



SURFACE VEHICLE/ AEROSPACE RECOMMENDED PRACTICE

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Reliability Physics Analysis of
Electrical, Electronic, and Electromechanical Equipment,
Modules and Components

RATIONALE

This recommended practice has been developed jointly by the SAE International Automotive Electronic Systems Reliability Standards Committee (AESRS) and the SAE Avionics Process Management Committee (APMC) to describe a standard process for reliability physics analysis (RPA) of electrical, electronic, and electromechanical (EEE) systems, equipment, sub-assemblies, modules, and components used in the aerospace, automotive, defense, and other high-performance (AADHP) industries.

RPA is a science based, engineering discipline that augments classical reliability prediction methods that are based on part counting tabulation of averaged, historic failure rates of generic component categories.

RPA combines failure mechanism models developed by physics-of-failure (PoF) research with lifetime load profiles to calculate durability life and likelihood of failure over time of specific designs incorporating various EEE parts, modules, or assemblies operating in specific applications. RPA leverages knowledge of material properties and failure mechanisms to identify failure risks, predict reliability-durability, and improve design robustness through durability simulations and models executed in a computer-aided engineering (CAE) environment.

RPA interacts with and augments traditional performance related EEE simulation methods, such as electrical, electromagnetic, thermal, and mechanical analysis. RPA uses the outputs of performance CAE tools to capture stresses due to usage conditions and environmental loads (e.g., shock, vibration, temperature, electric field, etc.) and uses this information to predict time to failure based on the material science principle of stress driven damage accumulation of materials for determining the rate and degree of damage accumulation over time or usage cycles.

This document standardizes and defines RPA best practices and provides a clear process for exchanging RPA results up and down the supply chain. RPA results may be used for:

1. **Assessment of new component technology and packaging:** Unlike traditional failure rate tabulations using handbooks of historic generic component failure rates, RPA can evaluate the potential reliability performance of new component technologies (i.e., 45 nm SOI, 22 nm FinFET, 10 nm planar, etc.) and packaging (i.e., BGA, QFN, CSP, SiP, 3D-IC, etc.) with minimal physical testing or field failure data.
2. **Design verification/validation of EEE modules:** Traditional qualification methods rely on physical tests that are expensive, time-consuming, and too late in the process to effectively identify all potential reliability issues/failure risks. RPA durability simulations allows for a virtual validation process that provides the Tier 1, OEM, and Airframe Integrator (for avionics) insight into reliability performance and failure risk identification so that the risks can be eliminated or mitigated early in the design process.

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3. Inputs to certification analyses of EEE equipment and systems (e.g., ISO 26262, Functional Safety or FAA Airworthiness Requirements).
4. Change evaluation and acceptance: Modifications to fielded products can be stymied due to cumbersome and ill-defined processes for reviewing and approving change requests from suppliers, and the potential for expensive physical retesting. RPA allow for a standardize evaluation process.

INTRODUCTION

This document describes a reliability physics analysis (RPA) process to assess reliability and failure risks of EEE equipment, modules, and components through the use of computer-aided engineering (CAE) durability modeling and simulations. RPA is based on understanding the physical processes and mechanisms that cause degradation and failure of materials, components, and assemblies. It starts by analyzing the loads and stresses (such as voltage, current, temperature, humidity, radiation, and chemical activity) to which an item will be exposed throughout its service life, correlating stress exposure to damage accumulation, then extrapolating damage accumulation to calculate probability of failure over time.

RPA usage in EEE systems is increasing in the AADHP industries along with all other forms of computer analysis and simulation. The CAE trend is driven by the processing power and speed of computers that continue to dramatically increase, which lowers its costs, while the increasing complexity of EEE equipment significantly increases the cost and time needed for physical testing. RPA also supports the need to accelerate qualification of new technologies (such as autonomous vehicles and aircraft) that have little or no field failure history.

As its use proliferates, RPA is being conducted, implemented, and reported in a variety of ways. The potential for divergence and misinterpretation of results is increasing, and it is therefore necessary to develop consensus among a range of industries and organizations on a “standard” RPA process as applied to EEE equipment, modules, and components. This document is intended to fill that need.

The capability and need to implement RPA can vary among organizations that design and use EEE equipment and modules. Therefore, the essential steps of a baseline process for RPA (see [Section 5](#)) are purposely stated at a high level and are quite general. The baseline RPA process includes five tasks for an evaluation of the following failure mechanisms (see [5.5](#) for more detail):

1. Thermal cycling board level reliability attachment fatigue.
2. Vibration board level reliability attachment fatigue.
3. Shock board level reliability attachment fracture.
4. Thermal cycling PCB via fatigue.
5. Wearout and aging of life-limited microcircuits (LLM) (i.e., integrated circuits).

The baseline process is intended for use in conjunction with a series of SAE J3168 slash (“/”) sheets that provide more detailed information for modeling and simulation of individual failure mechanisms. Slash sheets SAE J3168/1 through SAE J3168/5 address the failure mechanisms listed above. Other slash sheets will be prepared to address additional failure mechanisms, as needed.

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1. SCOPE

This recommended practice has been developed for use in any EEE system used in the AADHP industries. RPA is especially important to AADHP systems, which are often safety critical applications that must operate for long times in rugged environments. These EEE systems often use EEE components that were originally designed and produced for more benign consumer applications.

Although the focus of this recommended practice is on AADHP applications, the process described herein is not limited to AADHP and may be used for EEE systems and components in any industry.

1.1 Applicability

This recommended practice is applicable to all EEE systems, equipment, assemblies, and modules, and the EEE components within them. RPA is useful for evaluating the likelihood of occurrence, and the effects, of failure mechanisms that result from degradation of materials, or accumulated damage that impact the functional outputs of a system. RPA may be applicable to failures caused by design errors, based on the knowledge of the user. Typically, RPA is not applicable to failures caused by quality defects, assembly or installation errors, or misuse of the EEE system, equipment, assembly, module, or components. RPA is not applicable to software.

For the most part, RPA is applicable at the electronic assembly, component, or module level, rather than at the system or equipment level. For reliability, durability, and safety assessments, RPA is conducted for the various components or modules of the system or equipment and the results are combined to produce an assessment for the system or equipment¹. The same approach is taken for test development; the results are used to define the correct test types, conditions, and durations, as well as whether the tests are conducted at the system, equipment, module, or component levels. For qualification of EEE parts, modules, and sub-assemblies, RPA may be used to compare the item's capabilities with the qualification requirements, or in support of or to reduce qualification testing.

2. REFERENCES

2.1 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.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP5890	Guidelines for Preparing Reliability Assessment Plans for Electronic Engine Controls
ARP6338	Process for Assessment and Mitigation of Early Wearout of Life-Limited Microcircuits
ARP6379	Processes for Application-Specific Qualification of Electrical, Electronic, and Electromechanical Parts and Sub-Assemblies for Use in Aerospace, Defense, and High Performance Systems
SAE J1211	Handbook for Robustness Validation of Automotive Electrical/Electronic Modules

McLeish, J. and Haeberle, R., "Moving Automotive Electronics from Reliability/Durability Testing to Virtual Validation Modeling Using a Physics of Failure CAE App," SAE Int. J. Passeng. Cars - Electron. Electr. Syst. 7(2):369-376, 2014, <https://doi.org/10.4271/2014-01-0233>.

¹ The process for combining individual component RPA results to assessment of system reliability and durability is beyond the scope of this document.

2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM D696 Test for Coefficient of Linear Thermal Expansion of Plastics

2.1.3 IPC Publications

Available from IPC, 3000 Lakeside Drive, 309 S, Bannockburn, IL 60015, Tel: 847-615-7100, www.ipc.org.

IPC-4412 Specification for Finished Fabric Woven from E Glass for Printed Boards

IPC-TM-650-2.4.24c Glass Transition Temperature and Z-Axis Thermal Expansion by TMA (Thermal Mechanical Analysis)

IPC-TM-650 2.4.41 Coefficient of Linear Thermal Expansion of Electrical Insulating Materials

2.1.4 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

RTCA DO-160 Environmental Conditions and Test Procedures for Airborne Equipment

2.1.5 Other Publications

JEDEC JEP122 Failure Mechanisms and Models for Silicon Semiconductor Devices

JEDEC JESD94 Application Specific Qualification Using Knowledge Based Test Methodology

JEDEC JESD91 Method for Developing Acceleration Models for Electronic Component Failure Mechanisms

2.2 Related Publications

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

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J2816 Guide for Reliability Analysis Using the Physics-of-Failure Process

SAE J2940 Use of Model Verification and Validation in Product Reliability and Confidence Assessments

SAE J3083 Reliability Prediction for Automotive Electronics Based on Field Return Data

2.2.2 IEEE Publications

Available from IEEE Operations Center, 445 and 501 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-981-0060, www.ieee.org.

IEEE 1413-2010 IEEE Standard Framework for Reliability Prediction of Hardware

3. DEFINITIONS

NOTE: This section contains terminologies from both the aerospace/defense and automotive industries; some terms are common to both industries, and others are unique to one or the other.

AADHP: Automotive, aerospace, defense, and other high-performance industries.

ACCELERATED LIFE TEST (ALT): A test that subjects an item to conditions, e.g., temperature, vibration, exposure frequency, etc., in excess of its normal service parameters, to reveal potential failures in a shorter period of time. Care is required to ensure that excessive stress that would result in non-field relevant failure modes are not used.

ACCELERATION FACTOR: A number, derived from an appropriate acceleration model, that shows how time-to-fail at a particular stress level (for a given failure mode or mechanism) can be used to estimate/predict the equivalent time, mileage, or cycles to fail at a different stress level, acceleration factors can be express in various metrics such as time, miles, kilometers, or cycles.

ACCELERATION MODEL: An equation that predicts time, mileage, or cycles to failure as a function of operating, standby, transit, or storage conditions or stresses, also known as a failure mechanism model. Acceleration model factors show how time-to-fail at a particular operating stress level for a failure mode or mechanism can be used to predict the equivalent time or cycle to fail under different operating stress levels.

AGING FAILURE: A failure mode that develops over time due to parametric drift. Integrated circuit aging mechanisms include bias temperature instability (BTI), hot carrier injection (HCI), and others.

BOARD LEVEL RELIABILITY (BLR): The reliability-durability of EEE components when attached to a printed circuit board (PCB) (or other substrate) in a specific application.

CAD: Computer-aided design.

CAE: Computer-aided engineering.

CAM: Computer-aided manufacturing.

COMMERCIAL OFF-THE-SHELF (COTS): An existing item that is available in commercial marketplaces as opposed to an engineered product that is custom produced to meet specified requirement.

CTE: Coefficient of thermal expansion.

DURABILITY PERIOD: The time or operating conditions, e.g., cycles, hours, mileage, etc., over which an item remains operable.

DURABILITY: The ability of an item to remain operational while enduring usage and environmental conditions to the completion of the intended service life.

EEE BASE COMPONENT: A basic EEE part within an electronic system or equipment which cannot be dis-assembled without destroying the function of the item, such as a resistor, transistor, or integrated circuit that is susceptible to failure during operation, stand-by, storage, or transit; e.g., electronic piece parts, printed wiring assemblies, connectors, electronic modules, etc.

EEE EQUIPMENT: A physical interconnection of electronic piece modules that collects electronic signals, processes them, and re-distributes them (equipment is usually smaller and more localized than systems).

EEE MODULE: An assembly of EEE components that is treated as a unit and performs a defined function within a system or equipment. (See EEE sub-assembly.)

EEE SUB-ASSEMBLY: See EEE module; a typical EEE sub-assembly is a printed wiring assembly.

EEE SYSTEM: A physical interconnection of electronic piece parts, components, modules, and/or boxes that collects electronic signals, processes them, and re-distributes them (a system may include a wider range of components, distributed over a wider location, than equipment).

ELECTRICAL, ELECTRONIC, OR ELECTROMECHANICAL (EEE) ITEM: The item can be a component, assembly, sub-assembly, module, or other similar item.

ELECTRONIC COMPUTER-AIDED DESIGN (ECAD): Software programs for designing EEE devices and their printed circuit boards. Also known as electronic design automation (EDA).

ENGINEERED PRODUCT OR EQUIPMENT: An item custom designed to meet a customer's specification for form, fit, and functionality along with requirements for quality, reliability, durability, safety and design, product and process qualification, or validation requirements.

FAILURE MECHANISM MODEL: A mathematical representation of a failure mechanism in terms of a set of algebraic or differential equations from the perspective of its reliability implications, to provide an estimate of damage produced, or time, cycles, mileage exposures needed to produce a failure. (Also see acceleration model.)

FAILURE MECHANISM: The physical process (e.g., diffusion, crack propagation, etc.) that causes an item to fail.

FAILURE MODE: The way that a failure is perceived, sensed, or makes itself known.

FAILURES IN TIME (FIT): Equals to failures per billion operating hours (i.e., 10^9), a failure rate metric originally known as a failure unit.

FIELD DATA: Failure data obtained from operation, standby, storage, and transit of a system or component; field data that is useful for RPA includes sufficient information about the time of failure, the failure mechanism(s), and the operating and/or environmental stresses to which the system or component is exposed. Also called in-service data.

FR4: A class of PCB materials that meets National Electrical Manufacturers Association (NEMA) requirements for "Class 4 Flame Resistance" which is independent of all other PCB mechanical, thermal, and electrical properties.

FRACTURE: The separation of an object or material into two or more pieces under the action of stress.

HIGHLY ACCELERATED LIFE TEST (HALT): An incremental step stress technique to rapidly determine weaknesses in the design.

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (IEEE): An organization of technical professionals dedicated to the advancement of electrical and electronic technologies.

JOINT ELECTRONIC DEVICE ENGINEERING COUNCIL (JEDEC): This organization develops open industry EEE standards that include defining standard EEE component families and packages.

Lx/Bx LIFE PERCENT: Derived from the B10 bearing life metric that denotes the point in time or cycles when 10% of a product's or equipment's population has failed. Can be modified by specifying the life percentage of interest. L1 and L0.1 (1% and 0.1%) are often used to identify the time to first failure point. (Also see TTFF.)

MEAN TIME BETWEEN FAILURES (MTBF): The mean (average) amount of time that a device or product functions before failing; typically applied to a sample or population of items.

MEAN TIME TO FAILURE (MTTF): The mean (average) length of time a device or product is expected to last in operation.

OVERSTRESS FAILURE: A failure that occurs when the applied stress(es) exceeds the strength of an item's ability to withstand the stress, resulting in immediate or imminent failure, due to failure mechanisms such as fracture, yield, buckling, and electrical over stress (EOS).

PHYSICS OF FAILURE (PoF): A science-based approach to understanding the various mechanisms that cause failures in electronic systems, and developing mathematical models to estimate times-to-failure under various stress conditions.

PRINTED CIRCUIT BOARD (PCB): A substrate consisting of insulating layers and electrically conductive interconnections that provides mechanical support and electrical circuit connections to the PCB's EEE components; organized to perform a specific function. Also called a printed circuit card, printed wiring board (PWB), circuit card, or printed board.

PRINTED CIRCUIT BOARD ASSEMBLY (PCBA): The functional device created after all of its intended EEE and mechanical components have been populated and attached to a bare PCB. Also known as a printed circuit assembly (PCA).

PRINTED CIRCUIT BOARD ASSEMBLY PROCESS (PCBAP): The collection of manufacturing operations needed to populate a PCB with its intended EEE and mechanical components.

PRINTED WIRING BOARD ASSEMBLY (PWBA): Another term for printed circuit board assembly.

RELIABILITY ENHANCEMENT TESTING (RET): An aerospace/defense industry technique for reliability-durability improvement applied to existing fielded equipment whose reliability-durability performance is well below acquisition contract requirements. RET also may be known as HALT, an incremental step stress probing technique.

RELIABILITY GROWTH TESTING (RGT): A reliability improvement technique applied during the product design and development phase; includes physical testing of prototype products to detect failure risks so that they can be eliminated or mitigated by corrective actions. Also called design-build-test-and-fix.

RELIABILITY PHYSICS ANALYSIS (RPA): An engineering discipline that combines stress analysis of lifetime load profiles of specific electronic parts, modules, or assemblies in application specific environmental and usage conditions with failure mechanism models produced by physics of failure research to calculate durability life and likelihood of failure(s) risks over time in a specific applications. Sometimes referred to as physics of failure analysis.

REPAIRABLE: Capable of being repaired (as opposed to being disposed of). Alternative spelling: reparable.

RPA MODEL: An equation or algorithm used to calculate an estimated time to failure for a given failure mechanism.

RPA PROCESS OWNER: The organization or person that develops and implements the RPA process described in this recommended practice.

SERVICE LIFE: The period of time, miles, or cycles a product or equipment is expected be operational. Also known as the durability life.

SIMULATION AIDED TESTING (SAT): A life test interpretation (test to field correlation) methodology that uses CAE durability simulation to tabulate the amount of stress driven damage accumulation of the items that failed in an accelerated life test, then determine how long it would take for the same failure mechanism(s) to occur under actual usage conditions.

SIMULATION GUIDED TESTING (SGT): A field to test correlation methodology for designing accelerated life tests that are relevant to real world condition, through the use of CAE durability simulation to tabulate the amount of stress driven damage accumulation that occurs under expected operating and environmental condition to produce failures. Then designing the parameters of a life test to replicate the failure mechanism under accelerated conditions.

SOLDER: A fusible metal alloy with a low melting point used for joining less fusible metals to create a permanent bond between metal workpieces.

STEP STRESS TEST (SST): A test(s) that applies stresses at incrementally increasing levels of magnitude and/or duration to expose the "weak link" in the unit under test.

SUCCESS TEST: A qualification test conducted according to defined levels and durations of stresses, to verify that a "reasonable" level of reliability, durability, and robustness has been attained. Also called a "bogey test" or "good enough test."

TIME TO FIRST FAILURE (TTFF): The point at which early members in a population of parts, products or equipment are first susceptible to failure. Can be correlated to either a specific failure mechanism or the combination of all applicable failure mechanisms. Typically scaled to the point when a given fraction (e.g., 1%, 0.1%) of the items fails. (Also see Lx/Bx life percent.)

VIRTUAL RELIABILITY GROWTH (VRG): The process of identifying the failure susceptibilities weak links in a design so that the can be eliminated or mitigated through the use of models and simulations performed in a virtual CAE environment, instead of traditional physical design-build-test and fix physical reliability growth testing performed on prototype parts.

WEAROUT FAILURE: An age-related failure that occurs over usage and/or environmental exposure time, resulting from stress driven damage accumulation in materials; wearout failures often result from mechanisms such as fatigue, corrosion, contact wear, and time dependent dielectric breakdown (TDDB).

4. INITIALS AND ACRONYMS

NOTE: Many of the entries in this section are described in [Section 3](#) and are listed separately here for ease of use of this document. A set of initials that can be pronounced as a word is known as an acronym.

3D-IC	Three-Dimensional Integrated Circuit
AADHP	Aerospace, Automotive, Defense, and High-Performance
ALT	Accelerated Life Test
BGA	Ball Grid Array (an integrated circuit package)
CAE	Computer-Aided Engineering
CSP	Chip Scale Package
DV	Design Validation or Verification (industry dependent)
EEE	Electrical, Electronic, Electromechanical
FinFet	Fin Field Effect Transistor (a “fin” is a raised channel from source to drain)
FIT	Failure Unit or Failure in Time (a failure rate metric)
IC	Integrated Circuit
LLM	Life-Limited Microcircuit
LRU	Line-Replaceable Unit
Lx/Bx	Life Percent
MTBF	Mean Time between Failures
MTTF	Mean Time to Failure
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
PCBAP	Printed Circuit Board Assembly Process
PoF	Physics of Failure
PWB	Printed Wiring Board (another name for PCB)
PWBA	Printed Wiring Board Assembly

QFN	Quad Flat No Leads (an integrated circuit package)
RET	Reliability Enhancement Testing
RGT	Reliability Growth Testing
RPA	Reliability Physics Analysis
SAT	Simulation Aided Testing
SGT	Simulation Guided Testing
SiP	System in Package
SOI	Silicon on Insulator
SST	Step Stress Testing
TTF	Time to Failure
TTFF	Time to First Failure
VRG	Virtual Reliability Growth

5. RELIABILITY PHYSICS ANALYSIS

This document defines the steps in the RPA process that are used to assess or calculate the likelihood of failure risk in EEE systems, equipment, and/or components operating under expected usage and environmental exposure conditions over an expected durability period. In addition to the purposes described in the rationale section, RPA results may also be used for:

- a. Identification of specific components or design features that may be susceptible to failure during the required durability period or service life of the EEE item, so that weak links can be eliminated via a virtual reliability growth (VRG) process. This would be performed in a CAE environment, reducing or avoiding the cost of building and physically testing prototype parts and related discrepancy investigations and corrective action activities if needed.
- b. Designing and interpreting results of tests, e.g., reliability enhancement testing (RET), reliability growth testing (RGT), simulation guided testing (SGT), simulation aided testing (SAT), etc., to determine, or enhance, the performance or reliability of the system, equipment, or component.

The baseline RPA process is similar in format to those of JEDEC JESD94, ARP6338, and ARP6379, although its applicability is more general than in those references. The main steps of the RPA process are shown schematically in [Figure 1](#). The process flow has five baseline RPA durability simulation modeling tasks that focus on failure risk issues that frequently occur and on emerging new technology concerns in AADHP systems (see [Figure 2](#)). These are:

- Three board level reliability (BLR) EEE component attachment structural integrity issues related to thermo-mechanical cycling, vibration, and shock.
- Susceptibility to PCB circuit vertical interconnect (vias) fatigue cracking due to PCB expansion/contraction during thermo-mechanical cycling.
- Aging/wearout risks in advanced life limited microcircuits.

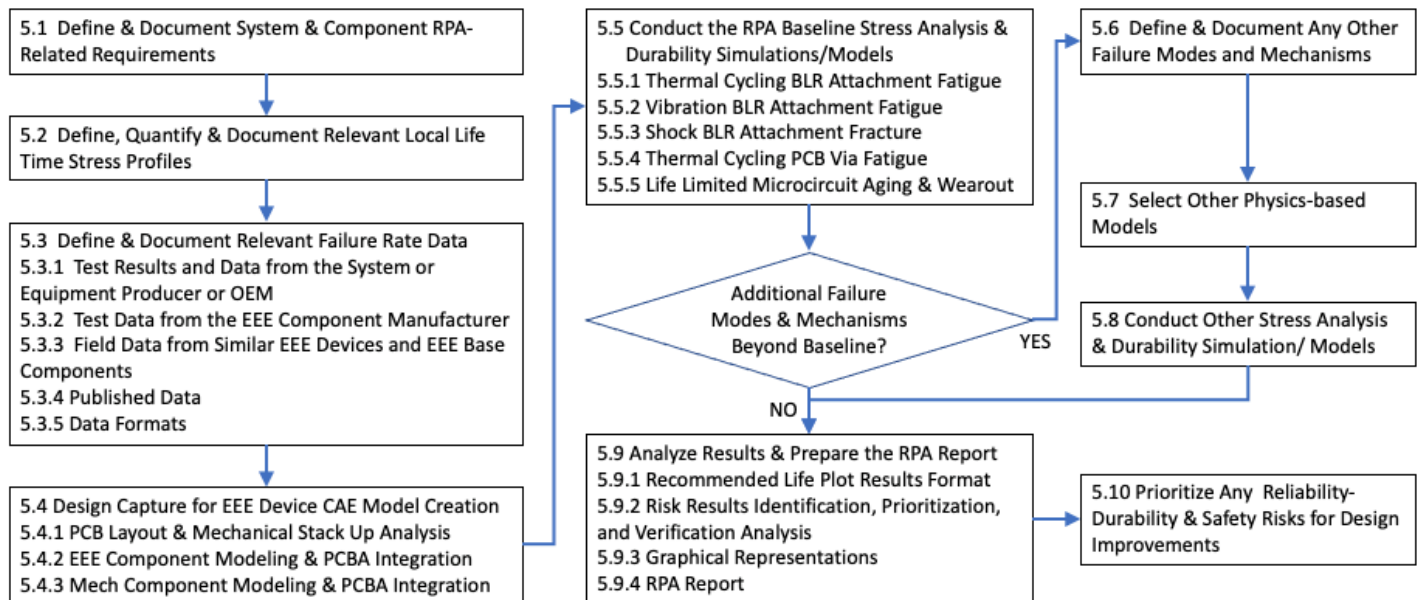


Figure 1 - Flow diagram of the RPA process

Modeling and analysis of other failure mechanisms (beyond those of the baseline tasks defined in [5.5](#)), may be included as optional tasks as warranted by the application and available modeling resources. Additional modeling tasks are defined and managed on the parallel process flow path denoted by tasks [5.6](#), [5.7](#), and [5.8](#). It is up to the RPA process owner to identify if additional failure modes need to be addressed and determine if appropriate additional failure mechanism model(s) exist that are sufficiently validated to be acceptable to the EEE device program stakeholders, customers, or end users.

Similarly, if it can be shown that any of the baseline failure mechanisms do not pose a risk to the performance, reliability, or durability of a specific EEE application, they need not be included in the RPA. For example, if an EEE device is mounted to a stationary structure, instead of being incorporated in a vehicle or aircraft, the in-service vibration and shock analysis may not be needed.

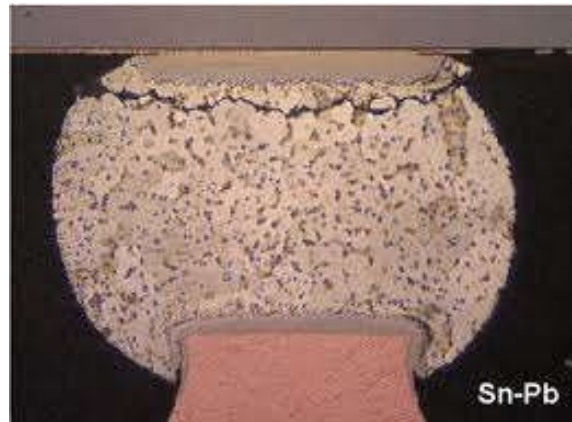


Figure 2A - BLR fatigue crack in a large BGA IC solder ball

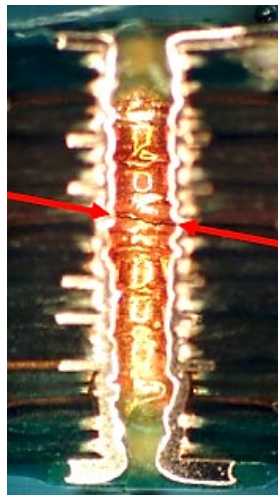


Figure 2B - Plated through hole via copper barrel thermo-mechanical cycling fatigue crack

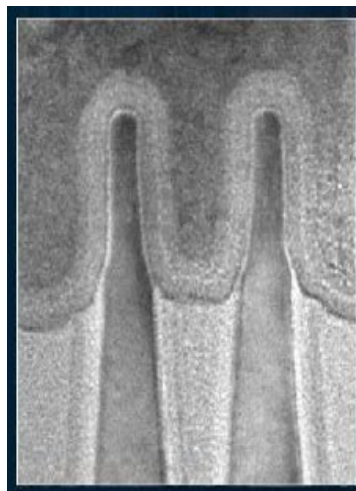


Figure 2C - SEM image of a fin field effect transistor (FinFET) in a microcontroller IC that may have life limited microcircuit risks, depending on the application

Figure 2 - Examples of RPA baseline failure concerns