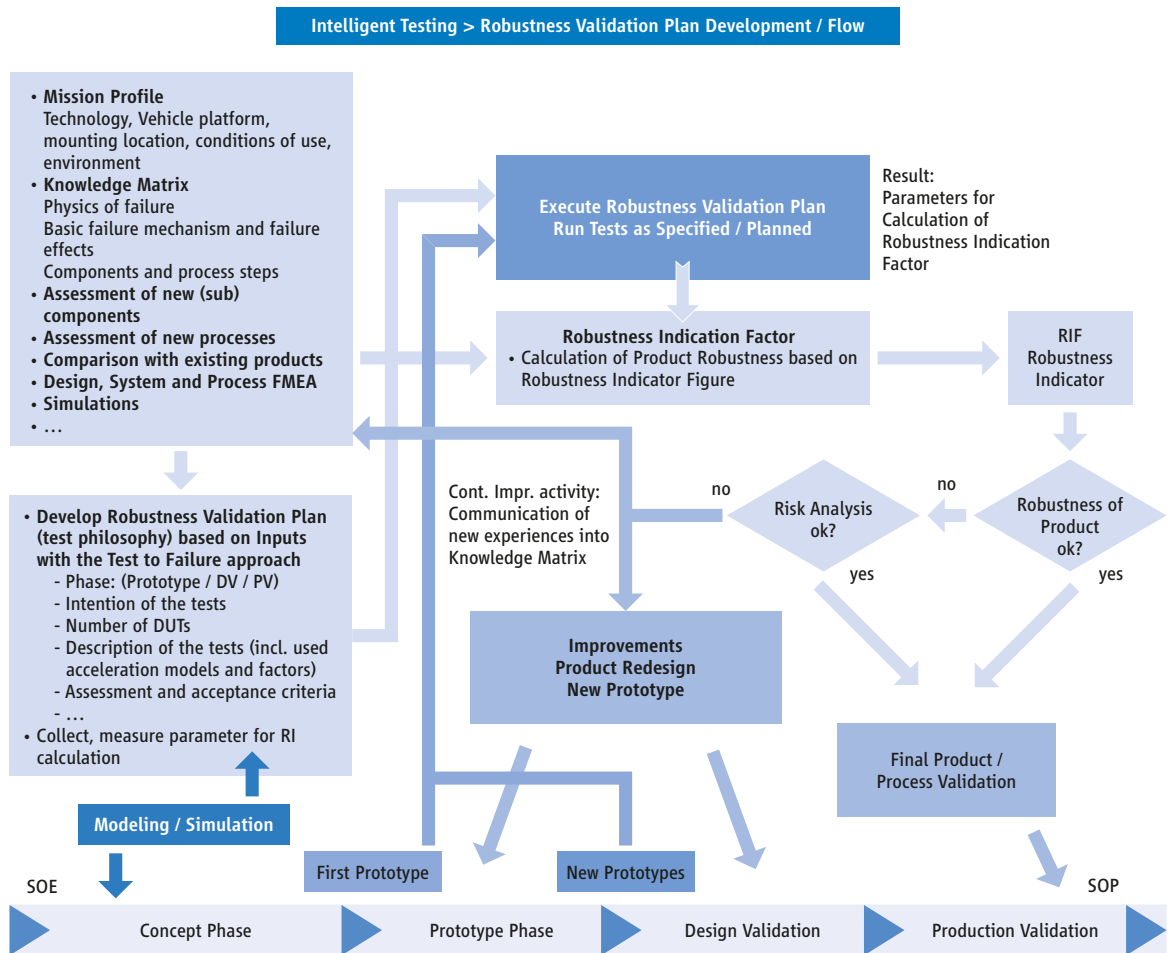
All assessment results shall be considered to create the RV Plan to define the right tests at the suitable point in time.

The RV Plan should include amongst others:

- Phase (Prototype / DV / PV)
- Intention of the tests
- Number of DUTs
- Description of the tests (including. used acceleration models and factors)
- Assessment and acceptance criteria

The RV Plan is intended to be a living document and should therefore be continuously reviewed based on the development progress, the product maturity level reached, and the test results. Strong communication is therefore needed between all involved parties. The DVP&R can be used to document all Robustness Validation activities, necessary for a complete Robustness Validation.

FIGURE 23 - Validation Plan Development Flow



Robustness Validation Testing

The actual stress testing in the RV Process extends from the Prototype Phase to the Design Validation Phase and finally to the Production Validation Phase, and is done according to the RV Plan created during the concept phase as described in this section.

The important aim of Intelligent Testing is to be able to describe the robustness of the product by means of robustness indicator figures and to verify the basic suitability of the product for use in a vehicle according to the defined mission life profile over the vehicle lifetime.

9.3.1 Prototype Phase Testing

To achieve these aims, testing during the Prototype Phase focuses on identifying potential weaknesses and on improving the product maturity rapidly with respect to these potential weaknesses in short development cycles. Especially new technologies, materials and (sub)-components should be tested in this early stage of development to see if these new technologies, materials and parts provide special weaknesses for the complete product.

Potential weaknesses can be identified by stressing the product to failure, then analysing the occurring failures and improving the robustness towards the occurring failures. Since it is very important during the Prototype Phase to realize fast improvements, the time for stressing the product until it fails is very limited. This is why highly accelerated stress

tests are to be used during the Prototype Phase either by strongly increasing the stress level of a test e.g. the temperature delta of a thermal shock test or by using multiple kinds of stress e.g. temperature, humidity and vibration either simultaneously or in sequences.

These highly accelerated tests are especially suitable to simulate one special failure mode e.g. a failure mode being related to a new technology used (failure mode specific testing). The information contained in the Knowledge Matrix should be the basis for choosing suitable highly accelerated test conditions for special technologies, materials or designs. By increasing the stress on the DUTs, failures could be easily generated on the one hand, but since these highly increased stress levels usually exceed the stresses occurring in real field use by far, special attention must be used on the other hand when analysing and interpreting the generated failures.

The failure analysis results must be carefully assessed to distinguish between failure modes caused by an exaggerated high test stress level that is exceeding basic physical limits of a DUT, for example, increased temperatures during test causing the used solder materials to melt, or failure modes that show real weaknesses of the product especially deterioration and wear out. A broad range of specialists should therefore be involved in the assessment of the failures.

The reduction of test times by increasing the test stress level provides the ability to repeat tests with modified DUTs rapidly, thus allowing engineers to judge the effect of any modification quite fast.

The second method for identifying potential weaknesses of a product quickly is the use of comparative test with highly accelerated stress levels. With these comparative tests, newer samples can be tested versus older samples showing the effectiveness of the improvements. Known good products (e.g. from series production) can be tested and compared to new products. This helps to assess the rele-

vance of failures which have occurred. If the new product fails at lower stress levels or earlier than known good parts, improvements are usually necessary, especially if the failure occurs with new technologies or materials. On the other hand, if the new products tend to fail after the known good parts it is likely that the new product is at least as robust as the existing one.

It should be noted that even with successful comparative testing, the correlation between the stresses in field use and the highly increased stresses used for highly accelerated testing is usually very poor. It is therefore usually necessary, in order to make accurate statements regarding the automotive suitability of a product for field use or statements regarding the robustness of a product, that further tests need to be performed.

9.3.2 Design Validation Testing

It is desirable to verify conformity to a customer specification on the one side and get end-of-life information within reasonable periods of time on the other side, to achieve this it is a good practice to perform the tests during the Design Validation Phase with stress level only moderately exceeding the DUTs specification stress levels. Exceeding the physical limits of a DUT must be avoided.

Design Validation Testing is generally performed at stress levels at or only very moderately exceeding the specification of a product, so it is possible to find a test-field correlation by the suitable acceleration models. Since the robustness limits of a product can only be determined based on the test time that is necessary to cause the DUT to fail, all tests during the Design Validation Phase shall be performed as test-to-failure tests.

For the Robustness Validation approach, the tests during the Design Validation Phase are most important, since the results of these tests are the basis for the calculation of the wear related Robustness Indicator Figures (RIF).

9.3.3 Production Validation Testing

The aim of the Production Validation Testing is to validate the product produced with series equipment and series production processes according to the customer specification and the agreed Mission Profile. Since all weaknesses in the design of the product should have been found and resolved during the Prototype Phase and the Design Validation Phase, the Product Validation Tests are expected to be successfully performed on first run.

Successful Production Validation Tests rule out unexpected systemic failures, failures caused by late design changes (that should be avoided anyway) and production related failures. To avoid the risk of generating failures without field relevance, all test conditions should be within the design limit specification of the product. This limits the possibilities to accelerate the necessary test times according to the used acceleration models and may jeopardize the time schedule. If necessary, the vehicle manufacturer and the module supplier could define acceptance criteria for pre-releasing a product (e.g. after 75% or 85% of the Product Validation Tests has been performed without problems) based on an agreed risk assessment.

After successfully completing the Production Validation Testing the suitability of the product for automotive applications and the desired robustness levels are generally confirmed. Statistical information from production ramp-up and series production can then be used to validate results on a statistically significant basis.

The supplier needs to alert the vehicle manufacturer if the full Production Validation cannot be completed. The PV risks can then be assessed using the Robustness Validation results.

9.3.4 Statistical Validation of Robustness Assessment Results

The increasing number of test samples available during production ramp-up allows a statistical analysis of the critical parameters found during the Robustness Assessments performed during development. This data can be used to validate the robustness results from all development tests on a statistical basis as the final step of the Intelligent Testing Process. For example ICT or EOL Test results, see Section 10.

9.4 Retention of Robustness during the Production Phase

Besides the product-independent process validation results, the results from all product-specific robustness assessments during Design and Product Validation should be considered to ensure that all identified critical parameters will be accounted for in the production control plan and may be monitored by statistical process control (SPC). In addition, 100% monitoring of identified critical parameters of end-of-line data should be analysed for drifts and anomalies, see Section 10 for further details.

In the event that there are product and/or process design changes a re-validation should be defined and performed according to this RV Process. In addition, a review should be performed annually to determine the necessity for re-validation activities. If a re-validation is found to be necessary, the re-validation should be completed according to the RV Process defined in this handbook.

10. Manufacturing Process Robustness and its Evaluation

10.1 Purpose and Scope

Manufacturing process robustness is needed to ensure that the work done to establish robustness during the design and development phases of a product life cycle is not eroded by the processes used to manufacture the product. It is necessary to have a knowledge and understanding of how, when and the significance of the issues that can occur during manufacturing which will reduce or affect the robustness of a product related to the Mission Profile or its' intended use.

Outlined in this section is a method to evaluate the degree of robustness or lack of robustness that can exist with a given or estimated manufacturing process. Defined and outlined is a matrix (CPI Matrix) to capture in a systematic manner this evaluation and to generate a Knowledge Matrix for manufacturing processes from incoming material transport and handling to finished product shipping and handling.

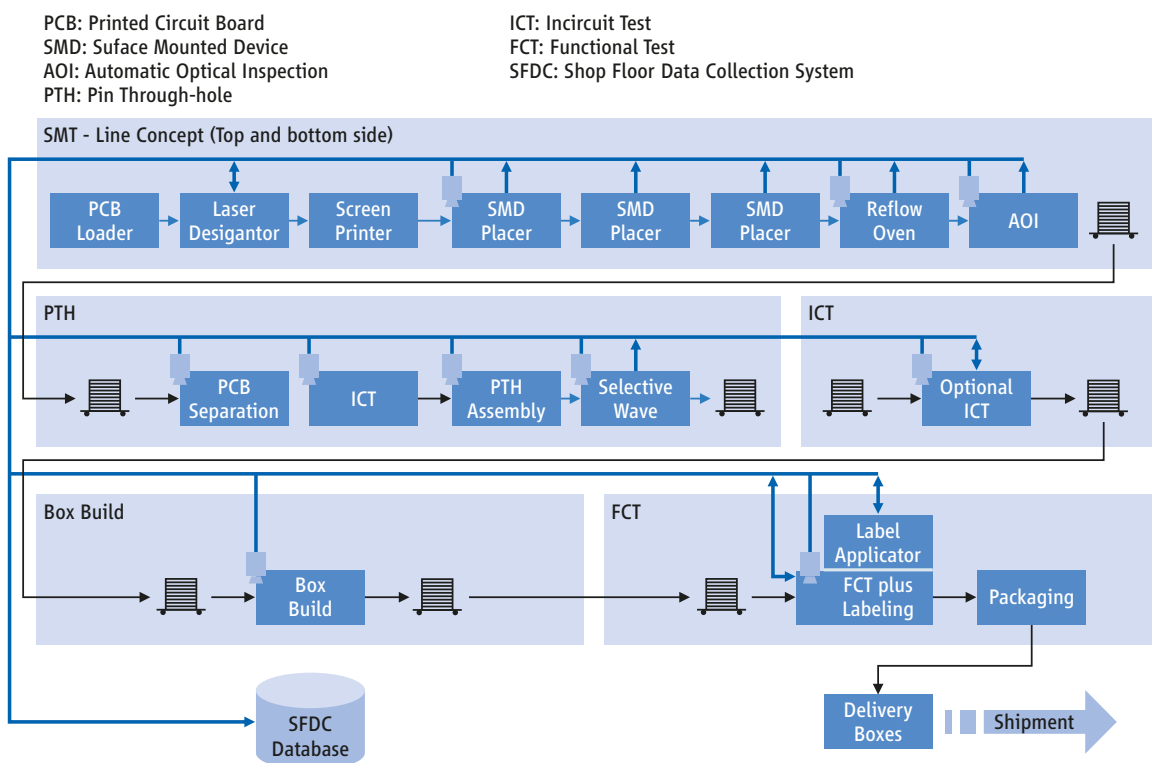
10.2 EEM Manufacturing Process

There are many combinations of manufacturing processes that can be used for different products. Outlined in Figure 24 is a typical manufacturing process for a typical EEM, for demonstration purposes, the users of Robustness Validation will need to adapt the examples used here to their own particular product manufacturing processes.

Current typical EEM's are manufactured with a double-sided reflow process, with solder paste printing, component placement and solder reflow followed by some back end processes to complete the product for components that cannot be assembled with standard Surface Mount Technologies (SMT).

The following example shows one possible manufacturing process flow to demonstrate how complex it can get and to give some background for the later discussion. Please note, that the implementation and use of the mentioned testers are also just for example.

FIGURE 24 - Typical EEM Manufacturing Process



Please note, that there may be new or additional product or process requirements not included in this example that must be considered, like conformal coating or sealing which may need to have some specific or special attention. Generally, there is no standard process - there is just standard equipment or tools which need to be setup in a manner which supports the Zero Defect Strategy [21].

Please note, that special care is needed in the use of the Incircuit Test (ICT) as they can sometimes have a negative impact on the EEM. This means that before a particular tester or equipment is used, all the positive aspects (e.g. test coverage increase) have to be balanced against the negative ones (e.g. electrical over-stress, mechanical damage).

As you can imagine there are many possible combinations and interactions between the manufacturing processes used to manufacture a product the product design and the components used in a product. A typical

manufacturing process is made up of many sub processes, each with their own variations and interactions. The intent here is to evaluate the interactions and noise variations caused by different material lots, equipment status, etc. to ensure that the manufacturing windows can be as wide as possible. This will assure the minimum amount of robustness erosion by getting the manufacturing process right the first time and to keep it sustainable over the product lifetime.

The following example in Table 7 shows one case where these interactions are demonstrated.

EXAMPLE:

Reflow soldering/component interaction.

Demonstrates:

- Flux influence
- Component influence
- Solder joint influence

FIGURE 25 - Typical Solder Reflow Profile

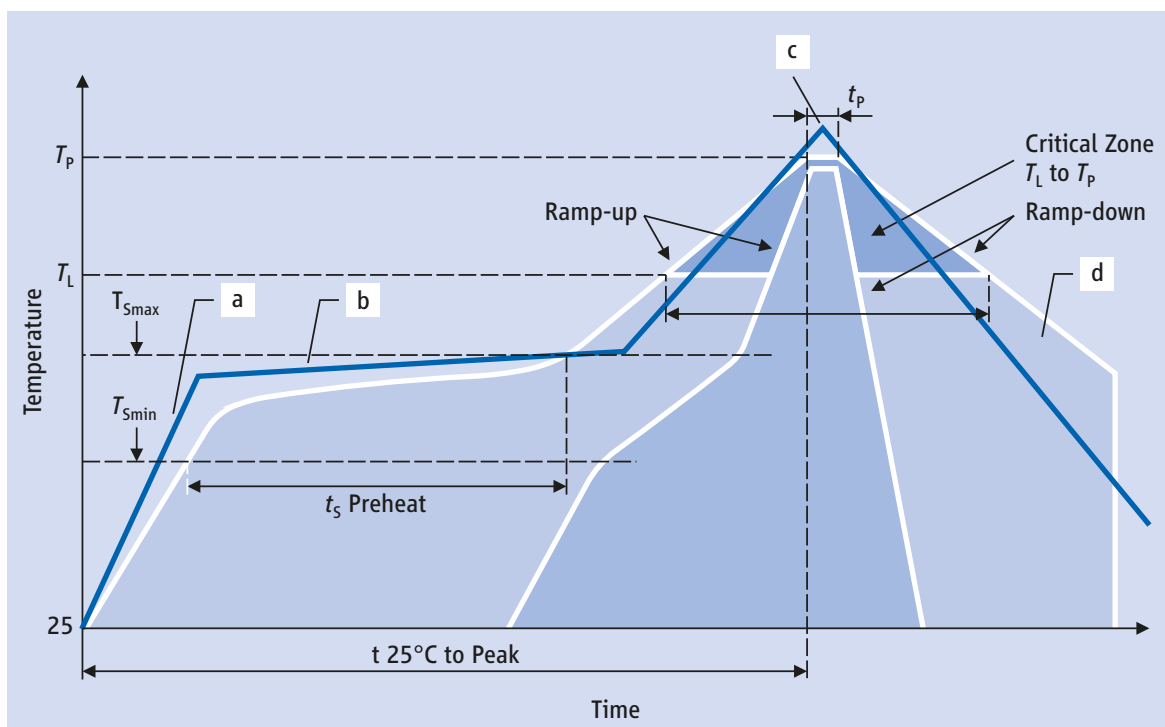


Figure 25 shows a typical reflow soldering profile and the JEDEC J-STD-020 MSL classification profile which defines the border lines between user application (manufacturing) and

qualification at the component manufacturer. The manufacturing process has to stay within the grey border profile as recommended by the component manufacturers or paste providers.

The blue line shows an arbitrary profile with the following potential failure modes:

- a. Ramp up too fast = Risk for thermal stress cracks in components.
- b. Ramp up to a too high soak level = Risk for premature exhaustion of solder flux = Poor solder joint.
- c. Too high peak temperature / too long time at peak = Risk for delamination, cracks, pop corning, and other thermal overload damage.
- d. Ramp down too fast = Risk for solder joint voids or weak solder joints.

In this section we outline a method to systematically evaluate and capture these interactions.

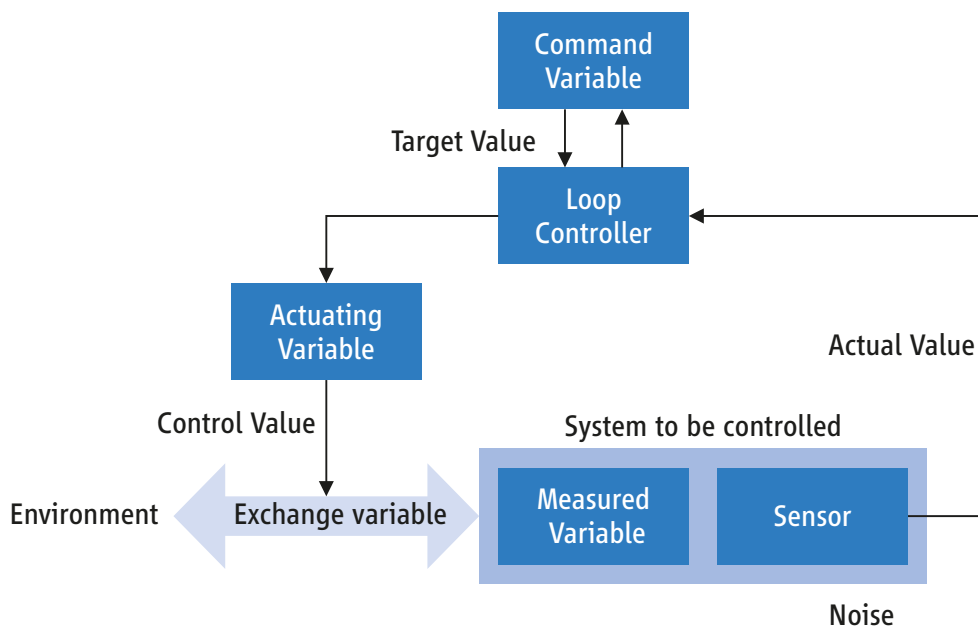
10.3 Robust Process Definition Process:

A process is any repeatable activity within an organization with the target of supporting a specified product or service. This may also include internal and external services and locations as well as logistics and packaging. It must have a defined input and output as well as a defined flow.

Robust Process:

A robust process is a process or sub-process which does not negatively affect the parameters of its output or consumes any of the robustness of its inputs. This requires processes which keep their parameters inside the setup limits under all noise factors and varying conditions.

FIGURE 26 - Controlled Process



The typical EEM manufacturing process in Figure 26 contains many control loops. The target is to optimize for each individual parameter the control deviation and to look always for a negative control.

The next challenge is to look also to all interactions or interrelations between the different process steps to optimize and assure that stable negative feedback loops are in place not only individually for each sub process but for the whole manufacturing system.

To get an understanding of the complexity involved a simple example can explain the case:

- A component is placed on a PCB and should be soldered with a reflow oven. The data sheet of the component specifies the basic soldering conditions, such as maximum temperatures, max temperature ramp up and down rates, maximum time and so on. As long as the reflow profile is within the specified component limits, a process is called robust against this specific material condition. If however the process parameters drift up to the component specification limits or if they exceed the specification, the process may negatively affect the component by damaging it.

It should be easy to stay within the component specification limits. However but taking into consideration that there is not only one component on the board and there are also other influences like solderability or wettability of the component and the recommended profile of the solder paste to comply with respect, the unidirectional picture becomes a multi-dimensional one and as a consequence the process parameters have to respect all of the component specifications of all of the components used.

FIGURE 27 - Example Robustness for Component Characteristics

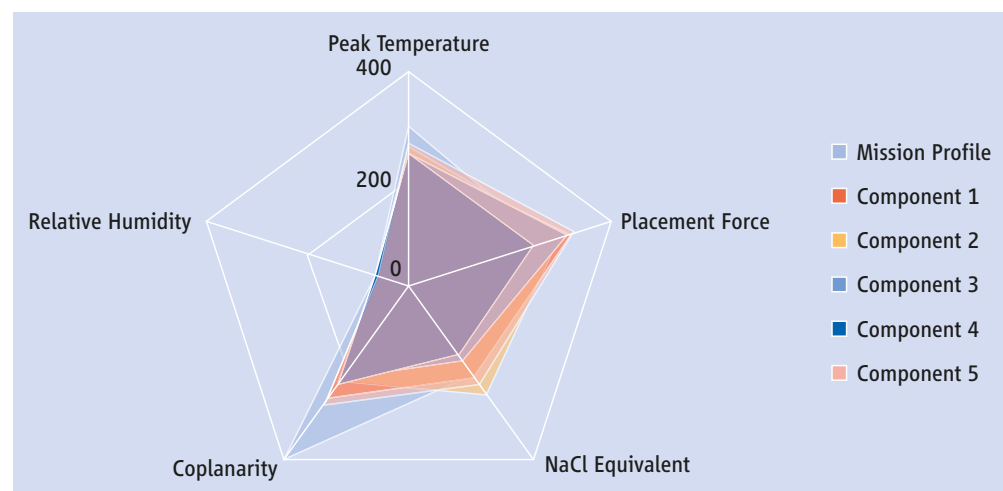


Figure 27 shows the comparison of all Mission Profiles to the basic Mission Profile of the EEM. All areas where no blue space is seen are potentially critical.

10.4 Process Interactions

There can be an almost infinite number of interactions between all the variables in a complete manufacturing process. However in this section we consider the main interactions between components and processes, which can be characterized by a matrix of four quadrants as shown in Figure 28.

- Materials on Materials Q1-1
- Materials on Process Q2-1

- Process on Process Q2-2
- Process on Materials Q1-2

In this section we will focus on the quadrant Process to Material Q2-1 to demonstrate the concept.

FIGURE 28 - Component Process Interaction Matrix

| Component Process Interaction Matrix | | | Material | Process |
|--------------------------------------|-----------|------------|------------|------------|
| | | | Subgroups | Subgroups |
| | | | Attributes | Attributes |
| Material | Subgroups | Attributes | Q1-1 | Q1-2 |
| Process | Subgroups | Attributes | Q2-1 | Q2-2 |

10.5 Component Process Interaction Matrix

The Component Process Interaction Matrix (CPI Matrix) is a tool which allows the evaluation of critical attribute interactions, the CPI Matrix.

- CPI Matrix is a four quadrant matrix which shows interactions between Components and Processes in different directions.
- This section shows two directions with the focus on Process → Material.
- The basic concept is to combine methods like QFD (Quality Function Deployment), FMEA (Failure Mode and Effects Analysis) and DFM/DFT (Design for Manufacturability and Testability) and to use the results in a direct synergy.

Extended use and scope of the matrix result.

- Define and get acknowledged potential random failures as a combination between the matrix factors and characteristics.
- Evaluate potential individual risks which are latent or intermittent restricted to certain failure modes.
- To localize these failure modes and to ultimately transfer them into the Knowledge Matrix.

The following sections show how to create it and to use it with a general scope and finally how to transfer the structure to individual projects.

a) Matrix Template Structure

The matrix structure is as shown in Figure 28 used in the example CPI Matrix and is derived from the QFD (Quality Function Deployment) matrix.

The matrix design includes 4 quadrants with the basic direction from rows to columns. These are marked in different colours, as shown above. In general it can be used to evaluate relationships in all directions. The focus is from **Material** source to Material and Process or from **Process** source to Material and Process - but both are also possible together. As a minimum evaluation it is also possible to use just one quadrant of the four by always respecting the row - column directions.

In total the matrix can generate more than 60,000 direct and individual attribute relations which are assigned by ranking numbers. The original file with an example of the working group can be downloaded from the SAE oder die ZVEI website (www.zvei.org/RobustnessValidation) as

well as a working file for individual use. The assessment and the mentioned numbers are only examples and can be used as the basis for starting your own evaluation but are an example evaluation only. It is the responsibility of the user of Robustness Validation to generate and evaluate their CPI Matrix from their product and process experiences.

b) Basic Use

The example CPI Matrix must be modified to the Robustness Validation Users' needs. It is possible to add individual groups, sub groups or single attributes (the existing file is just a proposal based on the current knowledge and experience). This makes it possible to setup a project or product related scope and to evaluate all the interactions for the EEMs under consideration.

The use and the structure are not directly comparable to the FMEA or similar tools but the output could be used to construct an efficient FMEA. Due to the fact that the CPI Matrix goes down to the detailed attributes it should be evaluated before the FMEA and used also as a living document.

The focus of the matrix is mostly on the random/non-systematic failures. The systematic ones are considered in the Knowledge Matrix in Section 7 but the aim is to transfer as much as possible over time from random to systematic once the failure mode and root cause becomes defined. This is strongly supporting a Zero Defect approach.

c) Result Expectations

The final output of the CPI Matrix will show the detailed interactions of the individual parameters in a ranked format. With this pareto type of presentation the user will see the most significant interactions or relationships according to his ranking of the attributes. This will allow him to assess the relative risk of not meeting the robustness requirements.

For the critical attributes it is recommended to go more into detail and assess further sub attributes not already contained in the

matrix. By applying this kind of filter the scope is focusing more and more on the most critical interactions and therefore supporting the elimination of the any remaining random/non-systematic failure risks. This learning curve will then allow a transfer of random/non-systematic failure modes to the systematic root cause which can then be added to the Knowledge Matrix.

CPI Matrix Development

As we are considering process and material interactions to start the development of the matrix we should consider the main process steps and components which are involved in the EEM under consideration. A typical but non exhaustive list could be as follows in this section. The Robustness Validation User must generate their own lists and they form the rows and columns of the matrix.

The process for CPI Matrix creation is:

- Step 1. Generate a list of process steps.
- Step 2. Define the significant attributes for each process step.
- Step 3. Generate a list of components.
- Step 4. Define the significant attributes for each Component.
- Step 5. Assign attribute weight factors for each attribute defined in steps 2 and 4.
- Step 6. Assign level of interaction factors for each attribute defined in steps 2 and 4.
- Step 7. Create pareto of interaction factors and determine actions.

10.5.1 Typical Main Process Steps (Process Categories)

1. Component Logistics:
 - Component design qualification.
 - Specification of the different components.
 - Component incoming quality.
 - Component kitting/setup.
 - PCB/component handling.
2. Front-End Assembly:
 - Solder paste printing
 - Glue printing
 - Component placement
 - Reflow soldering

3. Backend Assembly:
 - Manual assembly
 - Press fit
 - Wave soldering
 - Selective soldering
 - Depanelisation
 - Final assembly
4. Testing:
 - Automatic Optical Inspection, Automatic X-ray Inspection, In Circuit Test, Burn in, Run in, Boundary Scan, Flying probe.
5. Maintenance:
 - Actual and preventive taken together.
6. EEM Logistics:
 - Packing, Packaging and shipping/transport.

10.5.2 Process Step Attributes

For each process step identified in Section 10.5.1 above a sub-list of the significant thermal, electrical, chemical and mechanical attributes that impact the robustness of the final product should be generated from the following sources:

- Step 1. Field data (product performance)
- Step 2. FMEA (design, product, process)
- Step 3. Risk analysis
- Step 4. Knowledge Matrix/data base
- Step 5. Process performance data
- Step 6. Industry standards
- Step 7. Internal monitoring and screening

An example of a process step attribute list relating to the attributes influencing environmental factors for solder paste printing is shown in Table 6.

TABLE 6 - Process Step Attributes - Solder Paste Printing

| Attribute | Thermal | Chemical | Mechanical | Electrical |
|--------------------------------------------------------------------|---------|----------|------------|------------|
| Stability of environmental parameters (e.g. humidity, temperature) | X | X | | X |
| Solder paste material | | X | | |
| Printing type | | | X | |
| Stencil type (Laser Cut, Electro Formed) | | | X | |
| Stencil thickness | | | X | |
| Cleaning cycle | | X | X | |
| PCB support | | | X | |
| Printing shape | | | X | X |
| Hole filling (pin in paste) | | | X | X |
| Pad overprinting | | | X | X |
| Stencil use time | | | X | |
| Paste use time | | X | X | |
| Pump cleaning | | X | X | |

10.5.3 Typical Component Contents

a. Main Component Groups:

- Passive
- Active
- Interconnection
- Electro mechanical
- Housing
- Consumables

b. Component Sub Groups:

- Passive
- Active
- Hermetic
- Non Hermetic
- Electro mechanical
- Interconnection
- PCB
- Cables
- Connectors
- Housing
- Plastics
- Metal

10.5.4 Component Attributes

For each component group in Section 10.5.3 a sub-list of the significant thermal, electrical, chemical and mechanical attributes that impact the robustness of the final product, should be generated from the following sources:

- Step 1. Component data sheet
- Step 2. PPAP
- Step 3. Component questionnaires
- Step 4. FMEA (design, product, process)
- Step 5. Risk analysis
- Step 6. Knowledge Matrix/data base
- Step 7. Process performance data
- Step 8. Industry standards
- Step 9. Monitoring and screening

An example of a process step attribute list relating to the attribute's influencing environmental factor for a printed circuit board (PCB) as a component is shown in Table 7.

TABLE 7 - Component Attributes - PCB

| Attribute | Thermal | Chemical | Mechanical | Electrical |
|-----------------------------|---------|----------|------------|------------|
| PCB surface finish | | X | X | X |
| Substrate material | X | | X | |
| Solder mask | | X | X | |
| Warpage | | | X | |
| Pad design | | | X | X |
| Through hole plating | | | X | X |
| Contamination | | X | X | X |
| Delamination and track open | | | X | X |
| Via outgassing | X | X | X | |
| Wetability | X | X | X | X |
| Solderability | X | X | X | X |
| etc. | | | | |

10.5.5 Template of Full Matrix (4 quadrants matrix)

FIGURE 29 - Component Process Interaction Matrix Example

| Component Process Interaction Matrix | | | Material | Process |
|--------------------------------------|-----------|------------|------------|------------|
| | | | Subgroups | Subgroups |
| | | | Attributes | Attributes |
| Material | Subgroups | Attributes | X | X |
| Process | Subgroups | Attributes | X | X |

The Component Process Interaction Matrix (CPIM) shows the interaction between each main group (e.g. Process → Material). The target is to see the correlation between each individual attribute and how it impacts the robustness of the product. Emphasis can be put over all or special quadrants or upon request on a specific quadrant(s).

For example, one possible focus may be the process and how the process attributes impacts the material attributes (given BOM - Bill of Material / AVL - Approved Vendor List). Following the “Zero Defect Strategy” and being able to have an early involvement in the design phase, the reverse direction should also be evaluated.

10.5.6 Attribute Weight Factors (Importance Indicators)

To enable the generation of a pareto a linear weighting of

- 1 - Low importance
- 2 - Medium importance
- 3 - High importance

(other weighting models are possible) is given to each attribute.

The example CPI Matrix has weight factors assigned by experience consensus. This should be modified or adjusted and should be aligned with the individual process of each Robustness Validation User. The example weightings are intended as guidelines.

10.5.7 Level of Attribute Interaction

To enable the generation of a pareto a linear weighted ranking of

- 0 - No interaction
- 1 - Low interaction
- 2 - Medium interaction
- 3 - High interaction

(other weighting models are possible) is given to each attribute. Special values to express individual concerns (3.1) should only be used for special cases and not for a regular weighting.

A special value to express individual concerns (this should only be used for special cases - not for a regular weighting).

In the example CPI Matrix, the rating is assigned by experience and consensus of the working group. This should be individually modified or adjusted and should to be aligned with the individual process of each user. The example weightings are intended as guidelines.

This methodology is similar to the FMEA (RPN) procedure.

CPI Matrix Assessment of Interactions

FIGURE 30 - Level of Interaction Warpage

| CPI-Matrix Date: 2007-xx-xx | | <div style="display: flex; justify-content: space-around; border: 1px solid black; padding: 2px;"> Sort copy row </div> | | Connectors | Consumables | Consumables | Passive components | Passive components | Passive components | PCB | PCB | PCB | AOI post reflow | AOI post reflow | Component placement (automatic) | Component placement (automatic) |
|--------------------------------|--------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|---------------------|---------------------|----------------------|---------------------------------------|--------------------|--------------------|----------------------|--------------------------|------------------|-------------------|-----------------|---------------------------------|---------------------------------|
| Requirements | | Ranking: 0 to 3 | | retention force - C | Solder paste - Cons | Flux material - Cons | Substrate (mechanical stability) - PC | Termination - PC | Wetability - PC | surface finish - PCB | substrate material - PCB | pad design - PCB | Camera resolution | Camera angle | placement force | component size / weight |
| | | Weighting factor (1-3) | | | | | | | | | | | | | | |
| Process | AOI post reflow | Camera resolution | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Process | AOI post reflow | Camera angle | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Process | Component placement (automatic) | placement force | | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Process | Component placement (automatic) | component size / weight | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Process | FCT | Contact force | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Process | FCT | Warpage | | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 |
| Process | PCB / Component handling | ESD - comp-hand | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Process | Reflow soldering (convectional oven) | Temperature profile in general | | 0 | 2 | 2 | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 0 | 3 |
| Process | Reflow soldering (convectional oven) | temperature ramp rates | | 0 | 1 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Process | Reflow soldering (convectional oven) | solder balls | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 0 |
| Process | Solder paste printing | cleaning cycle | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Process | V-scoring | V-score depth | | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 |

For each intersection of the matrix the level of interaction needs to be assessed using the criteria defined in Sektion 10.5.7.

For example using Figure 30.

Functional Test - Warpage → Substrate (mechanical stability) passive component is evaluated with a 3 (High Interaction) because the bending stress of the Functional Tester has a high impact on the Substrate (mechanical stability) of passive components.

10.6 CPI Matrix Calculations

To enable the sorting and prioritizing of the interactions the weighting and interaction levels are used to create an assessment number similar to the FMEA RPN number.

a) Row calculation

The row sums of all attribute interactions multiplied with the weighting factors show the overall importance of the component or process to all other selected characteristics or attributes.

b) Sorting

The sorting of the line sums show the importance of the individual process or component importance.

c) Selections

To mark some attributes as specials it is possible to give them the value 3.1. This ensures that they will be always on the top of the sorted list.

The most important attributes can be specialized by applying e.g. the 80/20 rule. Individual parameter setting is possible.

d) View direction definition (e.g. effect of process on components)

One quadrant shows always just one direction of interaction. It is important not to mentally switch between the relationships directions during the assessment of the individual values.

e) **Rule application** (e.g. 80/20)
 For the application of the pareto rule the accumulated sums of all line sums will be calculated. The reference value (accumulated sum of line sums) will be multiplied

with the rule factor (in this guideline equal to 0.80 = 80%). The relation to the basic sum then shows the pareto limit.
 The file also allows an individual ranking by entering other ratios.

FIGURE 31 - 80/20 Rule Results

| CPI-Matrix Date: 2007-xx-xx | | Sort copy row | | Sub group | | Weighting factor (1-3) | | Attribute | | Accumulation of line sums | | Special Assessment | | Active components (non-hermetic) | | Connectors | | Consumables | |
|--------------------------------|--------------------------------------|-------------------------------------|--|------------------------|------|------------------------|---|-----------|-----|---------------------------|---|--------------------|---|----------------------------------|---|------------|---|-------------|-----|
| Requirements | | Ranking: 0 to 3 | | Weighting factor (1-3) | | 20 | | 371 | | 74.1 | | Special Assessment | | Active components (non-hermetic) | | Connectors | | Consumables | |
| Sub group | | Attribute | | Weighting factor (1-3) | | 20 | | 371 | | 74.1 | | Special Assessment | | Active components (non-hermetic) | | Connectors | | Consumables | |
| Component | PCB | surface finish - PCB | | 1 | 8.1 | 8 | 1 | 0 | 3 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.1 |
| Component | Active components (non-hermetic) | coplanarity (package warpage)- Acnh | | 3 | 12.3 | 0 | 1 | 0 | 3.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Process | Reflow soldering (convectional oven) | Temperature profile in general | | 3 | 24.0 | 24 | 0 | 0 | 3 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| Component | Consumables | Solder paste - Cons | | 2 | 6.0 | 30 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Component | Active components (non-hermetic) | Solderability- Acnh | | 3 | 0.0 | 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Component | Consumables | Flux material - Cons | | 2 | 10.0 | 40 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| Component | PCB | pad design - PCB | | 3 | 9.0 | 49 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

The example includes only selected attribute rankings and is just for demonstration.

The application of the 80/20 pareto rule shows in Figure 31 that 80% of the total impact of attributes is caused by:

- Special: PCB
 - Surface Finish
- Special: Active Components
 - Co Planarity
- Reflow Soldering
 - Temperature Profile

The matrix needs to be read from row to column.

Sum of Scores in Horizontal Lines:

Is an indication of "How does these row attributes effect column attributes" → The higher the score, the bigger the effect of the specific attributes.

Sum of Scores in Columns:

Is an indicator of "How this specific attribute is affected by all rows attributes" → the higher score is, the bigger this attribute will be affected.

This score is basically just for information and not automatically calculated within the matrix.

Examples of high, medium and low impact attributes are shown Figure 32.

FIGURE 32 - Example Attributes Listed by Degree of Impact

| | Sub group | Attribute | | | | | | | |
|-----------|--------------------------------------|-------------------------------------|--|---|------|----|---|---|-----|
| Component | PCB | surface finish - PCB | | 1 | 4.0 | 4 | 0 | 0 | 3 |
| Component | Active components (non-hermetic) | coplanarity (package warpage)- Acnh | | 3 | 12.3 | 0 | 1 | 0 | 3.1 |
| Process | Reflow soldering (convectional oven) | Temperature profile in general | | 3 | 18.0 | 18 | 0 | 0 | 3 |

| | | | | | | | | | |
|-----------|--------------------------------------|-----------------------------------------------|--|---|-----|----|---|---|---|
| Component | Consumables | Solder paste - Cons | | 2 | 6.0 | 24 | 0 | 0 | 3 |
| Component | Active components (non-hermetic) | Solderability- Acnh | | 3 | 0.0 | 24 | 0 | 0 | 0 |
| Component | Consumables | Flux material - Cons | | 2 | 6.0 | 30 | 0 | 0 | 3 |
| Component | PCB | pad design - PCB | | 3 | 6.0 | 36 | 0 | 0 | 2 |
| Process | Reflow soldering (convectional oven) | temperature ramp rates | | 3 | 6.0 | 42 | 0 | 0 | 2 |
| Component | Passive components | Termination - PC | | 2 | 0.0 | 42 | 0 | 0 | 0 |
| Process | Reflow soldering (convectional oven) | solder balls | | 2 | 0.0 | 42 | 0 | 0 | 0 |
| Process | FCT | Warpage | | 3 | 0.0 | 42 | 0 | 0 | 0 |
| Process | V-scoring | V-score depth | | 2 | 0.0 | 42 | 0 | 0 | 0 |
| Process | FCT | Contact force | | 3 | 3.0 | 45 | 0 | 0 | 0 |
| Component | Passive components | Substrate (mechanical stability) -PC | | 1 | 0.0 | 45 | 0 | 0 | 0 |
| Component | Active components (non-hermetic) | Moisture sensitivity- Acnh | | 3 | 0.0 | 45 | 0 | 0 | 0 |
| Component | Passive components | Wetability - PC | | 2 | 0.0 | 45 | 0 | 0 | 0 |
| Process | Component placement (automatic) | placement force | | 1 | 0.0 | 45 | 0 | 0 | 0 |
| Component | PCB | substrate material - PCB | | 1 | 0.0 | 45 | 0 | 0 | 0 |
| Process | Solder paste printing | cleaning cycle | | 1 | 0.0 | 45 | 0 | 0 | 0 |
| Process | AOI post reflow | Camera resolution | | 1 | 0.0 | 45 | 0 | 0 | 0 |
| Process | AOI post reflow | Camera angle | | 3 | 0.0 | 45 | 0 | 0 | 0 |
| Process | Component placement (automatic) | component size / weight | | 2 | 0.0 | 45 | 0 | 0 | 0 |
| Component | Connectors | termination material (contact resistance) - C | | 2 | 0.0 | 45 | 0 | 0 | 0 |
| Component | Connectors | plastic material - C | | 2 | 0.0 | 45 | 0 | 0 | 0 |
| Component | Connectors | retention force - C | | 1 | 0.0 | 45 | 0 | 0 | 0 |
| Process | PCB / Component handling | ESD - comp-hand | | 1 | 0.0 | 45 | 0 | 0 | 0 |

Note:
The examples are just for demonstration. Even the lower impact characteristics may have high impacts if the point of view will be changed or if there are other dependencies.

See more examples on how to use the CPI Matrix in the examples Section A.7.

10.7 Robustness Indicator to Describe the Process Robustness

The robustness indicators as described in Section 11 should distinguish between functional and process related factors. The focus of the functional related ones is on the specified function within the required conditions or Mission Profile. The focus of the process related ones is related to the applied parameters by the processes in combination with the design and the components used to manufacture the product.

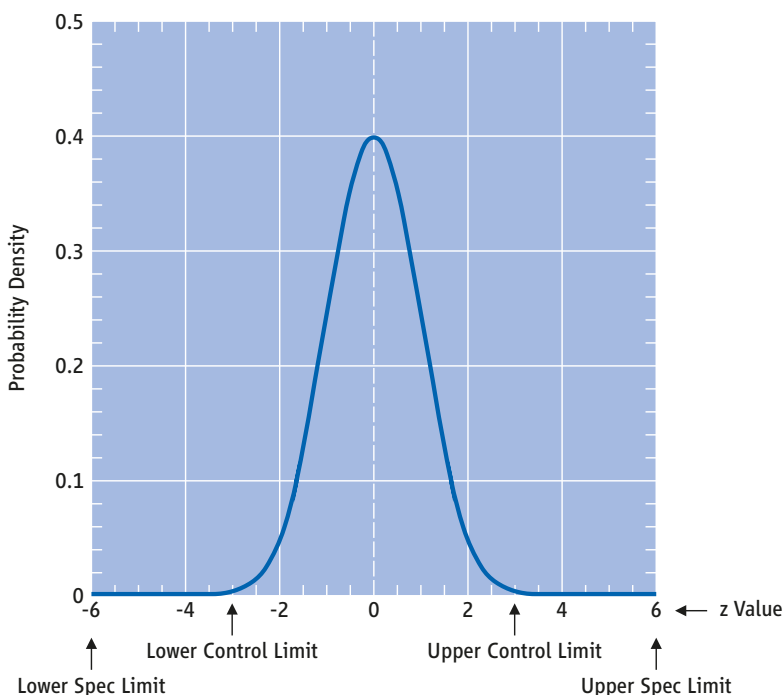
In general it is usual to express the process related factors by the general capability of equipment (machines) with the C_m , C_{mk} factors and the process itself with the C_p , C_{pk} factors - see ISO 21747 [5] for a more detailed explanation. The relationship of each is dependent on how detailed and specific the analysis is done. One general fact and disadvantage is still that the monitoring of all this is difficult and resource intensive and unfortunately not very often practiced. It is also the case that the data to generate these values are often not precise enough or trimmed to get the required values. A first step is potentially

to do tester verification using "Golden Samples" with a smaller characteristic window for defined special values to verify the stability and therefore the capability of the tester. An advanced method would be the use of online monitoring of these characteristics using all tested products. This would increase the statistical basis for the mean stability value and also the standard deviation variation. The result then needs immediate feedback to the manufacturing process to get the best robustness result.

To ensure that all potential risks and robustness erosion possibilities are covered it is also important and required that worst case samples of components are used in certain process capability measurements rather than the normal average component.

A worst case sample is a component which is still within the specified limits but has special significant characteristics at or close to the specification limits, see Figure 33. Potentially these samples have to be especially prepared by the component manufacturer (e.g. coplanarity on QFP).

FIGURE 33 - Worst Case Samples



Note:

Using Average samples it is considered that the values are around the mean value (between Lower Control and upper control **LIMIT**). To have the full range it is necessary to get the components **WITH SOME** special characteristics at the specified limit (lower and/or upper spec. limit).

This new approach is a little bit different to the hitherto applied method in that firstly the influencing factor relationships are analysed individually and secondly the most important factors have to be added to a continuous screening program.

By respecting this new approach it is possible to see the whole chain of tolerances and therefore the relationship of each influencing factor to all others. Beginning with the design related specific characteristics which are mandatory to be observed the next step is the combination of these with the material and the processes. This can be done also by using the CPI Matrix. Therefore the weighting factors have to be set accordingly as high.

Depending on the influence (negative or positive) the tolerance calculation should then be done for the worst case. If the evaluation still shows robustness against the process on the limits it can be assured to have a higher robustness by during serial production over the full range of values.

These details allow a very accurate analysis of each influencing factor and make it easier to decide which of them have to be added to monitoring or screening.

By doing this screening and applying the standard capability rules it becomes possible to get critical factors under control or show at least per step the individual capabilities.

For some situations the general capability calculation may not be detailed enough. Therefore it is recommended to go one step deeper and start with the DPMO (Defects Per Million Opportunities) calculation. This method will give a more accurate picture by looking into individual characteristics and by doing certain benchmarks whether on machine capabilities or on design / component / process combinations.

This monitoring allows the creation of more and long term data and pinpoints the potential optimizations regarding the short and midterm capability studies.

The monitoring can be done with regular tools, such as:

- Xbar R
- Multi Vari Chart
- Box Plot
- SPC

Process Robustness Indicator Example:

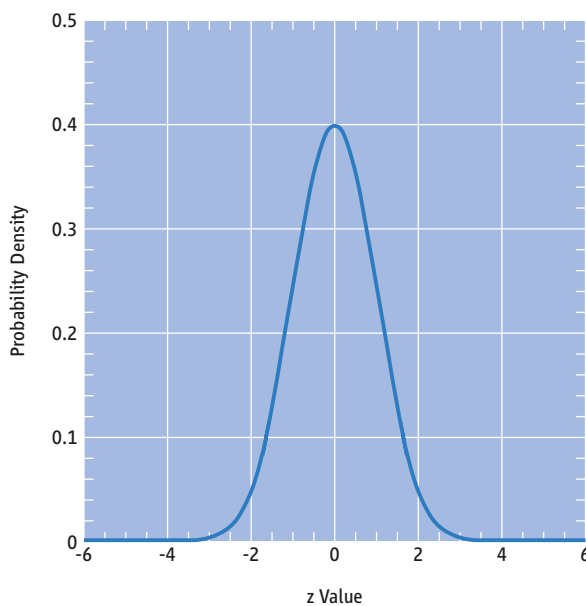
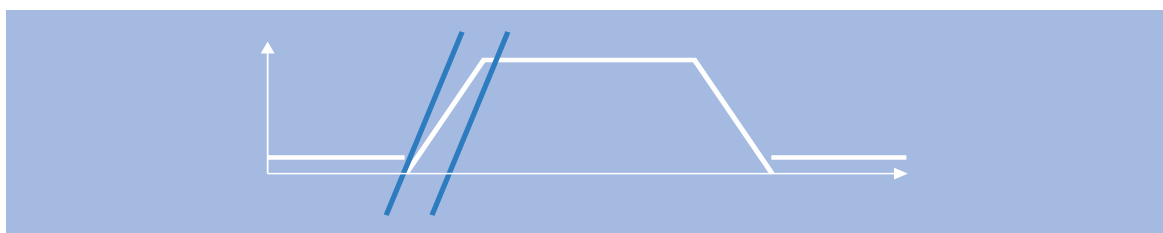
Monitoring of ICT Result for the following Ramp up Characteristics.

Sleep current of EEM → Parametric test on module level

Sleep current of one component → Parametric on component level

Switch on/Switch off characteristics → Characterization

FIGURE 34 - Example Process Indicator



Note:
Varying values related to the current ramp up rate, could be continuously measured and logged.
By monitoring the individual value, the distribution shows the functional related robustness of the component characteristic.
The picture shows one possible distribution. A continuous monitoring of the values allows the user to keep this factor under review and to see any potential influence to the expected life time of the component or finally of the EEM.

10.8 Extended Use and Scope of the Matrix Result

By using the matrix and having at least statistically relevant data it may become possible that evaluated random/non-systematic failures can be transferred to the companies' Knowledge Matrix. This individual Knowledge Matrix becomes more and more accurate over

time and use. By transferring the failure mode/root cause to the systematic Knowledge Matrix it should become a universal property of the organization to be used in a lessons learned process beginning from design to processing to shipping.

10.9 Preventive Actions and Side Benefits

The previous pages describe how to assess, evaluate and generate data for non-systematic failures on EEM level. It includes and focus's mostly on the manufacturing processes by taking into consideration how much robustness is consumed by the manufacturing of the EEM. This focus is the new concept, because in the past the robustness was mainly evaluated on the EEM level or on the components.

By using the CPI Matrix in combination with the design phase activities the loop is now closed. This means that now beginning with Design which delivers the special characteristics, to the components which deliver an individual robustness according to the data sheet or specification, to the process which is described in this section the EEM will deliver the requested over all robustness.

The most effective preventive action is to get a design and components which allows the use of standard manufacturing equipment and the application of regular characteristics and equipment parameters. This can only be done if there is a direct relation between Mission Profile, product design, material, process design and manufacturing.

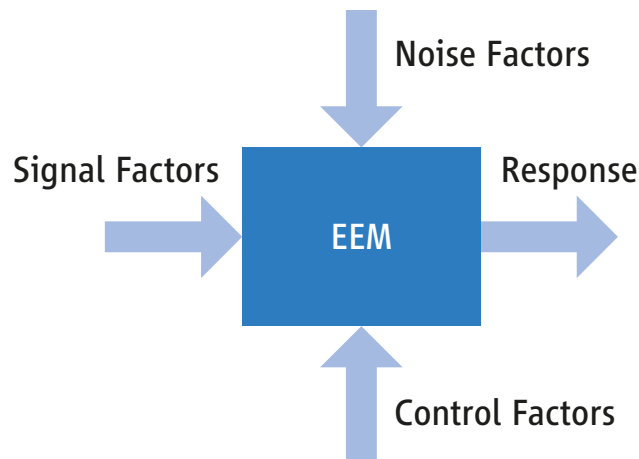
As side benefits the monitoring in parallel of the defined characteristics and parameters in serial production allows one to see already some small non conformities in advance. This allows a timely feedback to all involved parties whether just for acknowledgement or for reaction.

11. Robustness Indicator Figure (RIF)

11.1 Meaning and Need for a Robustness Indicator

Only if the robustness of an EEM is measured, is it possible to express the robustness in clear figures and to compare different designs or different suppliers. Otherwise, robustness would just be a diffuse definition. In general, robustness can be understood with the P-Diagram in Figure 35.

FIGURE 35 - Robustness P-Diagram



Noise factors for automotive products are represented by typical (environmental) stress factors like vibration, humidity or temperature. Furthermore, noises during the production (noises in soldering process or testing processes) can be taken into account.

Because robustness is defined to be the difference between the limits of the design or the product and the Mission Profile or the specification requirement, this difference shall be used to generate the RIF.

$$RIF = \frac{\text{estimated strenght}}{\text{required spec}}$$

- **estimated strength** = measured or calculated value of the item being considered, e.g. time to failure, CpK, Failure level, ect.
- **required spec.** = requirement value based on Mission Profile or specification, which can also be associated with certain failure level criteria's (e.g. 10 years with 1% accumulated failure level).
- **estimated strength** and **required spec.** should be compared at the same conditions (e.g. temperature and agreed failure level), for which models are often needed.

11.2 RIF Diagram

To visualize and report on the robustness figures a collection of RIFs can be represented by a Spider diagram with the Parameters being measured on each axis and with the Missions Profile and Actual EEM Performance for the parameter plotted on the relevant axis. The points for the Mission Profiles from each axis can then be joined to represent the Mission Profile for the parameter set (the red area) and the EEM measured performance point of the axis' can be joined to visualize the actual EEM performance for the set of parameters (blue Area), see Figure 36 and Figure 37.

The RIF Diagram uses a Radar, Spider or Kiviat Diagram. This chart is available in MS Excel however MS Excel allows only a single scale for the all the axes, other diagraming tools are available as well as add-ins for Excel which allow difference scales for each axis.

FIGURE 36 - Rif Plot for Capability Tests
 (Scale linear, with dimension e.g. °C, V)

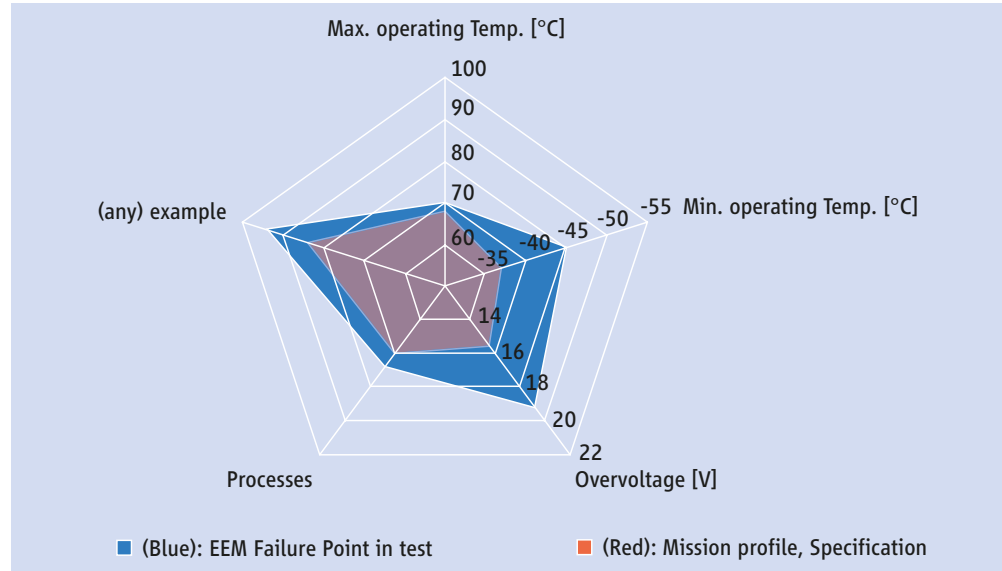


FIGURE 37 - Rif Plot for Durability Test
 (Scale linear, related to specified test time of each stress test, without dimension, calculated according to acceleration models)

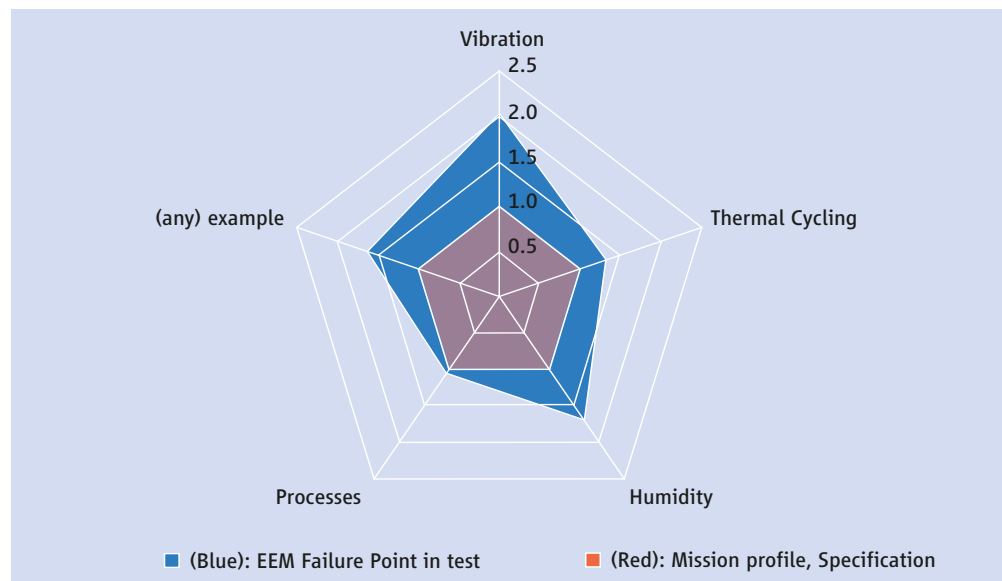
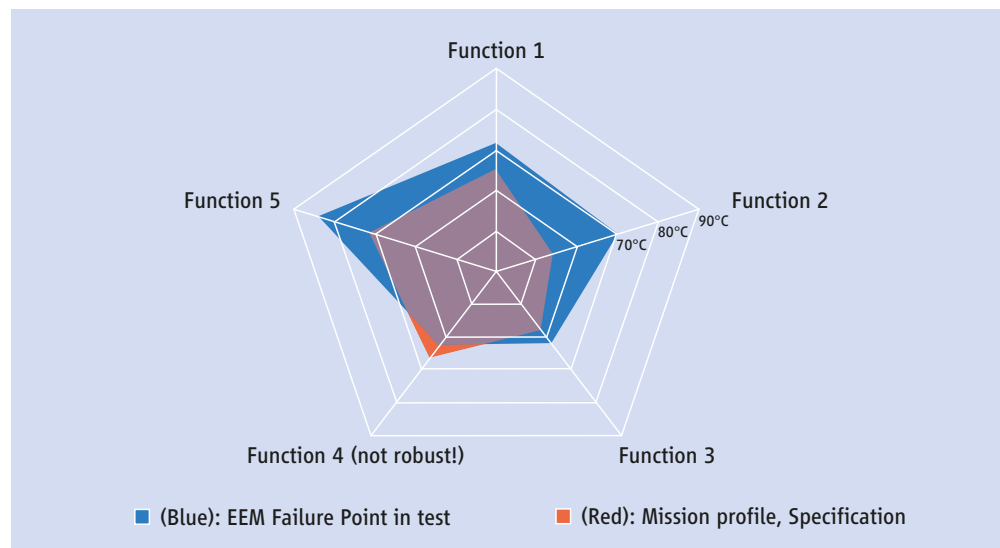


FIGURE 38 - Alternative/Additional Rif Plot for Different Functions
 (A DUT under one defined environmental stress e.g. temperature)



An example for functions of an Infotainment System radio, phone, CD/DVD, MP3, TV, Bluetooth etc. is shown in Figure 38.

Note, that the scale is arbitrary, and because Function 4 does not even cover the Mission Profile, the DUT is not robust!

11.3 Instructions for Generating a RIF

The RIF can be calculated for every category/every (reliability) influence factor such as Vibration, Thermal Cycling, Humidity, Processes or Intelligent Testing.

It is not useful to generate a RIF for "soft factors" like "communication".

If test data (e.g. from vibration test) are used to generate a RIF, then the first DUT, which fails in the test shall be taken to calculate the RIF.

In the determination of RIF, statistical considerations are not included. The DUTs used for testing shall be regarded as to be built with stable and controlled processes. Therefore, it is NOT necessary to test a statistical number of DUTs (e.g. 30) to determine the RIF. If test data (e.g. Vibration test) are used to generate a RIF, then typically one, two or three DUTs shall be tested.

Some examples of the most important RIFs are shown in this guideline. To add additional, product-specific RIFs, the calculation can be done according to the „General instruction for generating a RIF“ as follows.

A RIF shall be determined for:

- Capability testing/functional limits.
- Durability testing/destruction limit.

It is important to note, that in some cases, the Software of a DUT protects the Hardware in severe conditions by shutting off the DUT or parts/functions of the DUT. Therefore, such a Software-Function can influence or affect the determination of the RIF.

RIF-Plot:

For better visualization, the single RIFs can be shown in a RIF-Plot or different RIF-Plots, see RIF Figure 36, Figure 37 and Figure 38.

11.4 Generation of RIF RIF for Durability Testing

Durability Testing means the ability of a DUT to meet a defined requirement with consideration of durability items e.g. the capability to meet a requirement during the whole specified lifetime. For example, if a DUT is required to work at maximum temperature for 1,500 h but a failure occurs at 1,250 h, then the robustness is not sufficient.

11.4.1 RIF_{ARR} for Durability Testing with the Arrhenius-Model

For situations, where the Arrhenius model can be applied (e.g. high temperature tests, lifetime tests with constant temperature, etc.), it is necessary to compare different temperature conditions. The formula is:

$$\pi_B = e^{(E_A \cdot TF)} \quad (\text{Eq. 1})$$

with:

- E_A: Activation Energy [eV]
(eV: Electron Volt) (example: 0.44 eV)
- TF: Temperature Factor
- π_B: Acceleration Factor

$$TF = 1 / k [(1 / T_1) - (1 / T_2)]$$

with:

- k: Boltzmann Constant
- T₁: First temperature
- T₂: Second temperature

EXAMPLE:

Calculation of RIF_{ARR}

| | |
|--------------------------------------------------------------|--------------|
| Max. temperature according to the specification: | 85°C (358 K) |
| Test temperature (moderate accelerated conditions): | 95°C (368 K) |
| Required Test time (at 85°C) according to the specification: | 1,500 h |
| Failure at accelerated condition (95°C) occurs: | 1,963 h |

$$TF = 11,604.8 \text{ K} / \text{eV} [(1 / 358 \text{ K}) - (1 / 368 \text{ K})]$$
$$TF = 0.88$$

then:

$$\pi_B = e^{(E_A \cdot TF)}$$
$$\pi_B = e^{(0.44 \text{ eV} \cdot 0.88)}$$
$$\pi_B = 1.47$$
$$RIF_{ARR} = 1,963 \text{ h} \cdot \pi_B / 1,500 \text{ h} = 1.93$$

11.4.2 RIF_{CM} for Durability Testing with the Coffin-Manson-Model

For situations where the Coffin-Manson model can be applied (e.g. temperature cycling/temperature shock tests)

$$N_1 / N_2 = (\Delta T_2 / \Delta T_1)^k \quad (\text{Eq. 2})$$

with:

- N₁: Number of temperature cycles until defect at stress level according to specification
- N₂: Number of temperature cycles until defect at stress level in accelerated test
- ΔT₁: Temperature stroke at stress level according to specification
- ΔT₂: Temperature stroke at stress level in accelerated test
- k: Material constant

Note:

*k is dependent on the materials. It shall be determined in fundamental tests depending on the technology, used in the DUT.
See Table 8 next page for guidelines.*

TABLE 8 - Low Cycle Thermal Fatigue Coffin-Manson Model Exponent k (Eq. 2)

| Low Cycle Thermal Fatigue Coffin-Manson Model Exponent | | | |
|--------------------------------------------------------|----------------------|-------------------------------------------|----------------------------------------------------------------------------|
| Component Type | Structural | Complex Electronic with Lead Based Solder | Complex Electronic with Lead Free Solder |
| k Range | 3 - 25 ¹⁾ | 2 - 3 ²⁾ | 2 - 3 ²⁾ |
| Typical Recommended Value for k | 10 | 2.5 | 2.65 ³⁾ Use Modified Norris Landzberg for Temperatures > 100 °C |

Table Notes:

- 1) For structural materials based upon fatigue failure distributions from rotating beam specimen data.
- 2) Based upon time equivalence for observed thermal fatigue related failure modes.
- 3) It is recommended to use Coffin-Manson only up to 100°C max. temperature on solder joint.

It should be applied, if temperature level in the solder joint could achieve temperatures > 100°C.

Modified Norris-Landzberg Model:

$$N_1 / N_2 = (\Delta T_2 / \Delta T_1)^{k1} \cdot (t_2 / t_1)^{k2} \cdot \exp [k3 \cdot (1 / T_{1, \max} - 1 / T_{2, \max})] \quad (\text{Eq. 3})$$

t_x: Duration time at upper temperature level

T_{x, max}: Upper temperature level

with:

Factors for typical lead free eutectic solder SnAgCu

k1 = 0.6, k2 = 0.4, k3 = 4,800 K

Reference: H. Ehrhard, R. Becker, Th. Rupp, J. Wolff: Mission Profile and the reliability of lead free control units, VDI Report No 2000, 2007

EXAMPLE:Calculation of RIF_{CM} Temperature stroke according to the specification: $\Delta T_1 = -40^\circ\text{C} / +70^\circ\text{C}$ (110 K)Temperature stroke according accelerated conditions: $\Delta T_2 = -40^\circ\text{C} / +90^\circ\text{C}$ (130 K)Required number of cycles according to the specification: $N_3 = 200$ Failure at accelerated condition occurs: $N_2 = 325$ $K = 2$

$$N_1 = N_2 (\Delta T_2 / \Delta T_1)^k$$

$$N_1 = 325 [(130 \text{ K})^2 / (110 \text{ K})^2]$$

$$N_1 = 454$$

$$RIF_{CM} = N_1 / N_3$$

$$RIF_{CM} = 454 / 200$$

$$RIF_{CM} = 2.27$$

11.4.3 RIF_{LAW} for Durability Testing

The Lawson Model is used for the humidity enhanced corrosion failure mechanism, Lawson Model defines the acceleration factor due to the combined effects of high temperature and relative humidity. In situations, where the Lawson-Model can be applied e.g. High-Humidity-High-Temperature (HHHT-Tests), use the following equation:

$$A_{t/RH} = A_t \cdot A_{RH} = e^{[-(\frac{E_A}{k})(\frac{1}{T_1} - \frac{1}{T_2})] + b [(RH_1)^2 - (RH_2)^2]} \quad (\text{Eq. 4})$$

where:

$A_{t/RH}$ Combined acceleration factor of the Lawson Model considering temperature (T) and relative humidity (RH)

A_t Acceleration factor due to temperature

A_{RH} Acceleration factor due to relative humidity

b Constant ($b = 5.57 \times 10^{-4}$)

E_A Activation energy ($E_A = 0.4 \text{ eV}$)

k Boltzmann constant ($k = 8,617 \times 10^{-5} \text{ eV / K}$)

T_i Absolute Kelvin temperature [K]: $i = 1$ for test condition, and $i = 2$ for field conditions

RH_i Relative humidity [%]; $i = 1$ for test condition, and $i = 2$ for field condition

Note:

Generally, the values for the activation energies used in the Lawson Model and the Arrhenius Model are different, since both models describe completely different failure mechanisms.

The total test duration for HHHT test is calculated by:

$$t_{HHHT} = t_{non \text{ op. time}} / A_{t/RH} \quad (\text{Eq. 5})$$

where:

t_{HHHT} Test duration required for HHHT test

$t_{non \text{ op. time}}$ Non-Operating Time during service life in field (see Mission Profile)

$A_{t/RH}$ Combined acceleration factor of the Lawson model according

EXAMPLE:Calculation of RIF_{HHHT}

For an EEM located in the under-hood compartment and having a Service Life in Field of 10 years, the RIF_{HHHT} is calculated as shown below:

- A component is mounted outside the passenger cabin or trunk.
- The average temperature during Non-Operating Time is defined in the Mission Profile to be $T_2 = 23^\circ\text{C} / 296 \text{ K}$ and the average relative humidity is $RH_2 = 65\%$ (example, according to Mission Profile).
- Test conditions for HHTH-test are $T_1 = 85^\circ\text{C} / 358 \text{ K}$ and $RH_1 = 85\%$
- Application of Lawson's-equation with these values results in a combined acceleration factor of the Lawson of $A_{t/RH} = 80.4$.
- From the Mission Profile, the components Non-Operating Time during 10 years Service Life in Field is $T_{\text{non op. time}} = 79,600 \text{ h}$.
- The DUT in the accelerated test ($T_1 = 85^\circ\text{C} / 358 \text{ K}$ and $RH_1 = 85\%$) shows a failure after 1,200 h.

then:

$$RIF_{LAW} = 1,200 \text{ h } A_{t/RH} / T_{\text{non op. time}} \quad (\text{Eq. 6})$$

$$RIF_{LAW} = 1,200 \text{ h } 80.4 / 79,600 \text{ h}$$

$$RIF_{LAW} = 1.21$$

11.4.4 RIF_{VIB} for Vibration-Testing

$$RIF_{VIB} = T_0 / T_2 \quad (\text{Eq. 7})$$

$$T_0 = T_1 / (a_0 / a_1)^M$$

with:

a_0 =Power spectral density or sinusoidal acceleration (g peak)
until defect at stress level according to specification

a_1 =Power spectral density or sinusoidal acceleration (g peak)
until defect at accelerated stress level

T_1 =Time until defect at stress level according to specification

T_2 =Time until defect at stress level at accelerated test

1 / M: Material constant

For the Value of M please see Table 9 next page:

Please note, this table shows typical value to be used, the Robustness Validation Users should review their application of Robustness Validation and determine the best value of M to use in their own circumstances and document the value used.

TABLE 9 - Vibration Damage Equivalence Equation Exponent M (Eq. 7)

| | Vibration Damage Equivalence Equation Exponent | | | | | |
|------------------------------------------------------------------------|------------------------------------------------|----------------------|-----------------------|-------------------------|-----------------------|-------------------------|
| Vibration Type | Sine | Complex Periodic | Random | Random | Random | Random |
| Hardware Type | All | All | Simple Structures | Simple Structures | Complex Electronic | Complex Electronic |
| Units | Peak G | Peak G | RMS G | PSD G ² / Hz | RMS G | PSD G ² / Hz |
| M Range | 5 to 20 ¹⁾ | 5 - 20 ¹⁾ | 5 to 20 ¹⁾ | 2.5 to 10 ¹⁾ | 4 to 13 ²⁾ | 2 to 6.6 ²⁾ |
| Typical Most Conservative Recommended Value for M^{2/3} | 6 | 8 | 8 | 4 | 4 | 2 |

Table Notes see ref [6] and [7]

- 1) For structural materials based upon fatigue failure distributions from rotating beam specimen data with damping considerations.
- 2) Based upon time equivalence for observed vibration related failure modes.
- 3) Stress concentrations and high application stresses reduce the usable range of M.
- 4) Failure mode correlations should dictate the M value chosen.

EXAMPLE:

Calculation of RIF_{VIB}

Acceleration according Specification: $a_0 = 2.79 G_{rms}$
 Acceleration according Accelerated Condition: $a_1 = 3.81 G_{rms}$
 Required Duration according Specification: $T_2 = 24 h$
 Failure at accelerated Condition Occurs: $T_1 = 14 h$
 $M = 4.0$ (Electronic board)
 $T_0 = T_1 / (a_0 / a_1)^M$
 $T_0 = 14 h / (2.79 g / 3.81 g)^{4.0}$
 $T_0 = 48.7 h$
 $RIF_{VIB} = T_0 / T_2$
 $RIF_{VIB} = 48.7 h / 24 h$
 $RIF_{VIB} = 2.03$

11.4.5 RIF in Case of Step-Stress Testing

11.4.5.1 Vibration Step Stress Testing

If a vibration step-stress test is applied: then to determine the limits of the design / the DUT, the test condition (G_{rms} level) is increased in steps (e.g. one hour each step, 3 dB increase each step) until the first fatigue failure appears. This facilitates reaching the limits of the design in a short test time. In this case, the miner accumulation rule for fatigue damage can be applied.

Miner accumulation rule for fatigue damage:

Every Damage $D_1 = n_1 / N_1$, $D_2 = n_2 / N_2$ is accumulated to the total stress for the DUT.

with:

n_1 : Number of load cycles OR duration of test at stress level 1

N_1 : Number of load cycles OR duration of test till fatigue damage at stress level 1

Total Damage $D_{total} = \sum D_i = n_1 / N_1 + n_2 / N_2 + \dots + n_n / N_n$

Therefore, if a vibration step-stress test was performed, the formula in Section 11.4.4 shall be applied in this way:

$$T_0 = T_{11} / (a_{01} / a_{11})^m + T_{11} / (a_{02} / a_{12})^m + T_{13} / (a_{03} / a_{13})^m + \dots + T_{1n} / (a_{0n} / a_{1n})^m$$

$a_{01} \dots a_{0n}$: Acceleration levels at the different steps of the vibration-step test
 $T_{11} \dots T_{1n}$: Duration at the different steps of the vibration-step test

then:

$$RIF = T_0 / T_2 \quad (\text{see 11.4.1})$$

10.4.5.2 Humidity-Step-Stress-Testing

If a humidity step-stress test is applied, then to determine the limits of the design/the DUT, the test condition (humidity) is increased in steps (e.g. 10% RH each step, 12 h each step) until the first failure caused by humidity appears. This facilitates reaching the design limits in a short test time.

In this case, miner's accumulation rule for damage also can be applied (Note, that this is a new approach, not state of the art).

Miner's accumulation rule for damage:

Every Damage $D_1 = n_1 / N_1$, $D_2 = n_2 / N_2$ is accumulated to the total stress for the DUT.

with:

t_1 : Duration at humidity level 1

T_1 : Duration when humidity-caused failure occurs

Total Damage $D_{\text{total}} = \sum D_i = t_1 / T_1 + t_2 / T_2 + \dots$

Note:

Further examples of calculations are not given here, because to apply the miner-rule for damage for a step-humidity test is a new approach and not state of the art.

RIF for Capability Testing

Capability testing means the ability/capability of a DUT to meet a defined requirement without consideration of durability items. For example, the capability to meet a requirement concerning over voltage, max. or min. operating temperature. For example: if a DUT is required to work at -40°C, then the capability of the DUT shall be determined at what min. temperature the operation is according to specification. If a failure occurs at -35°C, then the robustness is not sufficient.

In capability testing, the durability aspect is not included. The durability/time influence is considered in the section „Durability Testing“.

EXAMPLE:

Calculation of RIF

Minimum operating voltage according Specification: $U_{\text{min } 2} = 9V$

Failure due to too low voltage in test occurs at: $U_{\text{min } 1} = 8.05V$

$$RIF = U_{\text{min } 2} / U_{\text{min } 1}$$

$$RIF = 9 V / 8.05 V$$

$$RIF = 1.12$$

RIF for Processes

11.4.6 Manufacturing Processes/Equipment Related

A DUT needs a defined number of manufacturing processes (component placing, soldering reflow, soldering SMD, ICT, final test...):

- The required CpK value shall be mutually agreed before.
- For each of the processes, a CpK value shall be determined according to the methods described in the Section 10.
- The RIF Processes for a single process is the CpK-value for this process.

EXAMPLE:

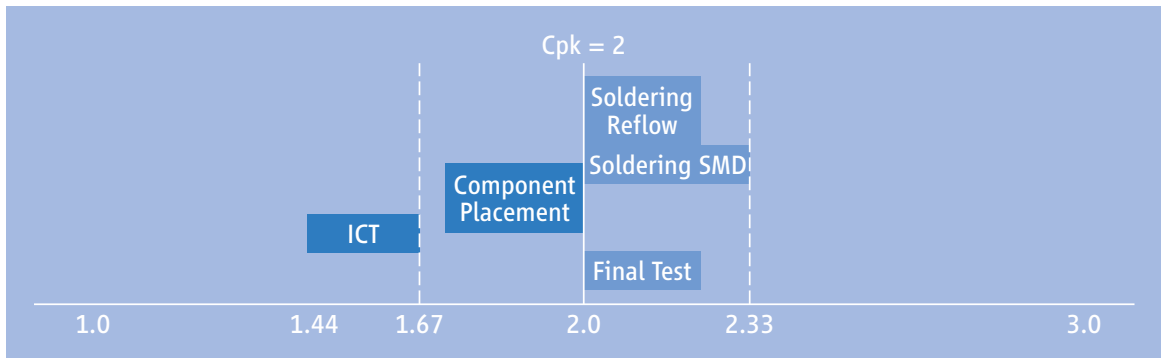
The required CpK for an in-circuit test to be robust was mutually agreed to be 2.0:

- The real CpK was determined to be $CpK = 1.44$.
- Then the RIF in circuit test = $1.44 / 2.0 = 0.72$ (and therefore not sufficient).

Example ranges of RIF figures for other manufacturing processes can be seen in Figure 39.

FIGURE 39 - Rif Plot for Processes:

Green, if the CpK is higher than the agreed value → robust!
Red, if the CpK is lower than the agreed value. → Not robust!



11.4.7 Monitoring Processes (Function Related)

- A DUT has characteristic functional values (key parameters) which shall be monitored with a monitoring process.
- For each type of DUT, the key parameters shall be determined according to the methods described in Section 10.
- These key parameters shall be monitored in the production line.
- These key parameters shall be shown as additional CpK-value.
- The monitoring parameters shall be visualized in a plot analogous to Figure 39 (only the variables are different.).
- The monitoring parameters shall be ranked according to the „importance number“ of this parameter in the FMEA.

EXAMPLE:

- The key parameter for the monitoring of an EEM was determined to be the slew rate of a signal.
- Because this key parameter has significant influence to the robustness of this product, it shall be evaluated in detail in the FMEA.
- The importance number for this signal in the FMEA was determined to be 6.
- The required CpK for this slew rate was mutually agreed to be 1.67.
- The real CpK for this slew rate was determined to $CpK = 1.83$.
- Then the RIF $\text{key parameter slew rate} = 1.83 / 1.67 = 1.10$.
- For the comparison of this RIF number with other RIF numbers of this product, the „importance value“ of the FMEA shall be considered.

Appendix A - Section Examples

A.1 Mission Profile

Example 1: Door Module

This example deals with a Standard EEM that is the controlling part of door systems. It connects to the car's power supply, to CAN-Bus and some actuators and sensors and is not necessarily complete.

Application Profile

The significant mechanical, climatic and chemical influences which impact on the component during its service life are summarized in the following application profile.

A.1.1 Door Module Service Life

| | |
|-----------------------------------|--------------|
| Service life in the field | 10 years |
| Mileage over the service life | 400,000 km |
| EEM on time | 8,000 hours |
| EEM off time (non operating time) | 79,600 hours |

A.1.2 Mounting Location of the Component

Inside the door, assembled on mechanical carrier

A.1.3 Environmental Loads

A.1.3.1 Climatic Stress (Temperature/Humidity)

| Operated in the vehicle (EEM on time) | Temperature profile ¹⁾ (Ambient temperature of the component at the mounting location ²⁾ | Temperature | Distribution |
|---------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|------------------------------|
| | | -40°C 23°C 60°C 80°C 85°C | 6% 65% 20% 8% 1% |
| | Humidity ³⁾ | Relative humidity up to 100% Condensation and icing | |
| Installed in the vehicle without operating (EEM non operating time) | Temperature | Minimum temperature: Maximum temperature: Typical temperature: | -40°C +85°C +23°C |
| | Humidity | Relative humidity up to 100%; Condensation and icing Mean 60% relative humidity ⁴⁾ Average temperature: +23°C | |
| Transportation | Temperature | Minimum temperature: Maximum temperature: | -50°C +95°C |
| | Transportation time | Max. 24 hrs. Uninterrupted at maximum temperature Max. 48 hrs. Uninterrupted at maximum temperature | |
| Storage ⁵⁾ | Temperature | Minimum temperature: Maximum temperature: | -10°C +55°C |
| | Storage time | 5 years | |
| | Humidity | Maximum 85% relative humidity | |

| | | |
|---------------------------------------------------------------|-------------------|----------------------------------------------------------|
| Long-term storage for after-series supply⁶⁾ | Temperature | Minimum temperature: -10°C Maximum temperature: +40°C |
| | Storage time | 15 years |
| | Humidity | Maximum 80% relative humidity |
| Temperature changes | Number | 7,300 temperature cycles over 10 years ⁷⁾ |
| | Temperature delta | Average: 34 K ⁸⁾ |

Remarks:

- 1) The temperature profile contains the assumed field load distribution world-wide (arctic- and hot climate). This distribution represents an envelope over typical use-cases.
- 2) $T_{\text{Vehicle Mounting Location Ambient}}$
- 3) In door.
- 4) Assumption similar to¹⁾.
- 5) Necessary storage time in the dealer's garage and additional in the centre of distribution.
- 6) Necessary storage time in the dealer's garage and additional in the centre of distribution.
- 7) In principle, every little temperature change experienced by the component during its Field Service Life in Years contributes to its total

thermo-mechanical stress. Despite this fact, only two large thermal cycles per day (for passenger cars) are usually sufficient to determine cumulative effect of thermo-mechanical stresses experienced by an E/E-component. Based on this assumption, the total Number of Temperature Cycles during Service Life in Field can be calculated by using a simple formula given below:

Number of Temperature Cycles during Service Life in Field = 2 * 365 * Service Life in Field.

- 8) Typical average temperature deltas based on field studies and engineering experience.

A.1.3.2 Dust/Water

| | |
|------------------|-----------------------------------|
| Water | Water drips (15° inclination) |
| Particles | Dust: smal particles, fine powder |

A.1.3.3 Chemical Stress/Resistance to Media

| | |
|--------------------------------|---------------------------------------------------------------------------------------------|
| Environmental influence | Salt fog atmosphere |
| Gaseous pollutions | Industrial climate (H ₂ S, NO ₂ , Cl ₂ , SO ₂) |

A.1.3.4 Mechanical Stress

| | | |
|---------------------|----------------------------|-----------------------------------------|
| Vibration | Random excitation | See below |
| Acceleration | Mechanical shock | Acceleration up to 500 m/s ² |
| | Mechanical shock endurance | 70,000 shocks driver door |

A.1.3.5 Random Vibration

| Vibration profile Random vibration | Frequency [Hz] | Power spectral density (PSD) [(m/s ²) ² /Hz] |
|---------------------------------------|------------------|---------------------------------------------------------------------|
| | 5 | 0.884 |
| | 10 | 20.0 |
| | 55 | 6.5 |
| | 180 | 0.25 |
| | 300 | 0.25 |
| | 360 | 0.14 |
| | 1,000 | 0.14 |
| | 2,000 | 0.14 |
| | RMS acceleration | 30.8 m/s ² |

Remarks:

Accelerated test condition, worst case field scenario envelope curve.

A.1.3.6 Transport/Storage/Crash/Assembly

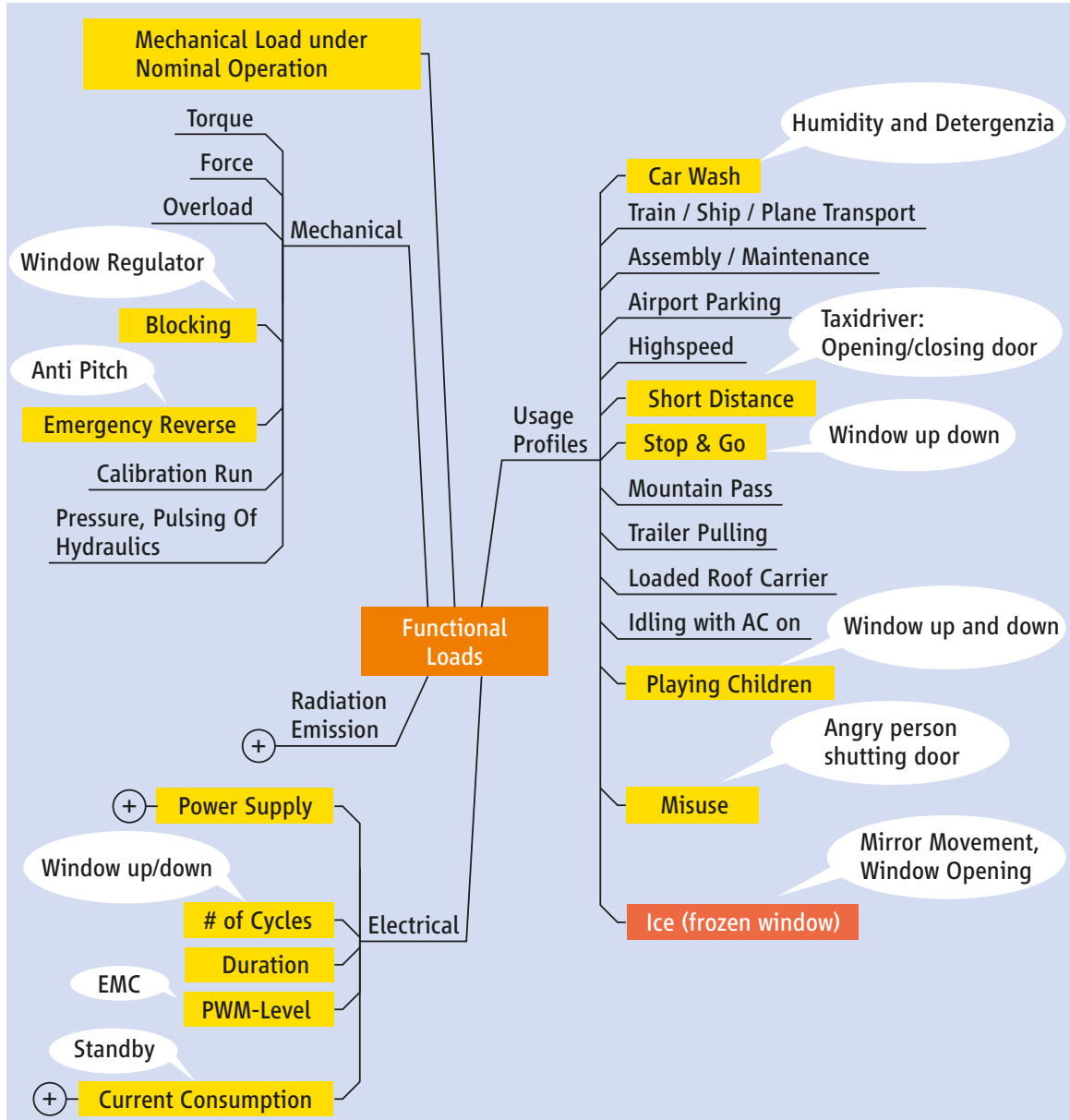
| | |
|---------------------------------|----------------------|
| Acceleration (single events) | Mechanical shock |
| | Drop (free fall 1 m) |

A.1.3.7 ESD

| | |
|------------------------------------------------------------|--------------------|
| OEM-Standards or ISO or IEC (worst case field scenario) | Up to +25 KV...ESD |
|------------------------------------------------------------|--------------------|

A.1.4 Relevant Functional Loads

FIGURE A1 - Tree Analysis Functional Loads Door Module



Note, that this assessment indicates relevant functional loads for a virtual product. Please check the relevance in detail for your design and application.

- Yellow: relevant load
- Red: additional relevant load
- Grey: load not relevant
- Bubble: comment

A.2 Mission Profile

Example 2: Mechatronic Transmission Control Module

This example deals with a mechatronic that is the controlling part of an automatic transmission system. It connects only to the car's power supply, to one CAN-Bus and to hydraulic lines of actuators. It contains hydraulic valves and an RPM-sensor.

Application Profile

The significant mechanical, climatic and chemical influences which impact on the component during its service life are summarized in the following application profile.

A.2.1 Transmission Service Life

| | |
|------------------------------------------|--------------------------|
| Service life in the field | 15 years |
| Mileage over the service life | 250,000 km ¹⁾ |
| EEM on time | 6,000 hours |
| EEM off time (non operating time) | 125,400 hours |

Remarks:

The service life time of the mechatronic is given by the mileage of the mechanical gearbox (limited by mechanical wear), which is 250,000 km.

A.2.2 Mounting Location of the Component

Bottom of gearbox, surrounded by oil

The connector is part of the gearbox outline

Remarks:

The mechatronic module itself is surrounded by oil (=chemical load), but the connector has contact to the medium outside.

A.2.3 Environmental Loads

A.2.3.1 Climatic Stress (Temperature/Humidity)

| | | | |
|----------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|------------------------------|
| Operated in the vehicle (EEM on time) | Temperature profile ¹⁾ (Ambient temperature of the component at the mounting location) ²⁾ | Temperature | Distribution |
| | | -40°C 23°C 100°C 130°C 140°C | 2% 18% 70% 9% 1% |
| | Humidity ³⁾ | Relative humidity up to 100% Condensation and icing | |
| Installed in the vehicle without operation (EEM non operating time) | Temperature | Minimum temperature: Maximum temperature: Typical temperature: | -40°C 140°C +23°C |
| | Humidity | Relative humidity up to 100%; Condensation and icing Mean 65% relative humidity ⁴⁾ | |
| Transportation | Temperature | Minimum temperature: Maximum temperature: | -50°C +95°C |
| | Transportation time | Max. 24 hrs. Uninterrupted at minimum temperature Max. 48 hrs. Uninterrupted at maximum temperature | |
| Storage⁵⁾ | Temperature | Minimum temperature: Maximum temperature: | -10°C +55°C |
| | Storage time | 5 years | |
| | Humidity | Maximum 85% relative humidity | |
| Long-term storage for after-series supply⁶⁾ | Temperature | Minimum temperature: Maximum temperature: | -10°C +40°C |
| | Storage time | 15 years | |
| | Humidity | Maximum 80% relative humidity | |
| Temperature changes | Number | 10,950 temperature cycles over 15 years ⁷⁾ | |
| | Temperature delta | Average: 70 K ⁸⁾ | |

Remarks:

- 1) The temperature profile contains the assumed field load distribution world-wide (arctic- and hot climate). This distribution represents an envelope over typical use-cases.
- 2) TVehicle Mounting Location Ambient: Oil temperature.
- 3) Only connector concerned.
- 4) Assumption similar to 1).
- 5) Necessary storage time in the dealer's garage and additional in the centre of distribution.
- 6) Necessary storage time in the dealer's garage and additional in the centre of distribution.
- 7) In principle, every little temperature change experienced by the component during its Field Service Life in Years contributes to its total thermo-mechanical stress. Despite this fact, only two large thermal cycles per day (for passenger cars) are usually sufficient to determine cumulative effect of thermo-mechanical stresses experienced by an E/E-component. Based on this assumption, the total Number of Temperature Cycles during Service Life in Field can be calculated by using a simple formula given below:
Number of Temperature Cycles during Service Life in Field = 2 * 365 * Service Life in Field.
- 8) Typical average temperature deltas based on field studies and engineering experience. Simplified estimation: 23°C + 70 K = 93°C; consistent to the temperature distribution maximum near 100°C.

A.2.3.2 Dust/Water

| | |
|------------------|-------------------------------------------------------------------------------------------------|
| Water | High-velocity water jet with increased pressure ¹⁾ |
| | Temporary immersion in water ¹⁾ |
| | Continuous submersion in water (e.g. water crossing and boat release maneuver) ¹⁾ |
| | High-pressure steam-jet cleaning ¹⁾ |
| Particles | Dust ¹⁾ |

Remarks:

1) Load (simplified Mission Profile)

A.2.3.3 Chemical Stress/Resistance to Media

| | | |
|--------------------------------|-------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| Environmental influence | Mechatronics | Connector |
| Media | Gear oil (= permanent 15a) | Salt fog atmosphere |
| Cleaning agents | | Differential lubricants, cold cleaner, car wash soap fluid, windshield washer, engine oil, gasoline, engine coolant, battery acid, engine cleaner |
| Gaseous pollutants | Atmosphere inside gear | Industrial climate (H ₂ S, NO ₂ , Cl ₂ , SO ₂) |

A.2.3.4 Mechanical Stress

A.2.3.5 Random and Sinusoidal Vibration

| Vibration profile Random vibration | Frequency [Hz] | Power spectral density (PSD) [(m/s ²) ² /Hz] |
|-------------------------------------------|------------------|------------------------------------------------------------------------|
| | 10 | 10.0 |
| | 100 | 10.0 |
| | 300 | 0.51 |
| | 500 | 5.0 |
| | 2,000 | 5.0 |
| | RMS acceleration | 96.6 m/s ² |
| Vibration profile Sinusoidal vibration | Frequency [Hz] | Amplitude of acceleration [m/s ²] |
| | 100 | 30.0 |
| | 200 | 60.0 |
| | 400 | 60.0 |

Remarks:

Accelerated test condition, worst case field scenario
envelope curve

A.2.3.6 Transport/Storage/Crash/Assembly

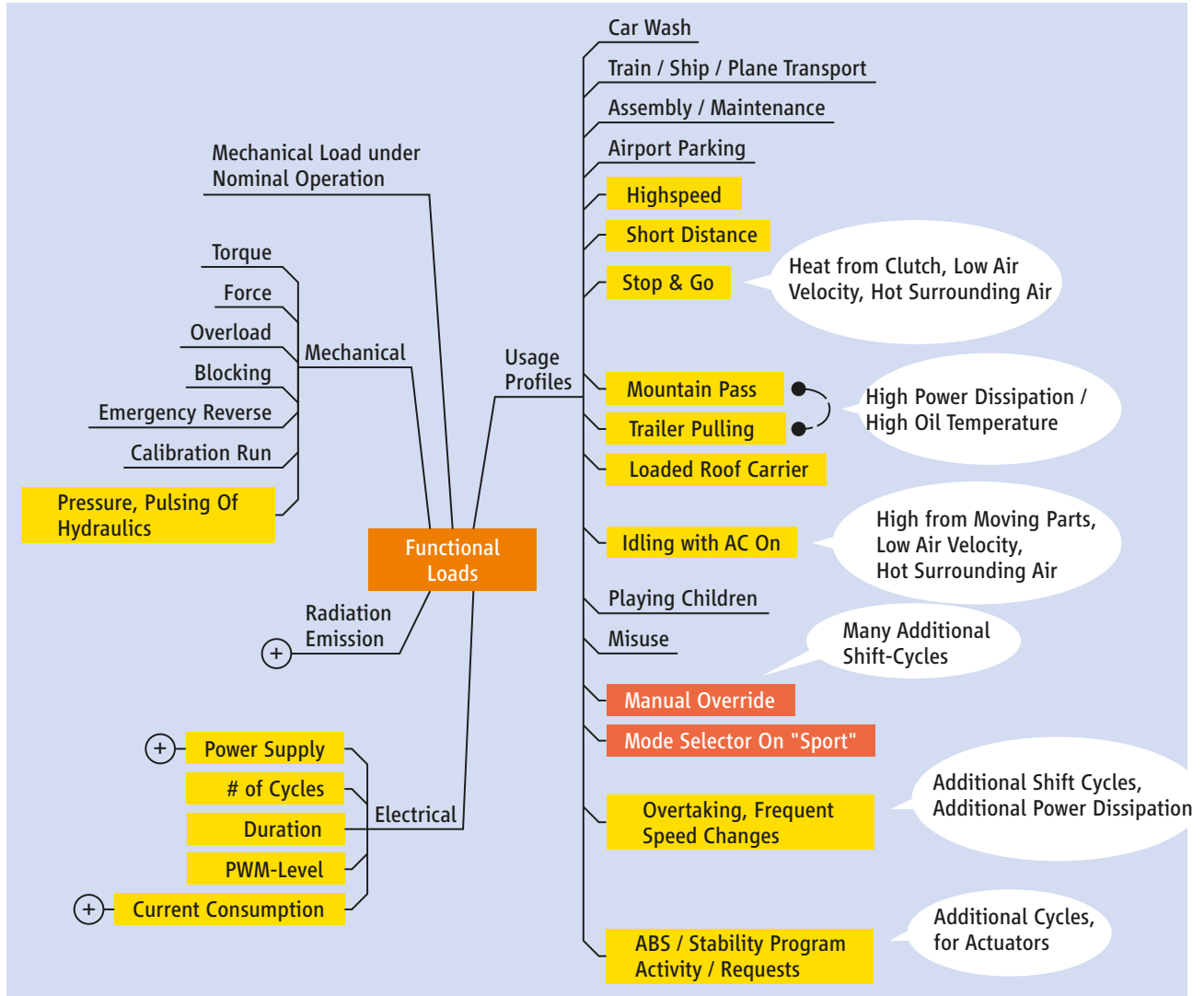
| | |
|---------------------------------|----------------------|
| Acceleration (single events) | Mechanical shock |
| | Drop (free fall 1 m) |

A.2.3.7 ESD

| | |
|------------------------------------------------------------|--------------------|
| OEM-Standards or ISO or IEC (worst case field scenario) | Up to +25 KV...ESD |
|------------------------------------------------------------|--------------------|

A.2.4 Relevant Functional Loads

FIGURE A2 - Tree Analysis Relevant Functional Loads for Transmission Control Module



Note, that this assessment indicates relevant functional loads for a virtual product. Please check the relevance in detail for your design and application.

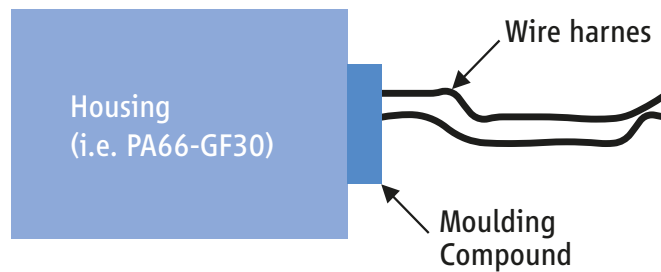
- Yellow: relevant load
- Red: additional relevant load
- Grey: load not relevant
- Bubble: comment

A.3 Knowledge Matrix Proactive

Example 1: Wire Harness Molded Connector Housing

An example for using the Knowledge Matrix during the design phase for Design FMEA is illustrated in this section. An EEM requiring a sealed interface at the entry point of the wire harness through the housing is shown in Figure A3. The process for using the Knowledge Matrix is given step by step.

FIGURE A3 - Illustration of Wire Harness Molded Into Module Housing



Step 1:
What is the Function?

The connector must have a stable and leak-free adhesion with the wire harness over the full lifetime of the vehicle.

Step 2:
Investigations in the Knowledge Matrix:

FIGURE A4 - Knowledge Matrix for Molded-In Wire Harness Example

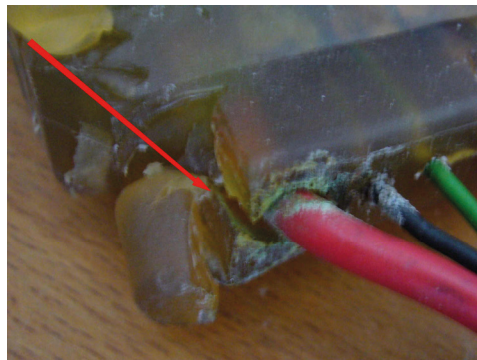
| 1a. Component Group | 1b. Component Sub Group | 1c. Technology Aspect | 1d. Assembly Aspect | 2. Robustness Aspect | 3. Product Life Phase | 4a. Failure Mode | 4b. Failure Cause | 4c. Failure Mechanism | 4d. F... |
|----------------------------------------------------------------------|------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|-------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|----------|
| Housing Interconnection Active Passive ElectroMechanical | Resistor Capacitor IC Transistor PCB Connector Inductor Diode | The Technology Aspect considered Metal or Plastic Clips Pufflow or Wave soldering Screwing into plastic of Metal | The Assembly Aspect considered Clipping Soldering Screwing Pivoting | The Robustness Characteristic considered What Aspect is Important for Reliability? What Characteristic defines the reliability of the Part? Mechanical Stability Inherent Fixing | Design Subsupplier Manufacturing OEM Assembly Customer Use | Effect by which a failure is observed to occur. | The specific process, design and/or environmental conditions that initiated the failure, and whose removal will eliminate the failure. | The specific process, by which physical, electrical, chemical and mechanical stresses act on materials to induce a failure. | |
| Housing | in wireharness | mechanical not protected | toped in | mechanical stability | Design | electrical damage | not ESD protected | ESD/EOS damage | |
| Housing | in wireharness | molding compound | moldet in | mechanical stability | Customer Use | molding compound breaks | no adhesion with isolation of the wire | function failure due to humidity in | |
| Housing | housing | Housing Geometry | in housing | mechanical stability | Design | componente break | warpage | because of warpage the housing component or housing break | |

- Complete the search in this way:
- 1a Main component group: Housing
 - 1b Component sub group: wire harness
 - 1c Technology aspect: molding compound
 - 1d Assembly aspect: molded in →
 - 2 Robustness aspects: mechanical stability
 - 3 Product life phase: customer use

- Find the three points, which can be used directly in the Design FMEA:
- 4a Failure mode: molding compound breaks
 - 4b Failure cause: no adhesion with isolation of the wire
 - 4c Failure mechanism: functional failure due to humidity ingress

Figure A5 shows an actual photograph of the failed wire harness connector housing. It would be recommended at this point to put this information in the Knowledge Matrix.

FIGURE A5 - Example of Delamination between Potting and Wire Harness



Step 3:

Columns 4a, 4b and 4c indicate a problem with this combination of material. This should be analysed further through the FMEA process.

→ Start of the FMEA procedure:

Deduced from the function → the malfunction = failure mechanism (see column 4c):

The connector will not have a stable and leak-free adhesion → Humidity ingress between wire harness and molding compound.

Failure mode (see column 4a):

Molding compound breaks.

Failure cause (see column 4b):

Insufficient adhesion between molding compound and isolation of wire harness.

Calculation of the RPN = O * S * D

(RPN = Risk Priority Number; O = Occurrence; S = Severity; D = Detection)

(With previously mentioned may be a problematic design).

For this example the following values are given:

Occurrence: O = 8 (very high)

Severity: S = 7 (high, risk of corrosion of wire and electronic damage)

Detection: D = 5 (medium)

RPN = O * S * D = 8 * 7 * 5 = 280! → Since the specified target is RPN_{target} ≤ 70

The RPN is too high! A redesign is necessary!

Step 4:

Redesign

A different mould compound should be used, for example polyurethane.

A further investigation using the Knowledge Matrix is desired:

It shows that no problems are known with this coupling of materials and the defined Mission Profile.

A new calculation leads to that: O = 2 (low).

RPN = 2 * 7 * 5 = 70

Conclusion → the design can now be released for further design steps and basic tests.

A.4 Knowledge Matrix Proactive

Example 2: PCB Electro-Chemical Migration

Step 1:

What is the Function?

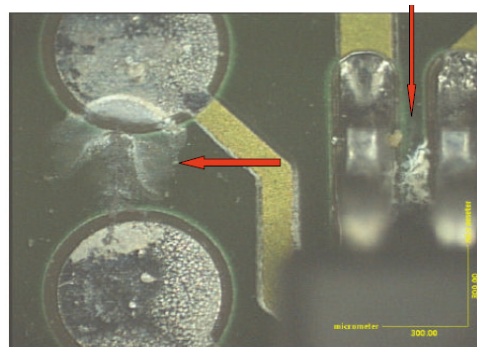
Prevent electro-chemical migration short circuits between circuit traces, pad and components to maintain electrical isolation.

Step 2:

Investigations in the Knowledge Matrix:

- Column 1a component group: Interconnection.
- Column 1b component sub group: PCB.
- Column 4c failure mechanism: Electro-chemical migration.
- Review column 4b failure causes.
- Failures can be prevented by sufficient solder mask coverage, enough distance between tracks...
- Contact PCB supplier and specify values to achieve best quality.

FIGURE A6 - Example of Electro-Chemical Short Circuits on Circuit Board



A.5 Knowledge Matrix Reactive

Example 1: PCB Electro Migration

Step 1:

4a failure mode: Reduced resistance (noticed in current consumption).

Step 2:

4c failure mechanism: Electro chemical migration (noticed during visual inspection).

Step 3:

1a component group: Interconnection.

Step 4:

1b component sub group: PCB.

Step 5:

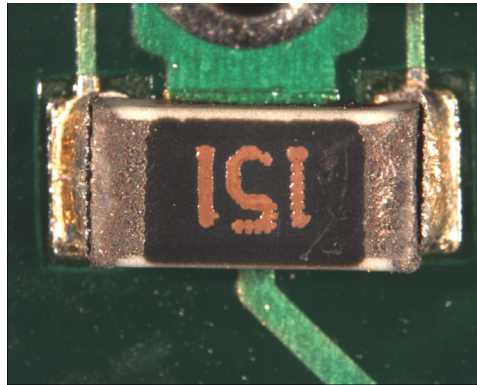
4b failure causes review (e.g. less track distance, less solder mask thickness...).

A.6 Knowledge Matrix Reactive

Example 2: Component Overload

Failure description - Resistor correctly soldered but early life solder joint failure causes product to fail. Product passed all product release specification testing but parts started to fail after 3 months in service.

FIGURE A7 - EEM Component Groups



Step 1:

Filter Knowledge Matrix for Component Group and Sub Group in columns 1a and 1b:

- In this case the failure is with the solder joint rather than the resistor as the resistor is fully functioning.
- Filter Knowledge Matrix for Component Group - Interconnection in column 1a.
- Filter Knowledge Matrix for Component Sub Group - PCB in column 1b.

Step 2:

Filter on Failure Mode - Open Circuit Solder Joint in column 4a:

- This yields a list of 6 potential failure causes in the example Knowledge Matrix see table below. Depending on the users experiences and history there may be more if the user Knowledge Matrix has been kept up to date.

| |
|---------------------|
| Current Load |
| Thermal Cycling |
| Mechanical Load |
| Insufficient Solder |
| Wettability |

- In this case the wettability and the insufficient solder causes can be eliminated as there it is clear from the photo that there was good wettability and sufficient solder.

Step 3:

Use the remaining list of potential causes to plan your failure investigation.

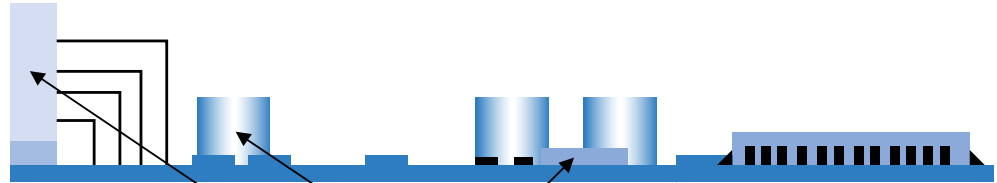
In this case, the failure was a result of excessive thermal cycling of the solder joint due to the current driven through the resistor by the controlling software and the insufficient dissipation of the thermal load from the PCB layout. This resulted in the earlier than expected failure of the solder joints as they aged at a significantly higher rate than normally expected for a solder joint due to continuous higher than normal thermal loading.

A.7 CPI Matrix Example

How to use the given matrix as a personalized tool:

EXAMPLE:

CPI Matrix file



Component groups connector, passive, active, PCB

Process flow

Solder paste printing → Component placement
→ Reflow soldering → Test → Final assembly.

Matrix development

- a. Start with the "Original Selection Table" and make a full copy for the new project. To create the personalized matrix, select with a cross in the "Selection Table" the used sub groups and attributes. In the example shown below not all possible or necessary attributes have been selected.

Sort

| Mark with x for selection for assessment | Group | Sub group | Attribute |
|------------------------------------------|-----------|----------------------------------|--------------------------------------|
| x | Component | Passive components | Substrate (mechanical stability) -PC |
| x | Component | Passive components | Termination - PC |
| | Component | Passive components | coplanarity - PC |
| | Component | Passive components | Body form / housing - PC |
| x | Component | Passive components | Wetability - PC |
| | Component | Passive components | Solderability - PC |
| | Component | Passive components | Processing thermal profile - PC |
| | Component | Passive components | contamination - PC |
| | Component | | |
| | Component | Active components (non-hermetic) | Body form / housing - ACnh |
| | Component | Active components (non-hermetic) | Termination / Lead- Acnh |
| x | Component | Active components (non-hermetic) | coplanarity (package warpage)- Acnh |
| | Component | Active components (non-hermetic) | Substrate - Acnh |
| | Component | Active components (non-hermetic) | Wetability - Acnh |
| x | Component | Active components (non-hermetic) | Solderability- Acnh |
| | Component | Active components (non-hermetic) | Processing thermal profile- Acnh |

After the selection, please press the sort button to sequence the used or chosen groups. If the security level for macros is high, this must be set to the lowest level.

(Please check in Excel: Extras - Macro - Security)

Copy then the full content of crossed lines (columns B, C, D).

Sort

| Mark with x for selection for assessment | Group | Sub group | Attribute |
|------------------------------------------|-----------|--------------------------------------|-----------------------------------------------|
| x | Component | Active components (non-hermetic) | coplanarity (package warpage)- Acnh |
| x | Component | Active components (non-hermetic) | Solderability- Acnh |
| x | Component | Active components (non-hermetic) | Moisture sensitivity- Acnh |
| x | Component | Connectors | termination material (contact resistance) - C |
| x | Component | Connectors | plastic material - C |
| x | Component | Connectors | retention force - C |
| x | Component | Consumables | Solder paste - Cons |
| x | Component | Consumables | Flux material - Cons |
| x | Component | Passive components | Substrate (mechanical stability) -PC |
| x | Component | Passive components | Termination - PC |
| x | Component | Passive components | Wetability - PC |
| x | Component | PCB | surface finish - PCB |
| x | Component | PCB | substrate material - PCB |
| x | Component | PCB | pad design - PCB |
| x | Process | AOI pre reflow | Camera resolution |
| x | Process | AOI pre reflow | Camera angle |
| x | Process | Component placement (automatic) | placement force |
| x | Process | Component placement (automatic) | component size / weight |
| x | Process | FCT | Contact force |
| x | Process | FCT | Warpage |
| x | Process | PCB / Component handling | ESD - comp-hand |
| x | Process | Reflow soldering (convectional oven) | Temperature profile in general |
| x | Process | Reflow soldering (convectional oven) | Temperature ramprates |

Sorting of the Matrix

Before sorting the matrix, first a copy of the assessed matrix should be saved. After sorting the list undo is not possible.

After the backup press the button sort. The list will be sorted and marked with the 80/20 rule.

| CPI-Matrix Date: 2007-xx-xx | | Sort copy row | | Sub group | | | | | | | | | | | | | | | | |
|--------------------------------|--------------------------------------|-------------------------------------|--|------------------------|-----------|-----------------------------|--------------------|----------------------------------|----------------------------------|----------------------------------|------------|------------|------------|-------------|-------------|--------------------|--------------------|--------------------|-----|---|
| Requirements | | Ranking: 0 to 3 | | Weighting factor (1-3) | Attribute | A accumulation of line sums | Special Assessment | Active components (non-hermetic) | Active components (non-hermetic) | Active components (non-hermetic) | Connectors | Connectors | Connectors | Consumables | Consumables | Passive components | Passive components | Passive components | PCB | |
| | | Weighting factor (1-3) | | 20 | 371 | 74.1 | | | | | | | | | | | | | | |
| Sub group | | Attribute | | | | | | | | | | | | | | | | | | |
| Component | PCB | surface finish - PCB | | 1 | 21.2 | 0 | 2 | 0 | 3 | 0 | 1 | 0 | 0 | 3.1 | 3 | 0 | 1 | 3.1 | 0 | 0 |
| Component | Active components (non-hermetic) | coplanarity (package warpage)- Acnh | | 3 | 12.3 | 0 | 1 | 0 | 3.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Process | Reflow soldering (convectional oven) | Temperature profile in general | | 3 | 57.0 | 57 | 0 | 3 | 0 | 3 | 0 | 0 | 2 | 2 | 0 | 1 | 0 | 1 | 0 | 1 |
| Component | Consumables | Solder paste - Cons | | 2 | 42.0 | 99 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 2 | 2 | 1 | 1 |
| Component | Active components (non-hermetic) | Solderability- Acnh | | 3 | 39.0 | 138 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Component | Consumables | Flux material - Cons | | 2 | 34.0 | 172 | 0 | 0 | 3 | 0 | 0 | 0 | 2 | 0 | 0 | 1 | 2 | 0 | 0 | 0 |
| Component | PCB | pad design - PCB | | 3 | 30.0 | 202 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Process | Reflow soldering (convectional oven) | temperature ramp rates | | 2 | 24.0 | 228 | 0 | 0 | 2 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 2 | 0 | 0 | 0 |

Assessment and Data/Information

Details of the results are:

- Sum of characteristics 371.
- 20% of 371: 74.1.
- 20% marked in green with the special assessment.
- For the special assessment there is the surface finish with two special interactions (solder paste and wettability) and the coplanarity with one (solderability). Without special assessment the coplanarity would now appear at the top of the matrix, because the sum of the attributes is only 12.3.
- Main interest should be to check the interactions of surface finish, coplanarity and temperature profile in general.

Process Robustness (Reflow Soldering)

Let us consider Pb-free reflow soldering as an example for process robustness.

This is not a detailed text book but just an overview of the multiple traps to be considered, when striving for process robustness.

Process Boundary Conditions for SAC-Type Soldering Leads Plated with Sn 100 In Mainstream Convection Oven

Approaching from the solder process, we encounter the following, fixed boundary conditions:

Nearly on a worldwide base, SAC (SnAgCu) type solders have become quasi standard, especially for all non-consumer PCBs, gradually including automotive now with their rigorous reliability targets.

These SAC solders have a liquidus of 217°C to 221°C. For safe and reliable soldering, sufficient wetting and solderability have to be assured even with no-clean solder fluxes. From years of experience, the minimum temperature to be reached at all solder joints has to be Tliquidus plus 10 K to 15 K. Therefore, a minimum peak lead temperature of around 230°C has to be reached by all solder joints. Also, the time at this temperature has to be long enough for complete wetting of the solder with the lead plating, again for all solder joints.

Due to vast differences in thermal mass of the components (from smallest chip resistors to large TO-220 packs or other big passive components, the difference in peak package tem-

peratures (PPT) and thus lead temperatures, is considerable. PPT is reached much later by big parts compared to small parts and the time at PPT minus 5 K is grossly different.

| Parameter | Smallest Part, PCB Surface | Big Components, Large Solder Joints |
|--------------------------|----------------------------|-------------------------------------|
| Peak Package Temperature | PPT plus up to 25 K | PPT |
| Time at PPT minus 5 K | t_{min} plus up to 30 s | t_{min} (approx. 10 s needed) |
| Delay to reach PPT | 0 | up to 25 s |

Since this is controlled by the laws of thermodynamics, not much can be done about them. One last resource would be using head shields for small parts - but is it practicable?

As we are locked into these boundary conditions, the components have to take the onslaught of the adverse process environment. That brings us to process capability of components for Pb-free soldering.

Process Capability of Components for Pb-free Soldering

Two properties need to be remembered regarding Pb-free soldering:

First, the components have to be compliant with Europe, China and other regions' RoHS. This is assured by the materials used for the components. Most components have no compliance problem - if not, they may fall under the 30 exceptions or so of the European RoHS.

Second, and this is a veritable Pandora's Box, the components have to be compatible to Pb-free soldering. Compatible means to be capable to endure the solder process without any loss of reliability. In other words, they have to offer the needed process robustness.

For soldering, the adequate stress test is laid down as JEDEC-J-STD 020D. It can be called an MSL classification test and it defines solder profiles for small and large parts which classify the limit between supplier guarantee and actual usage.

Process Robustness against Pb-free Soldering

Robustness of non-hermetic semiconductor components.

In ranking of importance, we have the following stressors during wave and reflow soldering: Package Peak Temperature (PPT). Its primary impact is the weakening of the adhesion of the mould compound (for the usual non-hermetic components) to the die surface, die sidewalls and the lead frame. Loss of adhesion results in delamination. This can be a gap of just a few microns, yet it offers an inroad for moisture - as can be proven by fluorescent dye penetration. Once humidity has penetrated, in conjunction with leached out ionic impurities, corrosion of the die metal structures raises its ugly head, especially under "cold" reverse bias. Delamination also will locally increase the thermal resistance die to ambient, which may be detrimental for power devices driven at the edge of their specification, as is usual design practice and as is promoted by the suppliers.

The so-called time at PPT minus 5 K is a measure of the hottest time during soldering. It also has an influence on delamination, although to a lesser degree as PPT itself. For SOIC-type packages, if there is delamination, it will be present already after less than 10 s and will not change significantly for longer times up to 60 s. Excessive times at hot will eventually change the mould compounds from a glassy to a rubbery state - if PPT gets close to or exceeds the glass transition temperature. This is nearly always the case during SAC soldering.

Finally, we have the temperature ramps-plus and minus dT/dt -given by the solder profile. These have a very weak influence on the integrity of the components as long as one stays below the 6 K/s ramps of the JEDEC J-STD-020D classification profile.

But the cooling rate has a definite influence on the robustness (crystal structure) of the solder joints!

Robustness of Printed Circuit Boards, PCBs

It is not much in focus, but it can well be that the reliability of the interconnect structures on PCBs is more critical than that of the solder joints themselves.

The single biggest threat to robustness of PCBs is the surface temperature they can reach in Pb-free soldering. It can raise up to 275°C, believe it or not. Therefore, improved formulations regarding PCB base and prepreg materials are imperative. Most critical are the integrity of plated through hole copper barrels and interconnects from barrels to inner layers. These and other requirements call for higher glass transition temperatures, less CTE (coefficient of thermal expansion) and higher decomposition temperatures. If one can disregard cost to a high degree, there are several advanced laminates available, fully robust against most severe Pb-free soldering and of course with extended lifetime in "hot" applications - moving into the realm of hybrids. The most advanced features include a T_g around 200°C, $T_{decomposition}$ close to 400°C, and a thermal expansion between 50°C to 250°C as low as 2.5%.

Flux and flux residues require close attention to assure the required increased cleaning efficacy with Pb-free soldering. The higher solder profile will cause the flux to decompose prematurely, leading to dewetting and solder balling. Cross linking (polymerization) at extended soak temperatures in the plateau of the profile renders the flux residues hard to remove with the risk for hygroscopic effects causing humidity-dependent parasitic conduction.

Robustness and Reliability of Solder Joints

A multitude of process parameters are influencing the reliability of solder joints. Let's consider a few here.

Insufficient wettability causes reduced effective solder joint cross section. This parameter tends to be more critical with Sn-plated component leads which are today's mainstream Pb-free plating solution. Crucial to robustness and reliability are the right selection of the flux paste and the optimum soak plateau of the solder profile. Too much heat causes the activator in the flux to become evaporated prior to the solder liquids being reached. Insufficient heat will not fully activate the flux. It's a tight rope walk and, on both sides, bad solderability is lurking. Today, for most less demanding applications (and some of the demanding ones as well, such as automotive), "no clean" pastes are used. These require a tight volume control during application; otherwise there is risk of residues on the underside of components.

The reliability of solder joints is assessed by rapid and slow thermal cycling. Plotting the results in Weibull diagrams illuminates the differences very well. For Pb-free, SAC type solder joints, the slow temp cycles with dT/dt around 0.05 K/s, are the critical ones. Compared to Sn63Pb37 solder joints, they show more total crack length after the same number of cycles. In contrast, SAC solder joints endure faster thermal cycles. Regrettably, it's the slow cycles which mainly take place in our modules and nothing can be done about that - unless recently developed SnCuNiBi solders achieve the promised solder joint reliability. The only other remedy is optimum layout of the solder pads and optimum wettability, so that no solder joint outliers are produced.

Conclusions

It is safe to state for this example for process robustness, that the process windows are tighter for SAC solder-based convection furnace reflow soldering. As a matter of fact, some effects work against each other (e.g. the soak phase is good for lower Delta T but bad for flux efficiency). Incidentally, for wave soldering, there appear to be less to no added problems from moving from eutectic to SAC solder. The solder temperature can stay at the

former 260°C or only need to be increased by 5 K to 10 K. But here we have the added problem of rapid corrosion of unprotected stainless steel solder pots and pumps. In order to at least keep the same process robustness as in "Lead Ages", improved materials - such as PCB substrates - and equipment with tighter control are required. All this is costly and is not complementary to the constant drive for lower module prices.

Appendix B - Prototype Test Examples

B.1 Purpose and Scope

This appendix is an example of the types of testing that is best accomplished during the early development stage to quickly identify many common issues. It is an example of a specific customer/supplier product test program agreement and is not intended to be copied blindly. Each testing program should be defined and agreed upon between customer and supplier to meet the needs of the specific program so that it:

- Allows maximum flexibility to experiment.
- Allows sufficient reaction time.
- Stage where failures are good (maximizes information).

The testing at this stage addresses product robustness in Electrical, Mechanical and Climatic categories. To promote such evaluation, these development methods use the simplest and most low cost techniques that require minimum lab facilities. They should be done with the design engineer present since some are not simply pass-fail tests but require product knowledge to evaluate the results.

The information in this appendix is not for any one specific product. It is a compilation of practices successfully used on a number of products, the Robustness Validation User must establish as part of the RV Process how appropriate a particular test is for their specific product and Mission Profile.

In this appendix the test (Temp., Hours or Cycles) values given represent one lifetime, when testing to failure it is customary to terminate the test a 3 times life if failure does not occur.

B.2 Procedures Summary

The following shows a list of the procedures addressed in this appendix.

TABLE B1 - Test Summary

| Item | Ref | Description |
|-----------------------------------------|------------------------|------------------------------------------|
| 1. Development⁽¹⁾ | | |
| a. General Evaluation | B.7.1.1 | Internal Inspection |
| | B.7.1.2 | Functionality |
| | | |
| b. Electrical | B.7.2 | Design Margins (voltage, temp), Method A |
| | B.7.2 | Design Margins (voltage, temp), Method B |
| | B.7.2 | Voltage Interruptions and Transients |
| | B.7.2 | Power Dropouts and Dips |
| | B.7.2 | Current Draw |
| | B.7.2 | Switch Input Noise |
| | | |
| | B.7.3 | Load Faults |
| | B.7.3 | Reverse battery current |
| | B.7.3 | Shorts to power-ground |
| | | |
| | B.7.4.1 ⁽²⁾ | Load Faults |
| | B.7.4.2 ⁽²⁾ | Leakage Resistance Immunity |
| | B.7.4.3 ⁽²⁾ | Sneak Path, Open Connections |
| | B.7.4.4 ⁽²⁾ | ESD |
| | | |
| c. Mechanical | B.7.5.1 ⁽²⁾ | Mechanical Disturbance |
| | B.7.5.2 ⁽²⁾ | Resonant Search |
| | | |
| d. Climatic | B.7.6.1 ⁽²⁾ | Moisture Immunity |
| | B.7.6.2 ⁽²⁾ | High Temp Exposure, Monitoring |
| | B.7.6.3 ⁽²⁾ | Combined Environments Exposure |
| | | |
| 2. Pre-Design Verification (DV): | B.7.7 ⁽²⁾ | Pre Qual, Qualification, Endurance, CERT |
| | | |
| 3. CERT | B.7.7.1 ⁽²⁾ | Reliability demonstration estimation |

- 1) Development tests in this document may not be all inclusive but is representative.
- 2) Addressed in this appendix.

B.3 General Methodology and Requirements

1. For many of these methods, system and interface issues shall be addressed. The module shall be tested in a sub-system configuration as much as possible. For example, include actual loads or interfaces if analysis indicates that they would have an effect on the results. Typical examples are:
 - Actuator coil change in resistance with temperature.
 - Wiring-connector resistance-inductance in ground and/or power circuits (default: 0.1 Ω , 10 micro henries, use a wire-wound resistor to address inductance)
 - Switch series-parallel resistance (default: closed switch = 50 Ω , open switch = 50 k Ω). This represents degradation in the switch and its associated connectors (corrosion, leakage).
2. For testing at temperature extremes, the DUT mating connector shall have been used for less than 20 insertions (approx). In addition, for validation and any testing that the connector interface may be affected (e.g. temp extremes), the mating connector shall remain connected to the DUT (add in line connector).
3. Place DUT in typical operating mode and monitor key output signals:
 - a. For DUTs with communications bus, connect communications bus analyser and oscilloscope. Operate DUT in mode that creates near maximum bus activity.
 - c. If the DUT exhibits abnormal behaviour during testing, monitor appropriate internal DUT signals to determine root cause. Some examples are: Resets, low voltage inhibits, comparators, V_{dd} , EEPROM writes, load management enables-disables.
4. To accelerate some tests, temperature constraints may need to be removed (e.g. plastics). If such is the case, the DUT may need to be remounted in a manner that results in similar mechanical stresses.
5. Standardized Test Fixture: A standardized test fixture configuration is used throughout the design process (Software, Hardware, EMC testing and validation). This minimizes variability-complexity and allows robustness testing to be done at various stages of the design process. Some key attributes are:
 - a. Compatible with test automation.
 - b. Compatible with EMC testing shall not influence immunity and emissions test results.
 - c. Signal Generator Inputs shall simulate DUT input waveforms and impedances.
 - d. Breakout Box allows easy access to DUT signals.
 - e. DUT loads (if applicable), should allow certain DUT loads to be exposed to thermal chamber.

Note:

Communications bus analysers can be sensitive to electrical noise and may need filtering or optical coupler.

- b. If applicable, also test in diagnostics mode. Verify that the diagnostics mode is not mutually exclusive to the particular test mode (e.g. don't place DUT in diagnostics mode during power start up unless possible in actual product application).

B.4 Acceptance Criteria

The DUT shall, in general, be monitored continuously to a degree necessary to observe responses to stresses including diagnostic codes if applicable. This can range from simple visual observation to a DAQ system including a communications bus analyser. Performance Classifications defines the operation of the DUT during and after exposure to disturbances. By classifying the performance of a component in this manner, the acceptability is determined. These acceptability limits must be clearly defined for the DAQ system to log, when the DUT is outside the defined limits and under what stress conditions.

- **Performance Class I:** The function shall operate as designed (within specified limits) during and after exposure to a disturbance.
 - Ia:** The function shall operate as designed (within specified limits) after exposure to disturbance.
 - Ib:** Response to disturbance results in acceptable degradation.
 - Ic:** Response to disturbance not customer perceivable.
- **Performance Class II:** The function may deviate from designed performance (within specified limits) during exposure to a disturbance, but shall not affect safe operation of the vehicle. The function will return to normal after the disturbance is removed without customer intervention. No effect on permanent memory. Normally, no effect on temporary memory unless per design requirements.
- **Performance Class III:** The function may deviate from designed performance during exposure to a disturbance but shall not affect safe operation of the vehicle. Simple operator action may be required to return the function to normal after the disturbance is removed. No effect on permanent type memory is allowed.
- **Performance Class IV:** The function may deviate from designed performance or be damaged during exposure to a disturbance but shall not affect safe operation of the vehicle.
- **Other:** No LU = No Lock-up, No DTC = No false Diagnostic Trouble Codes, Pre = Predictable response.
- There shall be no evidence of combustion in any components as a result of exposure to environmental tests contained in this document.

Note:

Many of the tests in the Development Stage do not have clear Pass-Fail acceptance criteria (discovery testing). The results must be interpreted by knowledgeable personnel (e.g. Core Design Team, Tech Specialist) to determine a course of action - acceptable, design change, etc.

B.5 Sample Size

Sample size, in most instances, does not need to be large in the RV Process for a number of reasons:

- Most electronic module issues are design related so DUT responses are similar.
- Focusing on DUT weaknesses via up-front analysis and testing at extremes (tail testing) maintains or improves the reliability and confidence numbers with smaller sample sizes.
- Combining stresses (e.g. thermal, electrical) also reduces sample size requirements.
- Variables data (e.g. measuring degradation during CERT) requires fewer samples.
- Using track history on similar products.

Smaller sample sizes also allow increased monitoring (less parametric testing during test flow required), less chamber loading and less facilities (allows more focusing on product and not „red herrings“).

B.6 Test Plan, Specific DUT Characteristics, Setup

To focus the testing and determine proper DUT modes of operation, the test plan must address the following:

TABLE B2 - Module Characteristics Summary

| | | |
|----|-----------------------------------|----------------------------------------------------------------------------------|
| 1 | Known Concern(s) | Description: |
| 2 | Key Off Functions | Active functions: |
| 3 | Sleep Mode | What initiates: Time: |
| 4 | Wake up | What initiates (inputs or network): |
| 5 | Time-Outs | Indicate event that time-outs a function: Time: Trigger: |
| 6 | Event Accumulator | Indicate event that changes DUT state and number of events required: |
| 7 | Delayed Accessory | Yes-No: Time: What triggers: |
| 8 | Communication | Type (e.g. CAN): Receive only or receive-transmit: |
| 9 | Communications with | Indicate what the DUT communicates with and type of information: |
| 10 | Monitored Diagnostic Codes | What is monitored: Acceptance Criteria: |
| 11 | Diagnostic Faults | What faults to verify: |

TABLE B3 - DUT Setup Summary

| DUT Mode ⁽¹⁾ | Test Conditions ⁽²⁾ | Monitored Parameters ⁽³⁾ | Acceptance Limits |
|-------------------------|--------------------------------|-------------------------------------|-------------------|
| A= | | | |
| B= | | | |
| C= | | | |

- 1) **Examples:** Radio = AM, FM, CD.
- 2) **Examples:** Radio = Volume setting. Instrument Cluster = Speed, RPM.
- 3) Include diagnostic codes - Initial, Final.

Useful Abbreviations: A = Amplitude, F = Frequency, PW = Pulse Width, DC = Duty Cycle.

B.7 Development Procedures

Mandatory (even if the customer does not request it).

Development testing may not be a large part of the typical verification validation plan. Such typical plans usually focus on verifying that a product functions in a known way with a given set of input conditions (i.e. meets requirements). What is often missed are those other unwanted things that result from complex dynamic interactions of hardware-software, timing, throughput, electrical excursions, extreme operation, system interactions and interfaces. Therefore the DUT should be tested in a sub-system configuration (realistic loads and interfaces).

B.7.1 General Evaluation

B.7.1.1 Internal Inspection

Before testing, it should be verified that the DUT is properly built and does not contain basic assembly, layout, solder joint, etc. flaws. It should be done with production representative parts. However, if this inspection impairs the function of seals, fasteners or mating surfaces, the inspection sample may need to be separate from those that go through the testing. In addition, this test may need to be run at the end of the test sequence for Conformity or TNI investigation so that the „evidence“ is not destroyed before the main sequence of testing.

Evaluation Methods

Method A, Visual:

- a. Solder Joint visual inspection. Use magnifier (minimum 10X) to inspect each observable solder joint. Things to observe include - proper component orientation with respect to pads, correct fillets, surface porosity, cracking, etc..
- b. Verify proper alignment of parts (e.g. SMDs).
- c. Verify correct parts (e.g. component rated temp, including plastics, consistent with test temp).
- d. Verify proper mounting of large parts (e.g. leaded electrolytic caps seated).
- e. Verify PCB traces > 0.3 mm to edge (> 1.0 mm to edge perforation).

- f. Check for interference - potential shorts, PCB trace proximity to metal parts, radio front bezel screws.
- g. Verify heat sink integrity, associated hardware such as screws tight.
- h. Connector, flex cable seating.

Method B: Solder joint mechanical stress. Usually done during thermal shock test at various intervals. For solder joints that appear to have crack, apply local mechanical stress (e.g. push on PCB - see B.7.5.1, method C) and electrically monitor circuit for intermittents.

B.7.1.2 Functionality

A key to addressing potential functionality concerns is getting the DUT in the right mode(s). Therefore before testing commences, refer to Appendix B.6 for identifying specific DUT characteristics, modes and test conditions that may affect the evaluation. Each customer perceivable function shall be exercised at V_{nom} and T_{amb} . Especially important are transition states. Transition states shall be exercised multiple times (20 minimum).

B.7.2 Electrical, Tests in Table B1, Ref SAE J2628

B.7.3 Electrical, Tests in Table B1, Ref ISO 16750-2 (also contains other tests)

B.7.4 Electrical, Tests in Table B1

B.7.4.1 Load Faults

This method verifies that the DUT is compatible with faults representative of load defects.

1. Conduct test at T_{amb} and V_{nom} unless analysis determines that other voltage or temperature is more appropriate for testing.
2. Activate DUT with probable load faults as per Mission Profile (e.g. open, short, partial opens-shorts, motor stall, over load etc.).

Acceptance Criteria: Performance Class III. Predictable response.

B.7.4.2 Leakage Resistance Immunity

This method verifies that a DUT is compatible with corrosion and leakage resistance due to faulty wiring or connectors.

1. Apply 50 k Ω between each DUT pin and power then ground, one pin at a time. There may be some exceptions to this for a circuit that cannot tolerate this low a resistance this is acceptable if designed for (e.g. sealed connectors). For switches, verify they work properly with resistance in circuit (default = 50 Ω).

Acceptance Criteria: Performance Class I

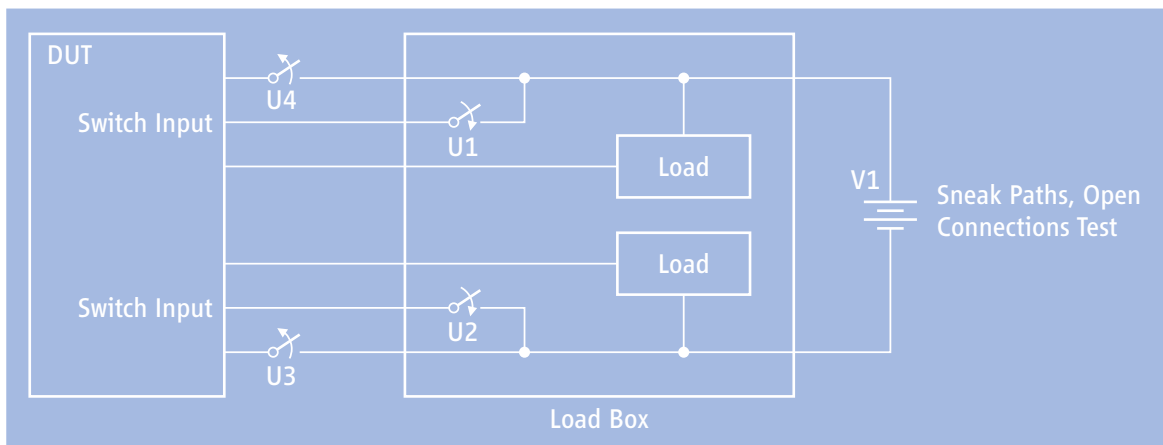
B.7.4.3 Sneak Path, Open Connections

This method verifies that a DUT does not have sneak paths. Some possible paths can be created by loads, vehicle assembly plant operations and lost power-ground connections.

Acceptance Criteria: Predictable response.

1. An analysis will need to be conducted comparing the vehicle connections to the DUT test configuration since these sneak paths are often not recreated on the bench.
2. With the DUT connected to all its normal inputs and outputs (assuming like the vehicle), verify no unintended power is supplied via a sneak path to the DUT.
 - a. Disconnect ground and power at DUT (one at a time).
 - b. Close switch inputs that go to ground and then open ground connection at DUT.
 - c. Close switch inputs that go to power and then open power connection at DUT.
3. DUT internal probing may be necessary (e.g. at the microprocessor V_{dd}) to determine if DUT is operational.

FIGURE B1 - Sneak Path Schematic



B.7.4.4 ESD - Verifies DUT Robustness to ESD

References: ISO 10605 or similar

1. UNPOWERED ESD: ± 8 kV, air discharge.
Acceptance Criteria: Performance Class III
2. OPERATING ESD, Customer Accessible: ± 15 kV, air discharge.
Acceptance Criteria: Performance Class II

B.7.5 Mechanical Tests in Table B-1

B.7.5.1 Mechanical Disturbance

Methods to verify that a DUT is not affected by mechanical shock.

B.7.5.1.1 Evaluation Method A

Reference: Article „Drop Tests vs. Shock Table Transportation Tests“ M. Daum and W. Tustin, <http://www.vibrationandshock.com/art5.htm>

The drop method gives a more realistic shock profile throughout the DUT. The drop height is reduced from the standard drop test height (not meant to be a destructive test).

1. If specified, the test shall be started a maximum of 2 minutes from the completion of test in Appendix B.7.6.3. The testing shall be completed within additional 3 minutes.
2. Supply 13.5V to DUT. Perform test in each DUT specified mode.
3. Elevate DUT 15 cm from metal surface (e.g. aluminum approx 1 inch thick). Orientate so that when released the DUT bottom will contact the surface squarely (not on an edge). It is permissible to do this test within the thermal chamber used for test in Appendix B.7.6.3.
4. Release DUT. Repeat 3 times.
5. Check for intermittent operation during and after drop (e.g. microphonics on audio products).

B.7.5.1.2 Evaluation Method B

Reference: Murata Electronics of North America papers on ceramic capacitor stresses.

This method addresses issues associated with part flexing (e.g. cracked capacitors, cold solder joints). This test may need to be run at the end of the test sequence for Conformity or TNI investigation so that the „evidence“ is not destroyed before the main sequence of testing.

1. For parts susceptible to flexing (e.g. PCB's, flex cables) that could affect proper operation, apply pressure to various points and continuously monitor for intermittent operation. For PCB's, if possible within constraints of packaging apply pressure to deflect PCB per following table (approx - use as guide):

| | | | | | | |
|------------------------------------|-----|-----|----|-----|-----|-----|
| PCB Unsupported Length (mm) | 20 | 40 | 60 | 100 | 140 | 200 |
| PCB Displacement (mm) | 0.1 | 0.4 | 1 | 2.5 | 5 | 10 |

Acceptance Criteria (all methods): Performance Class I

B.7.5.2 Resonant Search

The purpose of this method is to identify DUT mechanical resonances. The use of the CAE analysis activity should be first consulted to direct this evaluation.

1. The DUT shall be mounted on the vibration table through its normal points of attachment.

2. The method of resonance detection shall be determined: Accelerometer, Strobe, Visual.
3. Testing shall be carried out varying frequency, displacement and acceleration in accordance with the table at a rate sufficiently low to permit the detection of resonance.

| Frequency Range | Acceleration |
|------------------------|------------------------------|
| 5-200 Hz | 1 G (9.81 m/s ²) |
| 200-500 Hz | 0.5 G |

4. Sweep part or system in all 3 orientations per acceleration input shown in table above. Use a strobe light to locate the maximum displacement locations of the board, bracket, and module. CAE analysis data can replace this step of identifying maximum displacement locations if the analysis data is available.

5. Mount tri-axial accelerometers at the maximum displacement locations. Record accelerometer locations (pictures, distance from edges, etc.).
6. Sweep part or system in all 3 orientations per acceleration input shown in table above.

B.7.6 Climatic, Tests in Table B1

B.7.6.1 Moisture Immunity

This method verifies that a DUT is not adversely affected by leakage resistance on the PCB mainly caused by contamination, moisture or humidity (including dew point condensation). Also, susceptibility to dendritic growth is partially addressed. It should be assumed that some degree of moisture will be present on the PCB regardless of location in the vehicle. Test applies to non-conformal coated PCB's.

1. With DUT powered, expose one side of PCB to mist from atomizer (use water with wetting agent to minimize droplets so as to spread out water over PCB - e.g. Glass plus Glass Cleaner) until the PCB is uniformly covered (similar concentration as dew point condensation).
2. Keep DUT powered for approx 10 minutes and note operation.
3. Dry PCB (e.g. heat gun). Repeat for other side of PCB.

Note:

If a particular area of the PCB is suspect (e.g. microprocessor resonator-crystal circuit), apply moisture locally (e.g. mask areas not to be evaluated).

Acceptance Criteria: Performance Class III if not protected for moisture (after moisture removed). No evidence of combustion.

B.7.6.2 Hi Temp Exposure, Monitoring

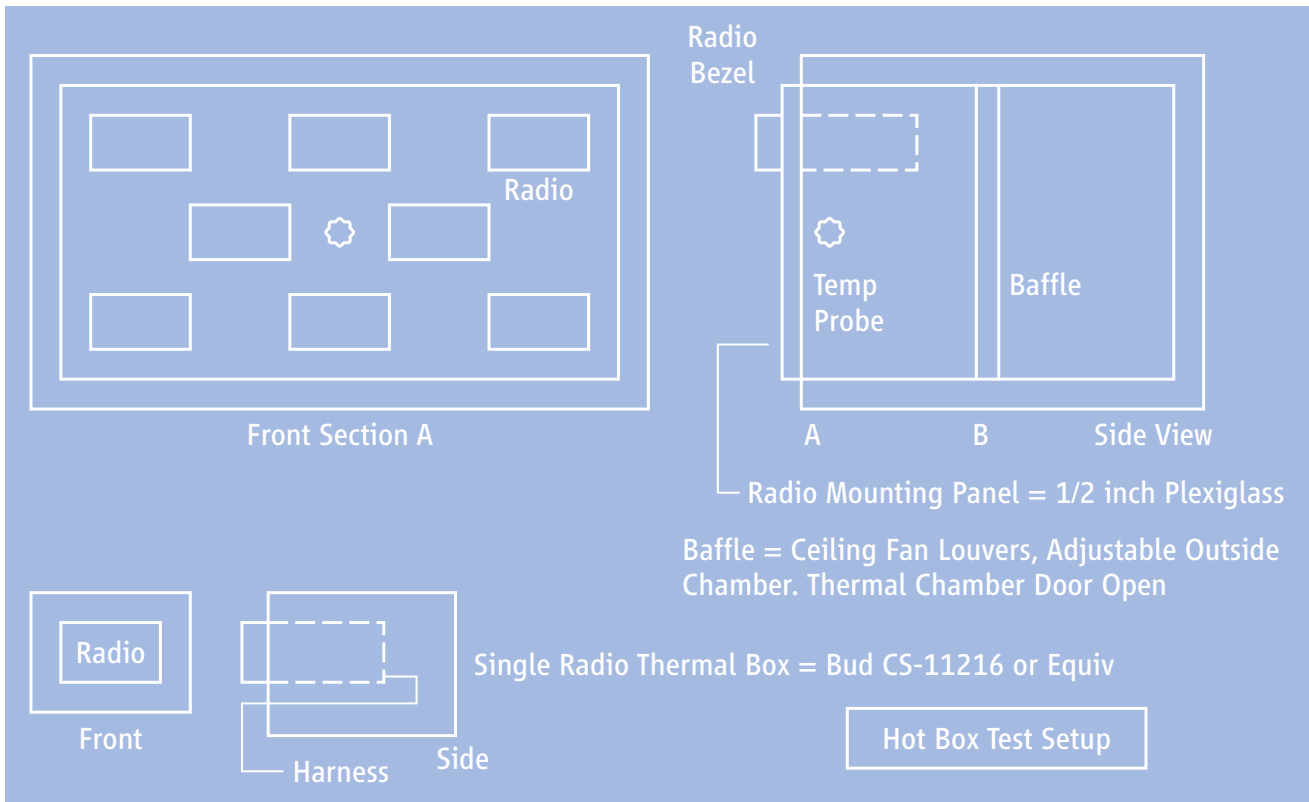
These methods apply to modules, which have potential to generate excessive heat.

1. Place DUT'(s) in thermal chamber. Monitor DUT hot spots at maximum stress mode and verify if within predetermined limits. If module is mounted in highly confined space without airflow, monitor temperatures in configuration that simulates that situation (e.g. hot box).
 - Option 1 = Single DUT in hot box. Raise box 10 cm to allow limited airflow through box.
 - Option 2 = Multiple DUTs in modified Thermal Chamber (fixture allows space for testing different types of DUTs simultaneously). Temperature probe for controlling chamber shall be located behind front mounting panel in centre. Adjust airflow via heat ducts to achieve airflow at probe = 0.05 to 0.1 m/s.
2. Apply 16V* to DUTs and place in most stressful mode (e.g. periodic CD eject).
3. Expose the DUTs until temperature stabilizes at T_{max} .
4. For displays, periodically visually monitor DUT operation.
5. Monitor suspect solder joints with probe and verify temperature is less than 135°C.
6. Also monitor temperature with DUT pin shorts to ground (conduct analysis to determine suspect pins).

Acceptance Criteria: Within temperature limits. Predictable response.

* Although lower voltages would aggravate some types of failure mechanisms (e.g. wouldn't tend to burn off filaments due to dendritic growth), 16V was chosen to maximize thermal stress (main purpose of the test).

FIGURE B2 - Hot Box Setup



B.7.6.3 Combined Environments Exposure

These tests are aimed at DUTs that contain highly mechanical devices (e.g. CD mechanism). It addresses:

1. Shipping/Handling damage due to high temperature and shock.
2. Concerns created by exposure to high operational temperatures which can be aggravated by a restricted airflow environment such as that in the Instrument Panel. As a secondary purpose, it also exposes the DUT to high humidity to precipitate other concerns such as contamination, dendritic growth and cracked capacitors.

B.7.6.3.1 Evaluation Method A, Power Off

3. DUT shall be in shipping condition (e.g. CD mechanism in ship mode).
4. Place DUTs in thermal chamber and expose for 1 h at T_{max} and 85% humidity (non-condensing).
5. If specified, the Mechanical Disturbance test in Appendix B.7.5.1, method B (Drop) must be done within a specified time after this test.

Acceptance Criteria: Performance Class I.

B.7.6.3.2 Evaluation Method B, Power On

- Place DUTs in thermal chamber. Configuration shall be designed to facilitate quick removal for Mechanical Disturbance, method B (Drop) without removing DUT connector.
 - Option 1 = Single DUT in hot box. Raise box 10 cm to allow limited airflow through box.
 - Option 2 = Multiple DUTs in modified Thermal Chamber (fixture allows space for testing different types of DUTs simultaneously). Temperature probe for controlling chamber shall be located behind front mounting panel in center. Adjust airflow via heat ducts to achieve airflow at probe = 0.05 to 0.1 m/s.
- Apply 16V** to DUTs and place in most stressful mode (e.g. periodic CD eject).
- Expose the DUTs for 2 h (or other time specified) at T_{max} and 85% humidity (non-condensing).
- For displays, visually monitor DUT operation at least every 60 min for 5 min.
- If specified, the Mechanical Disturbance test in Appendix B.7.5.1, method B must be done within a specified time after this test.

Acceptance Criteria: Performance Class I

B.7.7 Pre DV Readiness Evaluation

Prior to DV testing, an assessment of the product shall be conducted by an independent „expert(s)“. This expert must be knowledgeable in product design, manufacturing processes and testing. The result of this review is either OK or a list of minor-major issues. If the product is not considered ready, it can still proceed to DV but only after a risk assessment. With limited resources, such an approach is required to avoid a high retest rate. From past experience, this retest rate can be up to 80% if the product is not really ready for testing.

** Although lower voltages would aggravate some types of failure mechanisms (e.g. wouldn't tend to burn off filaments due to dendritic growth), 16V was chosen to maximize thermal stress (main purpose of the test).

TABLE B4 - Pre DV Tests

| Item | Description | Reference | Parameters | Acceptance Criteria |
|------|-----------------------------------|--------------------|---------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|
| 1 | Functional Check, General | | Exercise selected functions in random fashion. Emphasis on transitions. Monitor diagnostic codes. | Predictable response. No false diagnostic codes. |
| 2 | Functional Check, Test | | Verify basic functionality at T_{amb} Apply before-after tests. | No anomalies |
| 4 | Internal Inspection | B.7.1.1 | Detailed internal-external inspections (solder joints, SMD alignment, trace interference, etc.). | No anomalies |
| 5 | Current Draw | B.7.1.1 | On current at multiple voltages-temps. Off current. | Within spec. |
| 6 | Design Margins | B.7.2 | Ramp voltage, V_{nom} to 20 v to 0 v to V_{nom} ⁽¹⁾ T_{amb} | UOL-V (T_{amb}), hi = UOL-V (T_{amb}), lo = LOL-V (T_{amb}), lo = LOL-V (T_{amb}), hi = |
| 7 | Performance Evaluation (Tri-Temp) | B.7.2 Methode B | Measure and record component parameters at 5 temp-voltage points (guaranteed performance). | Within spec. |
| 8 | Lo Temp Operation | | 8 h ⁽²⁾ $T_{min} -5C =$ | No anomalies |
| 9 | Hi Temp Operation | | 8 h ⁽²⁾ $T_{max} +5C =$ | No anomalies |

- Hi-Lo values due to hysteresis. These limits are where DUT operation is erratic or ceases to operate.
- For multiple modes (e.g. CD, FM), divide time equally.

B.7.7.1 Combined Environmental Reliability Test (CERT)

This test can be used at various stages of the RV Process (Development or DV) for reliability demonstration-estimation. CERT typically includes a combination of various environmental stresses - Thermal Shock, Vibration, Thermal-Humidity Cycle (including Power Cycling), System Interface Issues such as Connector, Ground, Power and Switch Degradation over Time.

A key ingredient of CERT is the measuring of DUT parameters that could degrade over time. These degradation parameters are to be checked periodically at specified intervals during the test. This provides variables data (much more information than a „test for success“ type of test). For reliability estimating, these points can be used for plotting to estimate product life (extrapolation). Typical examples of degradation are:

- Vacuum Florescent Display Brightness.
- Plastic Deformation.
- Plastic Lens Clarity.
- Change in Current Draw or Standby Current (Test E-40).
- Change in Design Margins (Test E-10).

Since there are many environmental stressors and potential product susceptibilities (and modes of operation), the CERT test must use analysis to focus on those combinations most likely to precipitate a functional concern. This is especially critical for products with unproven designs (e.g. no field experience, new technology).

B.7.7.1.1 Evaluation Method

1. Sample Size = three (typical).
2. Determine DUT modes of operation and (if applicable) at what points in the test they would be activated.

The following provides an example for a typical product and illustrates the philosophy behind CERT when it is to be used for reliability demonstration-estimating.

Note:

The actual stress life of a product is extremely complex and varied. In most instances, it is impractical to come up with a test that accurately simulates that environment for all situations. Analogy is trying to estimate a newborn person's life time. However, a rough approximation can be derived that includes all the major stresses a product is likely to encounter.

B.7.7.1.2 Assumptions (Mission Profile)

1. 10 year (3,650 days) life, average of 2 thermal cycles/day.
2. # Cycles-test = # Cycles-actual (ΔT -actual / ΔT -test) 2.5 Exponent = 2.5 for solder fatigue.
3. ΔT average over worst part of winter-summer = 40°C.
4. ΔT average over rest of the year = 30°C.
5. Part of life would experience thermal shock (e.g. bringing cold vehicle inside heated garage).

Note:

Analytical models used to accelerate life testing should only be used as approximate estimates.

6. Ignition Power Cycles = 20 K.

TABLE B5 - Temperature Profile

| Test Cycle Temps | Actual Cycles $\Delta T = 30$ | Test Cycles | Actual Cycles $\Delta T = 40$ | Test Cycles | Total Test Cycles |
|------------------------------|----------------------------------|-------------|----------------------------------|-------------|-------------------|
| -40 to 85°C (typical) | 7,300 | 103 | 7,300 | 211 | 314 |
| -40 to 90°C (5°C from spec.) | Same | 85 | Same | 174 | 259 |

Note:
 It takes about 300 thermal cycles to simulate life. The number of cycles can be reduced by using thermal shock (within same temp limits). Each thermal shock cycle is twice as damaging as a powered thermal cycle.

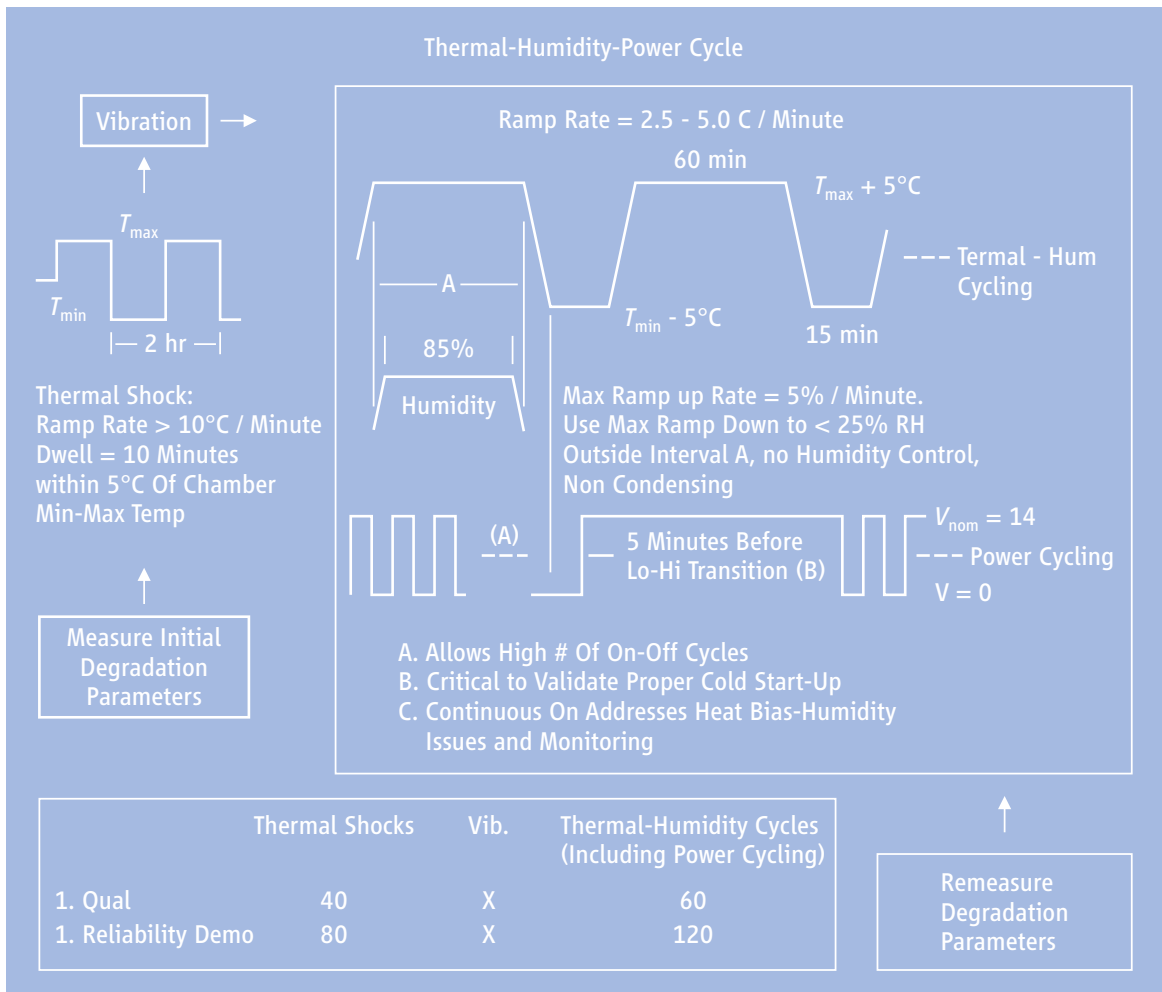
TABLE B6 - Cert Profile

| Step ¹⁾ | Test | Test Parameters |
|--------------------|--------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1a | Parametrics ²⁾ | Per Component Specification |
| 1b | Degradation Parameters ²⁾ | Examples: Vacuum Florescent Display brightness, Plastic deformation, Plastic Lens clarity, Change in current draw or standby current (Test E-40), Change in Design Margin (Test E-10) |
| 2 | Thermal Shock | Qual Cycles = 40, Reliability Demo = 80 Temp = T_{min} to T_{max} Dwel (hi, lo) = 10 minutes within 5C of chamber min/max temp. |
| 3 | Powered Vibration | Per ISO 16750 |
| 4a | Termal Cycle | Per ISO 16750 Qual Cycles = 60, Reliability Demo = 120 Ramp = 3-5 C/minute, Air = 5 fps nominal Temp = $(T_{min} - 5C)$ to $(T_{max} + 5C)$ Dwel cold = 15 minutes, Dwel Hot = 60 min |
| 4b | Humidity | 85% Humidity (non-condensing). Max Ramp up rate = 5% per minute. Use max ramp down rate to <25% RH. Outside humidity controlled interval, non-condensing. |
| 4c | Power Cycle | Apply throughout Thermal-Humidity Cycle as shown in Figure ^{3), 4)} . T-on = T-off = 15 sec (example only - depends on product). |
| 5 | Repeat 1a, 1b | |

- 1) Follows cumulative damage sequence.
- 2) Also determines if ready to test.
- 3) Power on/off times (simulates 10 yr/150 K ignition cycles, typically 15 K - 20 K cycles) depends on product stabilization time (typically 15 to 30 seconds each).
- 4) Continuous power on every other cycle addresses heat-humidity-bias issues such as power dissipation and dendrites. It also allows for monitoring. Monitoring ideally should be continuous. However periodic monitoring is acceptable, e. g. every 24 h, at least once, mon-

- itor operation. Pick points in the day, where the different portions of the profile can be observed (cold start, hot-cold temp extremes, temp transitions, rapid power on-offs). As an example of what to monitor, for radio:
1. Listen to the speakers (located outside thermal chamber).
 2. Look at display.
 3. Check radio operation via remote steering wheel switches or rear seat controller.

FIGURE B3 - Cert Profile



Appendix C - References

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- [5] ISO21747 Statistical Methods - Process Performance and Capability Statistics for Measured Quality Characteristics.
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- [20] SAE G-11 Reliability, Maintainability, and Supportability Guidebook, 3rd Edition, p. 261-264, 1995, Warrendale, PA, SAE, Inc.
- [21] Zero Defect Strategy - ZVEI Revision 1, 2007.
- [22] SAE J2837 - Environmental Conditions and Design Practices for Automotive Electronic Equipment: Reference Data from SAE J1211, 1978

C.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

C.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

| | |
|-------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| SAE J1213-2 | Glossary of Reliability Terminology Associated with Automotive Electronics |
| SAE J1739 | Potential Failure Mode and Effects Analysis in Design (Design FMEA) and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA) and Effects Analysis for Machinery (Machinery FMEA) |
| SAE J1879 | Handbook for Robustness Validation of Semiconductor Devices in Automotive Applications |
| SAE J2628 | Characterization, Conducted Immunity |

C.1.2 ZVEI Publications

All ZVEI Documents are available by free download unter:
www.zvei.org/RobustnessValidation

C.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

Other Publications:

- M. S. Phadke, iSixSigma LLC: „Introduction to Robust Design-Robustness Strategy“
- Dr. Ing. W. Kuitsch: „Umweltsimulation von Schwingungs- und Stoßbelastungen“, lecture at Technische Akademie Esslingen, 2004
- E. Pollino, Artech House Publishers: "Micro-electronic Reliability, Volume II: Integrity Assessment and Assurance" ISBN 0-890-06350-8, 1989
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- IEC 60300-1 Dependability management - Part 1: Dependability management systems, International Electrotechnical Commission, 2003
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ZVEI - Zentralverband Elektrotechnik
und Elektronikindustrie e.V.
Lyoner Straße 9
60528 Frankfurt am Main

Telefon: 069 6302-0
Fax: 069 6302-317
E-mail: zvei@zvei.org
www.zvei.org



Homepage Robustness Validation
Electronic Components and Systems Division