SAE Aerospace
An SAE International Group

# AEROSPACE RECOMMENDED PRACTICE

SAE ARP5890A

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Superseding ARP5890

## (R) Guidelines for Preparing Reliability Assessment Plans for Electronic Engine Controls

RATIONALE

This document has been reviewed by the E36 committee as part of the recommended a 5-year update plan. The committee felt this document should be updated to reflect current practice, which has moved on considerably since its initial publication.

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## 1. SCOPE

This document establishes guidelines for a Reliability Assessment Plan (herein also called the Plan), in which Electronic Engine Control manufacturers document their controlled, repeatable processes for assessing reliability of their products. Each Electronic Engine Control manufacturer (the Plan owner) prepares a Plan, which is unique to the Plan owner.

This document describes processes that are intended for use in assessing the reliability of Electronic Engine Controls, or subassemblies thereof. The results of such assessments are intended for use as inputs to safety analyses, certification analyses, equipment design decisions, system architecture selection and business decisions such as warranties or maintenance cost guarantees.

This Guide may be used to prepare plans for reliability assessment of electronic engine controls in which, typically, the impact of failure is high, the operating environment can be relatively severe and the opportunity to improve the equipment after the start of production is limited. In this and similar industries, accurate estimates of expected equipment reliability are necessary prior to the start of production. This guide was initially produced in response to the recognized need for alternative reliability assessment and prediction methods in the wake of the decline in the availability of mil-spec parts and the declining use of military specifications and handbooks.

Since the original publication of this document, a more advanced approach to handbook prediction has been developed, re-introducing this assessment method as a more viable option. This re-issue describes recent handbook advances while also highlighting a number of emerging reliability risks resulting from advances in electronic component development.

The approach to reliability assessment in this Guide:

- Encourages the equipment manufacturer (the Plan owner) to consider all relevant information regarding equipment reliability which may include the effects of design and manufacturing process as well as component selection issues. This is in contrast to more traditional methods that focus on component reliability as the most significant contributor to the equipment reliability.

- Encourages the equipment manufacturer to define and use the processes that are most effective for the manufacturer's own equipment. This guide does not attempt to prescribe a set of acceptable data, algorithms, methods, or equations to be used in reliability assessment, but rather to provide a 'toolbox' of complementary assessment methodologies based upon a number of current practices.

- Describes a continuous process, in which a reliability assessment can be updated as more information becomes available during the equipment life cycle. This information may be used to improve both the reliability of the equipment and the effectiveness of the assessment process.

Reliability assessment results should be viewed as objective evidence that it is expected the product reliability requirements and goals will be satisfied, by the proposed design. As such, they may be used, for example, to authorize advancement to the next step in product development, or to authorize progress payments, or to proceed with delivery and acceptance of products. Reliability assessment results should never be used to support a claim that the reliability requirements, goals, or expectations have been satisfied, in the face of clear evidence to the contrary from in-service experience.

Traditional approaches to reliability assessment, including Handbook Predictions and Durability Analysis described herein, primarily address unreliability resulting from hardware defects within the equipment. It is not the intention of the ARP to provide methods and processes to specifically address software and system reliability issues but it is recognized that system and software design errors contribute to product unreliability and that the use of Similarity Analysis, for instance, can encompass these sources of unreliability.

This SAE Aerospace Recommended (ARP) Practice is intended as a guide towards standard practice and is subject to change to keep pace with experience and technical advances.

## 2. APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

### 2.1 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.

ARP4754 Certification Considerations for Highly-Integrated or Complex Aircraft Systems

ARP4761 Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment

870050 Automotive Electronic Reliability Prediction

### 2.2 IEEE Publications

Available from Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854-4141, Tel 732-981-0060, http://www.ieee.org/.

IEEE 1413 Standard Methodology for Reliability Predictions and Assessment for Electronic Systems and Equipment

### 2.3 International Electrotechnical Commission Publications

Available from International Electrotechnical Commission, 3, rue de Varembe, P.O. Box 131, 1211 Geneva 20, Switzerland, Tel: +44-22-919-02-11, http://www.iec.ch/.

IEC 61508 Functional Safety of Electrical / Electronic / Programmable Electronics Safety related Systems

IEC 61709 Electronic Components – Reliability – Reference Conditions for Failure Rates and Stress Models for Conversion

IEC 62396 Process management for avionics – Atmospheric radiation effects

IEC 62239 Process management for avionics – Preparation of an Electronic Components Management Plan

### 2.4 Reliability Information Analysis Center Publications

Available from RIAC, 201 Mill Street, Rome, NY 13440-6916. http://theriac.org/riacapps/search/

RiAC EPRD- Electronic parts Reliability Data

RiAC VZAP Electrostatic discharge Susceptibility Data

RiAC 217Plus$^{tm}$ Integrated software tool for assessing system and component reliability

2.5 U.S. Military Publications

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, http://assist.daps.dla.mil/quicksearch/.

MIL-HDBK-217 Reliability Prediction of Electronic Equipment

MIL-HDBK-87244 Avionics/Electronics Integrity

2.6 Other Publications

ANSI / VITA 51.1-2008 Reliability Prediction MIL-HDBK-217 Subsidiary Specification

British Telecom Handbook “Handbook of Reliability Data for Components used in Telecommunications Systems”, British Telecom, Materials and Components Centre, 1987

British Telecom “Handbook for Reliability Data”, Issue 5 (HRD5)

Centre National D’Etudes des Telecommunications (CNET) Handbook

UTE-C 80811 FIDES - Reliability Methodology for Electronic Systems

GEIA-STD-0005-1: Performance Standard for Aerospace and High Performance Electronic Systems Containing Lead-free Solder

GEIA-STD-0005-2: Standard for Mitigating the Effects of Tin Whiskers in Aerospace and High performance electronic Systems

GEIA-HB-0005-2: Technical Guidelines for Aerospace and High performance electronic Systems Containing Lead-free Solder and Finishes

ISBN 0-471-78617-9: Lead Free Electronics: Edited by Ganesan and Pecht

JESD47F - JEDEC Solid State Technology Association - Stress-Test-Driven Qualification of Integrated Circuits

Nippon Telegraph and Telephone Handbook

Siemens Standard SN29500

Technical Reference SR-332 “Reliability Prediction Procedure for Electronic Equipment”, Telcordia Technologies



3. PLAN TERMS, DEFINITIONS AND ABBREVIATIONS

The Plan author should make every effort to prevent ambiguous or inconsistant statements within the plan by the utilisation of consistant terms and definitions. Abbreviations and acronyms should be spelled out and compiled if used frequently. The list below provides some examples, from this ARP, which may be of use to the author in the production of the plan.

Durability Analysis: An analysis of the equipment’s responses to the stresses imposed by operational use, maintenance, shipping, storage, and other activities throughout its specified lifecycle in order to estimate its expected life.

Electronic Components: Electrical or electronic devices that are not subject to disassembly without destruction or impairment of design use. They are sometimes called parts, or piece parts. Examples are resistors, diodes, etc.

Electronic Engine Control: Primarily LRU (EEC) but not excluding possible application to other elements of the control system.

Electronic Equipment: An item, e.g., end item, sub-assembly, line-replaceable unit, shop replaceable unit, or system, designed by the Plan owner.

FEA: Finite Element Analysis

FFOP: Failure-Free Operating Period

FMEA: Failure Mode and Effect Analysis

FMECA: Failure Mode Effect and Criticality Analysis

FRACAS: Failure Reporting, Analysis and Corrective Action System

FTA: Fault Tree Analysis

HCI: Hot Carrier Injection

Life-Cycle: A period of time extending from the equipment concept design phase through to the end of in-service support and disposal.

LOTC: Loss Of Thrust Control

LRU: Line Replaceable Unit

MFOP: Maintenance-Free Operating Period

MTBF: Mean Time Between Failures

MTBUR: Mean Time Between Unscheduled Removals

NBTI: Negative Bias Temperature Instability

OEM: Original Equipment Manufacturer

PCB: Printed Circuit Board

Reliability: The ability of an item to perform a required function under stated conditions for a stated period of time.

Similarity Analysis: The structured comparison of the elements of the equipment being assessed with those of predecessor equipment for which in-service reliability data are available.

SRU: Shop Replaceable Unit

TBBD: Time Dependent Dielectric Breakdown

TLD: Time Limited Dispatch

TTF: Time to Failure

## 4. RELIABILITY ASSESSMENT PLAN FOR ELECTRONIC ENGINE CONTROLS

### 4.1 Plan Content

A Reliability Assessment Plan for Electronic Engine Controls, prepared in accordance with this Guide, should record the processes used to satisfy the provisions of 4.1.1 through 4.1.5, shown schematically in the Assessment Diagram of Figure 1.

Detailed descriptions of the reliability assessment process should be included in the Plan owner's document. The Plan should show how the sub-processes of 4.1 fit together to form the entire reliability assessment process. Use of a diagram similar to that of Figure 1 is recommended to communicate the major elements of the Plan.

To avoid duplicating descriptions of processes that may already be documented elsewhere, the Plan owner may refer to other documents in the Plan owner's controlled document system as described in 4.6.

4.1.1 Process

Reliability assessments depend upon a correct understanding of the reliability requirements and should be conducted according to a documented, controlled, and repeatable process that combines those data and methods that are appropriate to the product type and its life-cycle stage (e.g., design, qualification, in-service, etc).

4.1.1.1 Equipment Reliability Requirements

A description of the process that the Plan owner will use to capture and interpret the equipment reliability requirements, reach agreement upon them with the customer and record them should be included. A standard format, such as that shown in Figure 2 is recommended for defining and reporting reliability requirements. Such a format may be used by the Plan owner to communicate reliability requirements to the purchaser of the equipment, regulatory agencies or any other entity holding a stake in the reliability of the equipment, including internal customers.

The primary sources for reliability requirements will be customer requirements specifications and regulatory agency regulations in conjunction with internal technical and business objectives.

Where reliability requirements from these sources are specified as tangible and unambiguous, then Figure 2 should include traceability to the original requirement.

For those reliability objectives that require further clarification, Figure 2 may be used to define and agree upon a set of derived requirements. These requirements should be based upon well defined reliability metrics, such as MTBF, TTF or MFOP, and should record the agreed interpretation of the requirement with any assumptions. Traceability from the derived requirement to the original higher level, less tangible, reliability objective should be provided.

The form of Figure 2 may be used to record test, analysis and in-service data. The form may then provide an ongoing indication of the predicted versus actual reliability performance of the equipment, as it progresses through the design and development cycle and into revenue service. Figure 2 may also be used to provide traceability from the original reliability requirement to each test and analysis activity carried out to verify that the equipment performance will meet its specified requirements.

4.1.1.2 Understand Product Reliability Risks

The plan owner should provide sufficient evidence to demonstrate a good understanding of the failure mechanisms most likely to manifest themselves at the product level. This knowledge may be determined from maintenance records for existing products, currently in service operation, or from data acquired from product test and qualification. At the most basic level it is important to distinguish between failures mechanisms characterized by the infant mortality, wear out and the useful life elements of the bathtub curve. This distinction is necessary to ensure the most appropriate analysis methods for reliability assessment are selected.

As an example, if a manufacturing process failure dominates In-Service returns for a previous product, it is likely that this product will demonstrate infant mortality, as represented by a decreasing failure rate model. Alternatively, it may be that endurance testing of the new product has highlighted a wear-out mechanism. In this case an increasing failure rate model may be more appropriate.

In the majority of cases, however, product failure will not be dominated by a single mechanism but by a combination of failure modes, each with their own characteristic.

Over the service life of the product, this combination of failure mechanisms will appear at a random [or constant] rate, indicating the 'useful life' period. It is for this reason that a constant failure rate model is predominately used as the underlying assumption for reliability assessment.

However, in making this judgment it is important to consider the context in which the assessment results may be used for decision making. While a constant failure rate model may provide a good indicator of comparative reliability over a long period of time, a warranty threshold may be best defined using a decreasing failure rate model, as this can better represent the impact of those failure mechanisms that display infant mortality. Likewise, if the assessment results are being used to determine an overhaul period or maintenance schedule, then an indication of specific wear out issues would be best provided to the decision maker, using increasing failure rate model.

In some cases, a review of maintenance records may indicate that the product failure rate is inconsistent with its removal rate. This skew can often be caused by ineffective maintenance systems or troubleshooting practice, where EECs are incorrectly rejected from the aircraft system and are subsequently tested to confirm no fault is present. If Rejection Rate is agreed as an important requirement, then assessment should include failures of the wider system as well as the EEC itself.

Since the initial issue of this document, an increased risk to reliability performance has been introduced with the use of lead free solders.

4.1.1.2.1 Lead Free Solder

Following the implementation of RoHS (Removal of Hazardous Substances) legislation within the EU, the use of Lead within electronic equipment has been prohibited. At the time of publication however, the Aerospace industry has been granted an exemption from the RoHS legislation, but it is unlikely that this exemption will remain into the future. In the short term, therefore, the Aerospace industry has not been mandated to manufacture products with non-lead based solder. However, the commercial electronic industry (e.g. computers and mobile phones), dominate the market need for electronic components and they must comply with RoHS legislation. This has consequently had an impact on component termination finishes which have, in the main, been converted from tin-lead to pure tin. The main impact of tin solder on reliability is the well known propensity for pure tin to spontaneously form whiskers. These whiskers can vary in length from a few microns to several millimeters. This effect introduces the possibility of short circuits being formed between adjacent unconnected circuit elements. Mitigation strategies to minimise the impact of whiskers on product reliability must therefore be considered, if pure tin termination finishes are to be used.

Lead free solders are generally comprised of tin, silver and copper, in various proportions; typically around 3% silver and 0.5% copper with the balance made up from tin. The alloy designation is generally abbreviated to SAC plus a number, where the number represents the silver and copper content; e.g. SAC305 contains 3% silver and 0.5% copper. These alloys are more brittle than conventional tin-lead solder and as a consequence are not as resistant to shock and vibration. The thermal cycle performance of solder joints made using SAC solder is very dependant on the test regime used so prediction of in-service performance and life expectation cannot be easily assessed with any confidence.

Furthermore SAC alloys melt at a higher temperature than conventional tin-lead solder and thus a higher degree of thermal damage to both PCBs and electronic components may occur during assembly, consequently affecting the reliability performance of the product.

4.1.1.2.2 Current Research into Lead Free Soldering

Extensive research into the reliability of lead free solder joints and tin whisker formation is being carried out at academic institutions throughout the world. The Centre for Advanced Life Cycle Engineering (CALCE) at the University of Maryland is at the forefront of research in the USA along with the National Physical Laboratory (NPL) in the UK. Current research focus is on both solder joint life and reliability and reliability prediction, on the understanding of tin whisker formation and perhaps more importantly on the mitigation of tin whiskers to prevent their formation impacting on unit functionality and reliability. In the Aerospace and Defense industry, research is being coordinated by the PERM (Pb-free Electronics Risk Management) consortium who are authors to the GEIA standards and handbook referenced below.

4.1.1.2.3 Recommended Reading

Useful publications which contain additional technical information are listed below

ISBN 0-471-78617-9: Lead Free Electronics: Edited by Ganesan and Pecht

GEIA-STD-0005-1: Performance Standard for Aerospace and High Performance Electronic Systems Containing Lead-free Solder

GEIA-STD-0005-2: Standard for Mitigating the Effects of Tin Whiskers in Aerospace and High performance electronic Systems

GEIA-HB-0005-2: Technical Guidelines for Aerospace and High performance electronic Systems Containing Lead-free Solder and Finishes

4.1.1.3 Understand Component Reliability Risks

The Plan owner should identify the types of electronic component that will be used within the equipment, particularly those with little service pedigree or high technological risk. The Plan owner should provide sufficient evidence to demonstrate a good understanding of the reliability risks associated with the specific components or technologies selected for use within the equipment design. This should include a reasoned argument as to the most appropriate data and analysis methods for carrying out an effective assessment.

Since the initial issue of this document, a significant risk to reliability performance has developed from a continued reduction in IC feature size; this is particularly noticeable in IC processes which fall below 1 Micron. A reduction in feature size below this value has been shown to significantly increase the wear out mechanisms within the IC while also increasing the threat posed by Single Event Effects (SEE). These issues are briefly described in sections 4.1.1.3.1 and 4.1.1.3.2 respectively.

It is recommended that the plan owner assess the feature size of all electronic components (particularly memory), within their proposed design, in order to determine whether they may pose a threat to product reliability. If this is the case the most appropriate means to assess this threat may then be selected.

4.1.1.3.1 Single Event Effects

Cosmic Rays that interact with the Earth's atmosphere produce a flux of high energy secondary neutrons. These secondary neutrons can produce Single Event Effects, SEE, within submicron electronic devices. The effects can be observed at sea level but at aircraft altitudes the high energy secondary neutron flux is much higher; over two decades higher at 40,000 feet altitude. The type of SEE may vary from simple upset (change of state) for a memory to more permanent events including latch up and burn out. Very low energy thermal neutrons are produced by interaction of the high energy neutrons with the aircraft; these can produce SEE in vulnerable devices with boron 10 in the BPSG passivation.

Work has been carried out to characterize the atmospheric radiation environment and there are several models that are available to calculate the secondary neutron flux at any flight location directly. However, a nominal value has been defined within the IEC technical specification 62396 which may be scaled for different locations. In order to assess the SEE tolerance of avionics equipment it is necessary to identify the potentially SEE sensitive parts and determine their SEE tolerance, this information can then be used to assess the impact at equipment and system level. IEC TC62396 provides a comprehensive means of assessing the impact of SEE on product reliability.

IEC 62396-1 Process management for avionics – Atmospheric radiation effects

Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment

IEC 62396-2 Process management for avionics – Atmospheric radiation effects

Part 2: Guidelines for single event effects testing for avionics systems

IEC 62396-3 Process management for avionics – Atmospheric radiation effects –

Part 3: Optimising System Design to accommodate the Single Event Effects, SEE of Atmospheric Radiation

IEC 62396-4 Process management for avionics – Atmospheric radiation effects

Part 4: Guidelines for designing with high voltage aircraft electronics and potential single event effects

IEC 62396-5 Process management for avionics – Atmospheric radiation effects

Part 5: Guidelines for assessing thermal neutron fluxes and effects in avionics

4.1.1.3.2 Wear-Out of Sub-micron Electronic Devices

Reliability assessment for semiconductor devices with feature sizes above 1 micron have been successfully performed using a constant failure rate assumption for many years. However with reducing feature sizes below 1 micron the internal stresses within the devices (power per unit volume, voltage and current) has greatly increased. This is predominantly because the device voltage and currents have not reduced in proportion with the geometric feature size reductions. At device feature sizes of about 0.1 micron the increased stresses and resulting degradation mechanisms may impact both the reliability and operating life in the application environment. For this reason, consideration must be given to potential wear out within its operational life, which suggests that an increasing failure rate model may best represent the reality.

Academic and industry consortia have carried out detailed investigation of potential degradation mechanisms and have concluded that four mechanisms dominate the behavior; Hot carrier injection [HCI], time dependant dielectric breakdown [TDDB], negative bias temperature instability [NBTI] and electro-migration. During operational usage, these devices will, as a population, degrade away from their initial characteristics. The time at which the devices fail intrinsically in the given application will be dependant on a complex function of a large number of factors which include feature size, deployment, environmental and application electrical stresses. However, effective derating as part of the design process, may enable such parts to meet operational requirements

Investigation of these effects in devices with geometric feature sizes below 0.2 microns has been carried out by the Aerospace Vehicle Systems Institute as part of projects AFE17 and AFE71. The following references are recommended for futher reading.

IEC TS 62239 - Process management for avionics – Electronic Components Management Plan

AFE17 Aerospace Vehicle Systems Institute, Methods to Account for Accelerated Semiconductor Device Wear Out

AFE71 Aerospace Vehicle Systems Institute, Reliability Prediction Software using FARBS and MaCRO

JESD47F - JEDEC Solid State Technology Association - Stress-Test-Driven Qualification of Integrated Circuits

4.1.1.4 Reliability Assessment Staging

The Plan should include a schedule that defines at which phases of the equipment life cycle the Plan owner will conduct reliability assessments. The intent is to define a progressive process in which the Plan owner will update the reliability assessment as more data become available throughout the design and development of the equipment. Following the equipment's entry into service, any updates to the reliability assessment will be determined by prior agreement between the supplier and purchaser of the equipment.

It is recommended that the reliability assessment process be continually updated as data become available throughout the equipment life cycle.

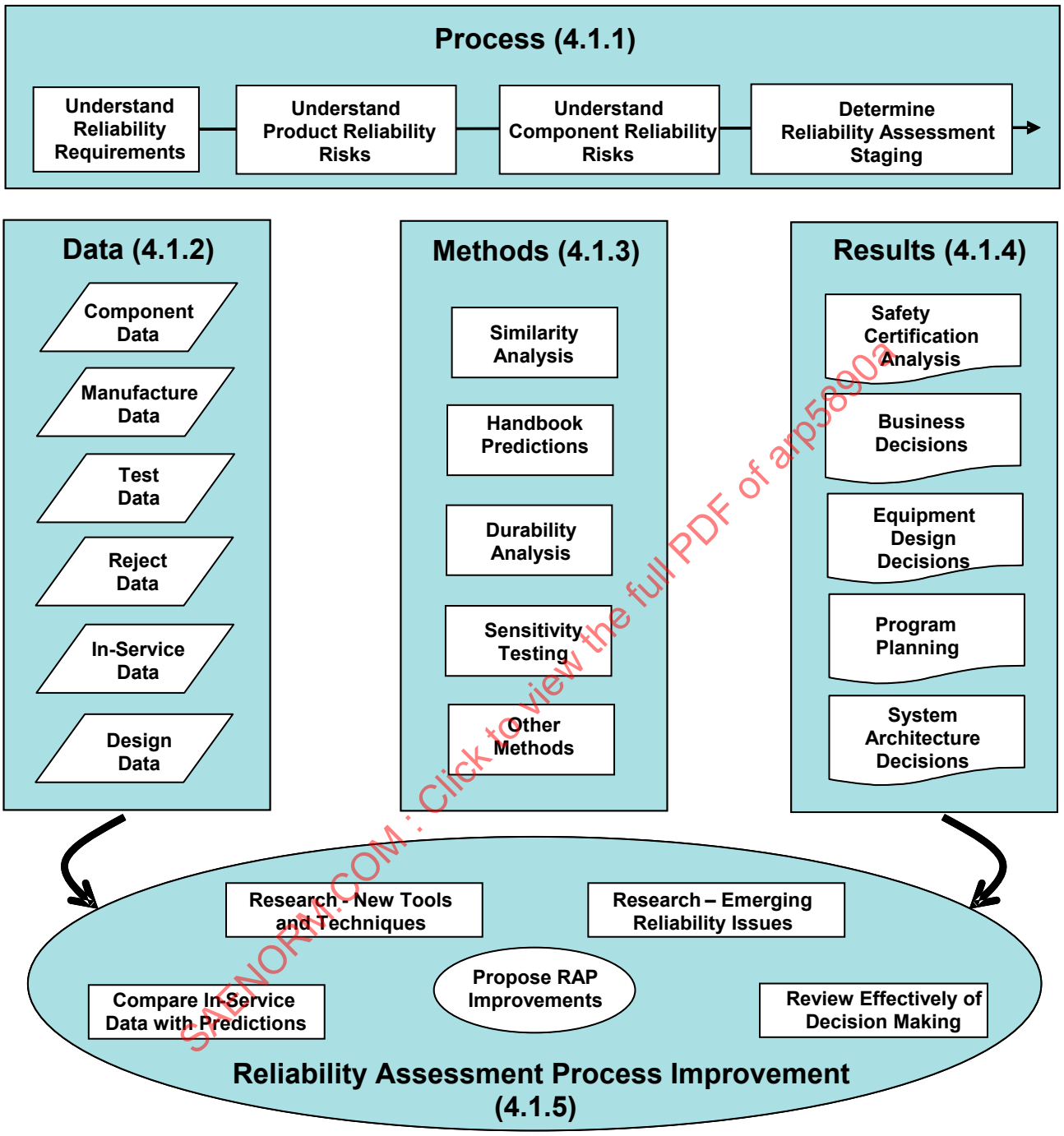




FIGURE 1 – RELIABILITY ASSESSMENT DIAGRAM

4.1.2 Data

Data used in reliability assessment should be obtained from credible and relevant sources and should be controlled, updated, accessed, and used according to consistent processes. Data may be obtained from equipment, sub-assembly or component testing, in-service performance, and other relevant data sources. A process that defines how the accuracy and completeness of the data are determined should be included in the Plan.

To avoid duplicating descriptions of processes that may already be documented elsewhere, the Plan owner may refer to other documents in the Plan owner's controlled document system to record the data management system.

4.1.2.1 Data Sources and Types

The data sources that the Plan owner may use as inputs to reliability assessment processes should be described. As a general rule, data from the Plan owner's equipment and component manufacturers are highly preferred over data obtained from general industry sources, provided that the population of data is sufficient to carry out a credible statistical analysis. Specific data captured directly from the Plan owner's equipment and component suppliers is preferred over general industry data because specific failure rate information for an LRU, sub-assembly or piece part will implicitly reflect the design and manufacturing process capability for the individual equipment supplier.

If sub-assembly or component level data is being used, an evaluation of the interaction of components in the design needs to be included to ensure failure modes included in the data are applicable and potential failure modes are not overlooked.

A description of the process, based upon sound statistical evidence, that defines how the Plan owner selects the most appropriate data source for the particular assessment application should be included in the Plan.

**RELIABILITY REQUIREMENTS REPORT**

Equipment ID No.: _____ Date: _____

Equipment Name: _____ Equipment Manager: _____

Reliability Engineer: _____

| Requirement Reference | Reliability Metric | Required Value | Actual / In-Service Performance | Test Reference | Analysis Reference |
|---|---|---|---|---|---|
| | | | | | |
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**Requirements Interpretation and Assumptions**

**Summary of Environmental and Operating Conditions**

**Summary of Type and Level of Maintenance**



FIGURE 2 - RELIABILITY REQUIREMENTS REPORT FORM

Examples of data from the Plan owner's equipment include:

1. Qualification test data from components and sub-assemblies;
2. Quality assurance test data from component and sub-assemblies;
3. In-service data from similar equipment and similar applications;
4. In-service data from components and sub-assemblies in similar equipment and similar applications;
5. Manufacturing and Statistical Process Control data from similar equipment, components, and sub-assemblies;
6. Development test data from engineering;
7. Environmental stress screening, functional test, and acceptance test data from production
8. Test and rework data from non-OEM facilities such as third party repair and overhaul facilities.

Examples of data from other sources are:

1. Data from component manufacturers;
2. Data from industry and consortia databases
3. Data from handbooks.

The types of information may include:

1. Maintenance action (Diagnostics activity, Scheduled/Non-scheduled, repaired, replaced, removed for use on other aircraft);
2. Fault indication and confirmation (BITE data, cockpit warnings/observed effects);
3. Failure effect or criticality (including loss of function and any effects of secondary damage);
4. Failure mode;
5. Failure mechanism;
6. Failure site;
7. Operating and environmental conditions to which the LRU is nominally subjected and those at which the failure occurred;
8. Hours and Cycles of the equipment or sub-assembly in which the failure occurred (including aircraft duty cycle, i.e. operating versus non-operating, powered hours);
9. Corrective actions for the failure;
10. Failure analysis results, including root cause;
11. Total population exposure time or cycles (possessed, operating, or flight).
12. Trending and prognostic data.

It is essential to select data that will enable calculation of appropriate reliability metrics.

#### 4.1.2.2 Data Collection, Storage, and Retrieval

A description of the processes the Plan owner will use to collect, store and retrieve reliability assessment data should be included in the Plan. The data are usually integrated into a larger database, as opposed to a separate reliability assessment database. If this is done properly, all relevant data, including lessons learned, are available to design and manufacturing personnel for use on current and future equipment. When using field data for the purposes of reliability assessment it is crucial to understand the accuracy of the data and the integrity of the data collection process itself. For example, when using field data to predict a critical failure rate, such as LOTC, for a safety analysis, it is necessary to ensure that source data is current, complete and provided by a collection process that will focus on capturing all pertinent data.

Limitations in both the scope of recording and accuracy of reporting data must be understood. Clearly for the purposes of data analysis, equipment's failure rate would be seen as zero if the level of its test coverage is insufficient to detect particular faults. The same optimistic analysis would result if faults were detected, but were not reliably reported. Confidence in data is critical when determining unit safety as it often involves two failures, one of which, may be dormant.

When defining the scope of the data collection process, the Plan owner should consider the ability of the process to detect and record those failures that subsequent data analysis may be used to predict. A description of those processes that ensure controlled, repeatable data collection should be included in the Plan. Further data management information is described in ATA Specification 2000.

### 4.1.3 Methods

Reliability assessments should be conducted using documented, controlled, and repeatable methods and techniques which may include analyses and/or testing. These methods should undergo some form of validation. The Plan should include the results of validation carried out to indicate the accuracy and limitations of each method. This information may be used to determine the applicability of an assessment method to a particular reliability assessment activity. Continued validation of each assessment method will be available in the form of in service data. Current correlation between predicted and actual reliability performance can be provided to justify the selection of a particular method for any subsequent assessment, taking credit for any proven process improvements. Guidelines for managing reliability assessment validation and improvement are detailed in 4.1.5.

A description of all the methods the Plan owner will have available for assessing the expected reliability of a given equipment (including the necessary calculations) using the data described in 4.1.2, should be included. The Plan owner may select the methods described within this section or other methods that the Plan owner intends to have available. The intent is for the Plan owner to document all the analysis and calculation processes that will be available.

More than one method may be applicable to the subject equipment. In fact it may be advantageous for the Plan owner to apply more than one method to a single product in order to establish a representative reliability assessment. The Plan should include a justification for the selection of the particular assessment method(s). The justification process should be described in the Plan and include sound statistical evidence that can demonstrate that the data source and method are applicable to the assessment application in question.

#### 4.1.3.1 Similarity Analysis

Similarity analysis includes the use of in-service equipment performance data to compare newly designed equipment with predecessor equipment for predicting end item reliability. Appendix A offers guidelines in the form of examples of this method.

Comparisons of similar equipment may be made at the end item, sub-assembly, or component level using the same field data, but applying different algorithms and calculation factors to various attributes, described below. Comparison with similar equipment may also be made at the functional level to provide base failure-rate data for safety analysis or architectural decision making.

Attributes to be compared may include:

1. Operating and environmental conditions (measured and specified);
2. Design features;
3. Design processes;
4. Design team experience with similar designs;
5. Manufacturing processes, including quality control;
6. Manufacturer's experience with similar components and processes;
7. Built in test and fault isolation features;
8. Test and maintenance processes;
9. Components and materials;
10. Date or other measure of technology maturity and
11. Quality of the reliability assessment processes.

For each of the above attributes, a number of lower level attributes should be compared. As examples, operating and environmental conditions may include steady-state temperature, humidity, temperature variations, electrical power, duty cycle, mechanical vibration, etc.; equipment design features may include number of components (separated according to major component family), number of circuit card assemblies, size, weight, materials, etc. Similarity analysis should include necessary algorithms or calculation methods used to quantify the similarities and differences between the equipment being assessed and the predecessor equipment.

Although the concept of similarity analysis is based very much on locating a 'similar' design, it is finding the critical 'differences' between them, at the appropriate level, that makes the methodology effective. With this in mind it is important that the specific failure modes associated with existing products are reviewed for relevance to a design or technology in a new product.

When an end-item similarity analysis is not possible because no predecessor equipment is sufficiently similar or available for a one-to-one comparison with the newly designed equipment being assessed, then a similarity analysis may be conducted at a lower level (e.g., subassembly, module or component level). The lower level analysis may include the structured comparison of elements of the new equipment with similar elements of a number of different predecessor equipment, for which reliability data are available.

Figure 3 shows a sample checklist that may be used to facilitate an effective similarity analysis and concise results report.

## SIMILARITY ANALYSIS CHECKLIST

The following items are recommended for inclusion in a product reliability assessment report, which uses the similarity analysis method.

GENERAL INFORMATION

[ ] 1) Analysis Date
[ ] 2) Analysts Name
[ ] 3) Approvals – As required
[ ] 4) Program Phase
[ ] 5) Usage of Results

REFERENCES

[ ] 6) Applicable Reliability Assessment Plan Document
[ ] 7) Reliability Assessment Procedure Document
(Alternately, procedure may be included in the analysis portion of the report document)
[ ] 8) Predecessor Data Archive

PRODUCT IDENTIFICATION

[ ] 9) Name of New Product
[ ] 10) Part Number of New Product
[ ] 11) Name of Predecessor Product(s)
[ ] 12) Part Number of Predecessor Product(s)

ANALYSIS

[ ] 13) Level of Analysis (LRU, SRU, Functional, etc.)
[ ] 14) Predecessor Product Data Summary(ies)
[ ] 15) Attributes Compared
[ ] 16) Basis for Quantifying Attribute Differences
[ ] 17) Algorithm or Calculation Method(s)

RESULTS

[ ] 18) Reliability Assessment Metric(s) (MTBF, Failure Rate, etc.)
[ ] 19) Expected variability of Reliability Metric(s)
[ ] 20) Reliability Requirement Metric(s) (If applicable)

FIGURE 3 - SIMILARITY ANALYSIS CHECKLIST

4.1.3.2 Durability Assessment

Durability assessment may include analysis, testing or a combination thereof. It is a structured process that includes the following major steps:

1. Determine operational and environmental loads that the equipment will experience throughout its life, including shipping, handling, storage, operation, and maintenance.

2. Determine transfer functions between applied loads and boundaries of FEA, for example box to circuit card vibration resonances and damping.

3. Determine the magnitudes and locations of significant stresses using, for example, FEA.

4. Determine the likely failure sites, mechanisms and modes using, for example, FEA

5. Determine how long the significant stresses can be withstood or sustained using the appropriate damage models, e.g., Arrhenius equations, inverse power laws, etc

6. Report the results as a list of failure sites, mechanisms, and modes; rank-ordered according to the time expected for failure to occur.

Results from accelerated test methods are recommended as sources of test data for input to the durability assessment.

The durability assessment process should be capable of evaluating, as a minimum, the long term effects of thermal, vibration, and electrical stresses. Capability for other stresses, such as humidity, should be included as needed. It is highly desirable that the assessment be capable of evaluating the effects of a number of stresses simultaneously. Physics of Failure models can be useful for this purpose.

A durability assessment is not limited to use at an LRU level. In fact in some cases it may be difficult to provide an overall reliability assessment for an equipment which contains many devices, each with multiple failure modes. In these cases durability assessment may be used effectively at a lower level, to analyze specific failure modes and mechanisms within the equipment, which cannot be represented by a constant failure rate. The results of this analysis may then be used as part of a higher level analysis, to assess the reliability performance for the overall equipment. Durability analysis can also be used to determine the degree of similarity between LRUs or devices. Given a validated computer model of durability for a predecessor design, it can potentially be used for a similar design to establish the extent of similarity of the response to similar or different operational environments.

Figure 4 shows a sample checklist that may be used to facilitate an effective durability assessment and concise result report; more information is provided in Appendix B.

## DURABILITY ASSESSMENT CHECKLIST

The following items are recommended for inclusion in a product reliability assessment report, which includes the durability analysis method.

GENERAL INFORMATION

[ ] 1) Analysis Date
[ ] 2) Analysts Name
[ ] 3) Approvals – As required
[ ] 4) Program Phase
[ ] 5) Usage of Results

REFERENCES

[ ] 6) Applicable Reliability Assessment Plan Document
[ ] 7) Durability Assessment Procedure Document
(Alternately, procedure may be included in the analysis portion of the report document)

PRODUCT IDENTIFICATION

[ ] 8) Name of Product Assessment Applies To
[ ] 9) Part Number of Product Assessment Applies To

ANALYSIS

[ ] 10) Identify applicable operational and/or environmental stresses
[ ] 11) Identify transfer functions and their source (test/analytical or both)
[ ] 12) Identify magnitude and locations of stresses
[ ] 13) Identify likely failure sites, mechanisms and modes
[ ] 14) Identify expected life using appropriate damage model(s)

RESULTS

[ ] 15) Identify how analyzed failure modes will impact overall reliability metric(s)
[ ] 16) Expected variability in Assessment results

FIGURE 4 - DURABILITY ASSESSMENT CHECKLIST

4.1.3.3 Sensitivity Testing and Analysis

Equipment failure may be dominated by a few well understood failure modes then a structured accelerated test process can provide reliability assessments.

Step stress testing is gaining popularity as a sensitivity test. Its goal is to produce failures in a short time in order to determine the likely failure mechanisms. It will also provide information about design margins with respect to operating and environmental stresses. It is performed on a small sample of the near-final product or a subassembly thereof. In some specialized instances, step stress testing is known by various other names, such as STRIFE (STRess-IIFE), HALT (Highly Accelerated Life Testing), RET (reliability enhancement testing), and others.

Step stress tests are conducted by exposing the units under test to relatively low levels of stress, and then increasing those levels in a controlled, stepwise manner until at least one of the following occurs:

- Stress levels are reached that are significantly higher than those expected in service;
- All the test units fail irreversibly and beyond repair; or
- Irrelevant failures begin to occur or dominate as new failure mechanisms become evident at higher stress levels. Irrelevant failures are those which are not associated with the design of the test unit, such as equipment failure, handling damage, or defects in the production of the test unit.

Statistical analysis techniques (such as Bruceton methods) are used to estimate the reliability parameters. The Reliability Assessment Plan should select which equipment will be subjected to these methods and which analysis methods (or commercially available software) will be used.

Figure 5 shows a sample checklist that may be used to facilitate an effective sensitivity analysis and concise results report.

## SENSITIVITY TESTING AND ANALYSIS CHECKLIST

The following items are recommended for inclusion in a product reliability assessment report, which uses the sensitivity testing and analysis method.

GENERAL INFORMATION

[ ] 1) Analysis Date
[ ] 2) Analysts Name
[ ] 3) Approvals – As required
[ ] 4) Program Phase
[ ] 5) Usage of Results

REFERENCES

[ ] 6) Applicable Reliability Assessment Plan Document
[ ] 7) Sensitivity Testing and Analysis Procedure Document
(Alternately, procedure may be included in the analysis portion of the report document)

PRODUCT IDENTIFICATION

[ ] 8) Name of New Product
[ ] 9) Part Number of New Product

TEST/ANALYSIS

[ ] 10) Failure modes investigated
[ ] 11) Test methodology and its basis
[ ] 12) Test results
[ ] 13) Statistical method for conversion of test results for use in reliability metric(s)

RESULTS

[ ] 14) Impact of results on reliability metric(s)
[ ] 15) Expected variability in reliability metric(s)

FIGURE 5 - SENSITIVITY ANALYSIS CHECKLIST

#### 4.1.3.4 Handbook Predictions

Handbook predictions are made by following the directions in the handbook chosen for use, or in the software used for implementing handbook predictions. Examples of reliability prediction handbooks are:

- ANSI / VITA 51.1-2008
- British Telecom Handbook;
- Centre National D'Etudes des Telecommunications (CNET) Handbook;
- FIDES
- IEC 56 Sec 60348;
- MIL-HDBK-217;
- Non-electronic Parts Reliability Data NPRD-95;
- Nippon Telegraph and Telephone Handbook;
- RiAC 217 Plus;
- RiAC-EPRD;
- RiAC-VZAP;
- Siemens Standard SN29500 and
- SAE 870050.
- Telecordia SR-332

It is expected that the appropriate handbook will be selected for each application. Handbook users should ensure the applicability and currency prior to use. Plan owners may wish to supplement or replace the handbook data with data from their own operations or other sources. Some handbooks such as SR-332 provide explicit direction on how to do this for test (Method II) and field (Method III) data. If modifications using data are not within the specific handbook methodology, it should be recorded as an exception to the handbook process. Figure 6 shows a sample checklist that may be used to facilitate an effective handbook prediction and concise results report.

With the combined electronics market trend of faster time to market, greater use of commercial electronics in high reliability applications, increasing processing speeds, higher power densities and decreasing feature sizes, the relevance of using traditional handbook reliability predictions in the design process has reduced. Reliability predictions are needed, not only as a deliverable to a customer or as a generalized metric for logistics and program planners, but also as a tool to identify design and process improvements or environmental mitigation measures. To accomplish this, the analysis must provide detailed assessment of physical failure mechansims in the expected environments; most handbooks fall short of this need.

This is not to say that handbook methods do not have their place. Handbook methods may be necessary to support legacy requirements or be mandated by the Plan owner's customer. There may also be a need for individual component reliability predictions to support system safety analysis, for which handbook methods may be the only viable option. However the weakness of the traditional handbook approach in neglecting causes of failure, other than individual component reliability, needs to be recognized if reliability improvement is to be realized.

Efforts are underway in industry, the DoD and academia to define new handbook methods that better support design and provide detailed physics of failure based assessments. RiAC published a physics of failure handbook in 2008, based on research that was done by the Aerospace Vehicle Systems Institute (AVSI) in semiconductor wearout mechanisms. GEIA-STD-0009, published in 2008 and adopted by the DoD in 2009 provides a program standard for using reliability in a systems design process emphasizing reliability growth and placing less emphasis on predictions. The VMEbus International Trade Association (VITA) working group VITA 51 is developing a physics of failure based reliability prediction standard for electronics modules, VITA 51.2. Finally, the preparing authority for MIL-HDBK-217, the Naval Surface Warfare Center (NSWC) at Crane, Indiana, is investigating using physics of failure based models for future revisions of MIL-HDBK-217, possibly starting with Rev H.

## HANDBOOK PREDICTION CHECKLIST

The following items are recommended for inclusion in a product reliability assessment report, which uses handbook prediction method.

GENERAL INFORMATION

[ ] 1) Analysis Date
[ ] 2) Analysts Name
[ ] 3) Approvals – As required
[ ] 4) Program Phase
[ ] 5) Usage of Results

REFERENCES

[ ] 6) Applicable Reliability Assessment Plan Document
[ ] 7) Reliability Prediction Handbook
[ ] 8) Reliability Prediction Procedure Document
    [ ] 8a) Applicability
    [ ] 8b) Currency
    [ ] 8c) Changes from Handbook method (If applicable)
    (Alternately, procedure may be included in the analysis portion of the report document)
[ ] 9) Tools used to implement Handbook Prediction (If applicable)

PRODUCT IDENTIFICATION

[ ] 10) Name of New Product
[ ] 11) Part Number of New Product

ANALYSIS

[ ] 12) Level which prediction is performed at
[ ] 13) Applicable input data for Handbook method

RESULTS

[ ] 14) Reliability Prediction Metric(s) (MTBF, Failure Rate, etc.)
[ ] 15) Expected variability in Reliability Metric(s)
[ ] 16) Reliability Requirement Metric(s) (If applicable)

FIGURE 6 – HANDBOOK CHECKLIST

#### 4.1.4 Results

Reliability assessment results should be reported in a consistent format, with sufficient information provided to understand their uses, limitations, and uncertainties.

The reports should be controlled and accessible.

Neither the method of storing nor the distribution of the reliability assessment results are discussed herein because they may be unique to the Plan owner or may be controlled by contractual agreements. The Plan owner should, however, address them either in the Reliability Assessment Plan or in some other controlled document, referenced in the Plan.

##### 4.1.4.1 Uses of Reliability Assessment Results

Reliability assessment results are typically used for:

- Reliability Program Planning and Monitoring;
- Safety Analyses;
- Business Decisions;
- Equipment Design Decisions and
- System Architecture Decisions.

Results reports should include all relevant data with sufficient supporting detail to enable the user of the report to understand the uses, limitations, and uncertainties of the results.



###### 4.1.4.1.1 Reliability Program Planning and Monitoring

Reliability assessment results may be used as deliverables at various milestone points in the product design, development, production, and service life cycle. Reliability program planning should include reliability assessments based on various activities carried out at different stages in the cycle (examples include assembly screening planning, reliability development test planning and reliability verification test planning). Quantitative reliability metrics such as MTBF, failure free operating period, time to failure, reliability growth management goals and reliability acceptance requirements should also be identified. The Reliability Assessment Plan should ensure that sufficient analysis and/or testing is conducted so that these metrics can be produced with the accuracy and confidence required to support reliability program planning decisions in a timely manner. Bayesian statistics may be used to reduce required test sample sizes if the basis of the prior distribution is identified and justified in the Reliability Assessment Plan.

###### 4.1.4.1.2 Safety Assessment

Safety Assessment is the disciplined approach to identifying system hazards and their causes, and to assessing their risks. An output of the reliability assessment is failure rate (LRU, module, piece part or functional level) which is used in various analyses for safety assessment, for example:

- Fault Tree Analysis (FTA);
- Markov Analysis;
- FMEA and
- FMECA.

Traditionally, the handbook approach to reliability assessment has been used exclusively to provide base failure rate data for use in system safety assessment. However, with future designs containing fewer military parts and showing an increasing trend in the usage of very complex, highly integrated devices and COTS products, the handbook approach to reliability assessment became less attractive but was still mandated in many customer contracts and specifications.

If the traditional handbook approach is to be used, its fundamental weakness in neglecting causes of failure, other than individual component reliability, needs to be recognized and made explicit in any reporting. Efforts are underway to define new handbook methods that better support the design activity and provide detailed physics of failure based assessments. It is hoped that these methods will provide the means for carrying out a Safety Assessment with more accuracy and confidence.

In the meantime, this document describes a number of alternative reliability assessment methods that can provide failure rate data from an equipment level down to a functional or piece part level. (For System Safety Analysis the ability to assess the reliability of specific functions is particularly important). When selecting a particular methodology for a specific application, the Plan owner should review the accuracy and limitations of the approach to provide a justification for its usage, within the Plan. This justification should include the uncertainty and confidence factors associated with the assessment method results.

SAE ARP4761 provides guidelines for use of reliability assessment results for a Safety Analysis.

4.1.4.1.3 Business Decisions

Examples of business decisions that rely heavily upon the results of reliability assessment include warranty decisions, maintenance cost guarantees and power-by-the-hour-agreements, planned design updates, spares provisioning, maintenance scheduling, budgeting and staffing. Applicable metrics may be expressed in cost of ownership terms such as service delay and cancellation or operator maintenance burden.

The Plan owner should be able to demonstrate how the results of the reliability assessment are used to substantiate the business decisions.

Since business decisions often involve proprietary, sensitive, or confidential cost information, reliability assessment reports for these decisions should be carefully controlled and may be maintained separately from results for other purposes. Furthermore the degree that this information is shared between business entities (e.g., customer, supplier, user) should be the subject of business or contractual agreements.

4.1.4.1.4 System Architecture Decisions

System architecture is the high-level description, in functional terms, of the structure chosen to satisfy design requirements. This high level description ensures that system objectives and requirements are understood by all interested parties, all relevant factors are considered in the design, all elements of the design are defined and understood at the appropriate level, all elements of the design are evaluated correctly and alternative solutions are considered.

The Plan owner should be able to demonstrate how the reliability assessment results are used to substantiate system architecture decisions. It is also important assess at which point in the product development that the reliability assessment data will become available to aid in architectural decision making.

Examples of system architecture decisions that can be supported by assessment results are:

- Fault tolerant design and Built In Test; , e.g. test method, coverage, or frequency;
- Top level hardware and functional partitioning;
- Protection Circuit Policy
- Redundancy requirements, and
- Maintenance support for prognostics.

4.1.4.1.5 Equipment Design Decisions

Examples of equipment design decisions which should be based upon reliability assessment include, but are not limited to:

- Comparing hardware technologies, e.g., digital processor, digital logic array versus analog;
- Comparing detailed circuit architecture alternatives;
- Comparing utilization, duty cycle, or electrical stress de-rating alternatives;
- Comparing components, e.g., integrated versus discrete;
- Comparing packaging technologies, e.g., surface mount versus through-hole;
- Comparing environmental management techniques, e.g. vibration damping or cooling and
- Identifying and correcting design deficiencies in a timely manner.

As with system architecture decisions the Plan owner should be able to demonstrate how the reliability assessment results are used to substantiate equipment design decisions.

4.1.4.2 Limitations of Reliability Assessment Results

Limitations and uncertainties should be quantified, if possible. The statistical significance, based upon the population of the source data and including appropriate confidence intervals, should be detailed to highlight any uncertainty and limitation of reliability assessment results. If limitations and uncertainties cannot be quantified, they should be described concisely, in sufficient detail for the user to understand and apply them appropriately.

Careful attention needs to be placed on understanding how the environmental and operating conditions may differ between the existing [similar] product and the final design. The reliability assessment should reflect whichever stresses are more severe, e.g. component self-heating in the new design may cause an increase in the operating temperatures compared to the existing [similar] product. Where this can not be effectievly assessed the confidence in the results should be suitably adjusted.

For those applications where an absolute failure rate is essential, such as for input to an SSA or Power By The Hour cost model then only quantified data should be used.

Uncertainties arise when the results are subject to variations in manufacturing processes, components and materials, e.g., variations in a component output or a material property that may affect the equipment's susceptibility to failure. Uncertainties also arise when relationships among factors are not completely known, e.g., if the actual number of operating hours for an MTBF estimate are not known, and must be in part, estimated, the statistical level of confidence in the result will be reduced.

If a reliability estimate differs significantly from the measured in-service performance of similar equipment in similar applications, then the measure of uncertainty in the result will be recorded as part of the validation process described in 4.1.5.1. The output from this ongoing validation activity can then be used to guide in the selection of the most appropriate assessment method for any subsequent analysis, based upon the most current understanding.

4.1.5 Reliability Assessment Process Improvement

Reliability assessment results should be used to improve the reliability assessment process, and are a source of information for improvement of the equipment throughout the equipment life-cycle.

A description of the processes the Plan owner will use to improve the reliability assessment process, based on the achieved reliability results of equipment in service should be included. It includes descriptions of the processes for verifying reliability assessment results, and for using those results to improve the processes.

#### 4.1.5.1 Validating Reliability Assessment Results

A description of the processes the Plan owner will use to measure the in-service performance of equipment, and to compare those results with reliability assessment results should be included.

Types of validation include:

- Comparing calculated results from reliability assessments, e.g., MTBF, MTBUR, time-to-failure, etc., with in-service data;
- Comparing failure sites, modes, and mechanisms predicted by reliability assessments with those obtained from in-service data; and
- Comparing in-service environmental, operating, and maintenance conditions with those assumed in reliability assessments.

The schedule for reporting results from the validation activity should be described in the appropriate section of the Plan.

#### 4.1.5.2 Improving the Reliability Assessment Process

A description of the processes the Plan owner will use to improve the reliability assessment process, using reliability assessment results should be included. It includes:

- Improvements to the data collection process
- Improvements in the selection of appropriate data source and method for a given assessment application.
- Modifying the equations, algorithms, and calculation methods of 4.1.3;
- Adoption of developing reliability assessment methods from industry, research establishments and academia as their use proves viable for Aerospace application.
- Identifying further predecessor equipment for similarity analysis modeling.
- Improved guidance for interpreting assessment results for effective decision making

Plan owners may already have processes in place for data collection and analysis, or systems in place to use factory data, customer reject data, and in-service data to improve the design and manufacturing processes for equipment improvement, e.g., FRACAS, reliability growth, reliability enhancement, statistical process control, etc. The processes that are documented should build on those processes and add information for improving the reliability assessment process, rather than replace or supersede them.

### 4.2 Plan Applicability

The Plan should define the range of equipment designed or manufactured by the Plan owner, to which the Plan applies.

The range of equipment is not intended to be a list of part numbers. It may include, for example, the applicable market segment or equipment line, e.g., “This Plan applies to all equipment manufactured for aerospace applications.” It also may include a time frame, e.g., “This Plan applies to all equipment manufactured after the date this Plan is approved.” The range of equipment also may be limited or required by certain contractual agreements.

### 4.3 Plan Organization

In order to facilitate an effective review, the Plan should be organized in such a manner that each of the topics listed in 4.1 of this document are addressed clearly, concisely, and unambiguously.

4.4 Plan Implementation

The Plan owner should provide objective evidence that the provisions of this document are met, and that the Plan has been implemented.

This activity may be accomplished by third party audit.

4.5 Plan Focal Point

The Plan should identify an authority or an organization to serve as the primary interface between the Plan owner and outside parties in matters pertaining to the Plan. The focal point should assure that the Plan is reviewed and updated as needed.

4.6 Plan References

The Plan should include a definitive list of all the documents referenced in the Plan, including this Guide, other industry and government documents, and the Plan owner's internal documents.

5. NOTES

A change bar (|) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

# APPENDIX A - SIMILARITY ANALYSIS EXAMPLES

## A.1 SCOPE

This Appendix provides information to aid in understanding the similarity analysis method for Reliability Assessment. It presents example implementations of the similarity analysis method.

## A.2 HOW TO USE THIS APPENDIX

The choice of the most appropriate reliability assessment method for any given application depends on product type, reliability requirements and available data. In addition, there are many ways to implement similarity analysis, and the most appropriate method and implementation should be selected.

This appendix includes descriptions of the data required (see A.3.1), an example of the method (see A.3.2), use and limitations of results (see A.3.3), and reliability assessment process improvement (see A.3.4).

Although the example in this appendix addresses calculation of MTBF, it also could be used for other reliability metrics.

## A.3 EXAMPLE SIMILARITY ANALYSIS

Two implementation options for the similarity analysis are described. These two options are referred to as: High Level and Low Level similarity analyses. The primary difference between the two options is that a higher level of similarity is required for the high level similarity analysis. To show the versatility of the similarity analysis method, the high level example will be performed at the LRU level and the low level example will be performed at the functional level, though either method can be applied at any level.

### A.3.1 Data

#### A.3.1.1 In-Service Reliability Data

In-service data collection and analysis are foundations of the similarity analysis methodology. The in-service reliability data typically includes the number of in-service failures, information on failure causes or failure modes, and end item operating hours.

The first two pieces of information are available from the company database that contains information on all repair activity. The database should identify the specific equipment (end-item or assembly) being repaired, as well as component replacements and a narrative field for maintenance personnel to identify end item failure types. End item failures may result from hardware faults, software faults, customer abuse, design errors, manufacturing errors, and other causes. The plan should describe the means by which the repair facility categorizes failure modes and in particular whether testing at component level is carried out to verify the source of failure, following component replacement. These data are used to calculate failure mode distributions for a product or assembly.

Operating hour data are collected from customer records or estimated from typical utilization rates. These records are maintained in accordance with company practices. These data combined with the failure information, described above, are used to calculate the field failure rates and MTBFs of products or assemblies.

#### A.3.1.2 Product Characteristic Data

Product characteristic data are obtained from both in-service end-items and end-items which are under development. The data consist of all the documentation that defines the end-item, as well as information defining the design process, manufacturing process and end use environment. Examples of end-item documentation are requirement documents, electrical and mechanical parts lists, and layout drawings. This data is used to identify characteristic differences between new and predecessor end-items. A listing of potential characteristic differences is shown in Figure A1.

### A.3.2 Methods

The process steps, spreadsheets, and calculations used in the example similarity analysis methods are described in the following paragraphs. Figure A2 contains an overall flowchart for this process.

A.3.2.1 Physical Model Categories

Similarity analysis uses the physical model categories described in this section to compare new and predecessor end-items or assemblies.

The first 5 categories cited below, are part type component level categories that quantify the field failures due to components. The next two categories are design and manufacturing processes. Additional categories may be added for equipment-specific items not related to part type or process categories. In the example below, manufacturing-induced component failures are categorized under manufacturing processes (Category 6), and component misapplication and overstress are categorized under the design processes (Category 7). The following categories are cited as examples of a physical model:

Category 1: Low-Complexity Passive Parts (Resistors, Capacitors and Inductors)

Category 2: High Complexity Passive Parts (Transformers, Crystal Oscillators and Passive Filters)

Category 3: Interconnections (Connectors, Flex Tape, Printed Wiring Boards and Solder Joints)

Category 4: Low Complexity Semiconductors (Discretes, Linear IC's and Digital IC's)

Category 5: High Complexity Semiconductors (Processors, Memory and field programmable gate arrays, application-specific integrated (ASICs) circuits and Hybrid devices)

Category 6: Manufacturing Process

Category 7: Design Process

Category 8: Other Failure Causes which are specified by the user to describe failure mechanisms that do not fit into categories 1-7, or that the analyst wishes to track separately due to high frequency of occurrence. Examples are life limited failure modes such as lamp or switch life, and specific hardware or software modifications performed as a corrective or preventive action.

| PHYSICAL | PROCESS | ENVIRONMENTAL |
|---|---|---|
| Critical Components | CAD Usage | Cooling Provisions |
| Degraded Operation | CAM Usage | Dormancy Factors |
| Deviations & Waivers | Document Control | Duty Cycle |
| Durability | Customer Training | ESD Susceptibility |
| Electrical Stress | Derating & Stress Analysis | Field Application |
| Expected Life | ESS, HASS | Repair Environment |
| False Alarms | Field Representatives | Use Environment |
| Fault Isolation | FMEA | |
| Functional Changes | FRACA/FRB | |
| Modes of Operation | Fault Tree Analysis | |
| New Software | Reliability Development Testing | |
| Percent Reusable SW | Material Composition | |
| Power Dissipation | Material Quality | |
| Safety Factors | Part Obsolescence | |
| Scheduled Maintenance | Part Quality | |
| Technology Maturity | Part Screening | |
| Test Points | Prototyping | |
| Volume | Second Source Suppliers | |
| Weight | Simulation | |
| | Software | |
| | SPC | |
| | Timing Analysis | |
| | Worst Case Analysis | |

Abbreviations used in Table:
CAD – Computer Aided Design
CAM – Computer Aided Manufacturing
ESD – Electrostatic Discharge
ESS – Environmental Stress Screening
HASS – Highly Accelerated Stress Screening
FMEA
FRACA – Failure Reporting Analysis and Corrective Action
FRB – Failure Review Board
SPC – Statistical Process Control



FIGURE A1 - EXAMPLE CHARACTERISTIC DIFFERENCES

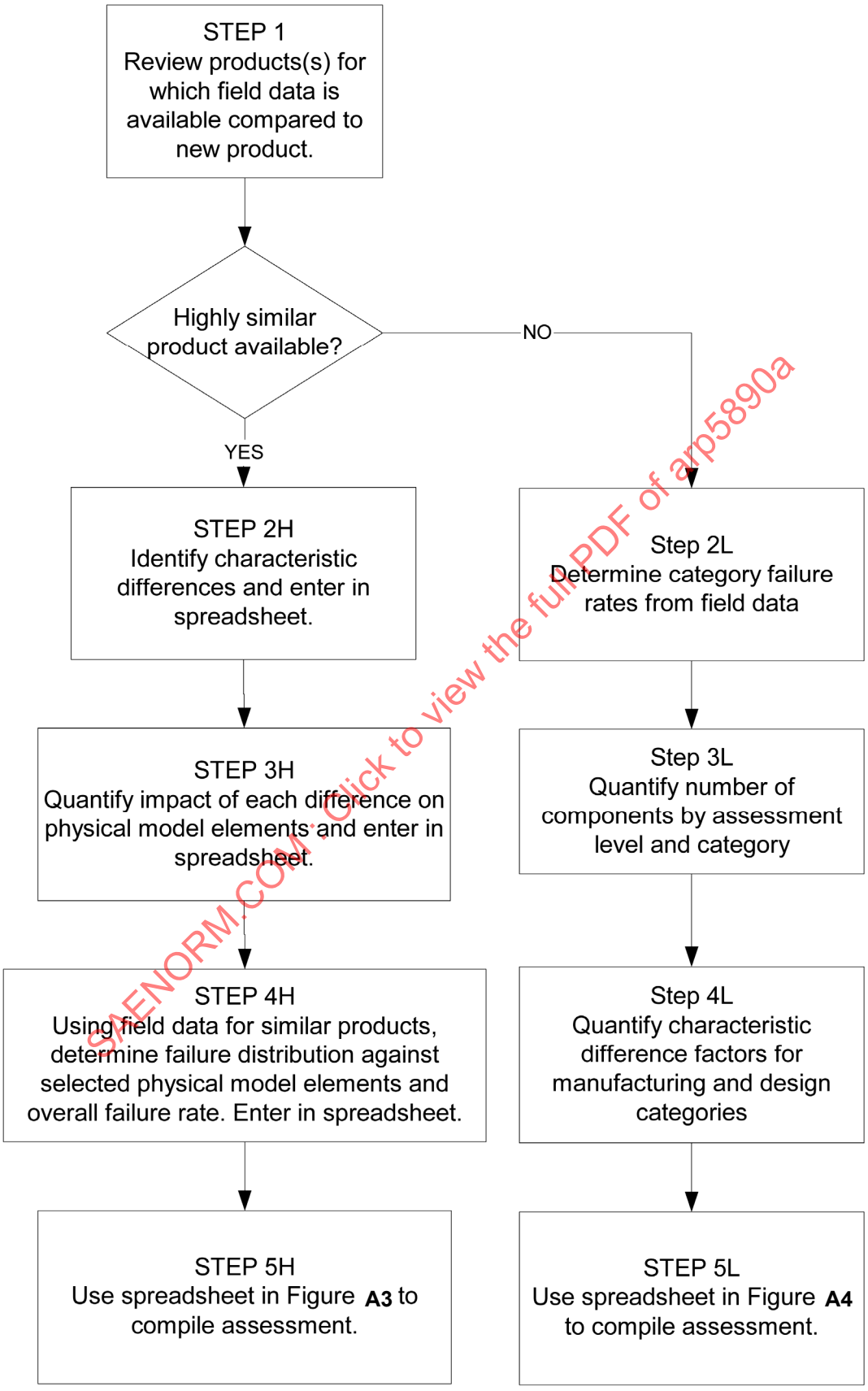





FIGURE A2 - EXAMPLE SIMILARITY ANALYSIS FLOWCHART

A.3.2.2 Process Steps

Figure A2 contains a flowchart of the process steps for similarity analysis. Descriptions of each process step with applicable references to the example spreadsheets of Figures A3 and A4 are contained in the following paragraphs.

Step 1: Compare the new equipment with equipment for which in-service data exist. This can be done at the end-item or the assembly level. If it is done with multiple predecessor end-items or at the assembly level, then the remaining steps may need to be performed individually for each predecessor end-item or assembly.

The output of this step is identification of one or more end-items or assemblies, which are sufficiently similar to the new equipment, or its assemblies, that comparable levels of reliability are anticipated. Sufficient similarity is determined on the basis of the analyst's knowledge of the equipment involved, the relevant reliability drivers, and experience with the process. Process experience may indicate that, if the number of differences exceeds a specified number, reliability assessment results are no longer usable.

Decision Block: If a high degree of similarity is found between the new and predecessor item, either at the device or assembly level, then a high level similarity analysis would be the appropriate choice. In this case continue with steps 2H-5H. The remaining process steps and equations for the high-level similarity analysis are described in A.3.2.2.1.

If insufficient similarity is found to perform a high-level similarity analysis, a low-level similarity analysis approach may still be used. Proceed with steps 2L-5L to perform a low level similarity analysis if the comparison in step 1 has identified that field data for a group of predecessor products has sufficient similarity to the new product. A high level of similarity is not required for conducting a low level similarity analysis but greater levels of similarity will improve the assessment accuracy by reducing variability. The remaining process steps and equations for the low-level similarity analysis are described in A.3.2.2.2.

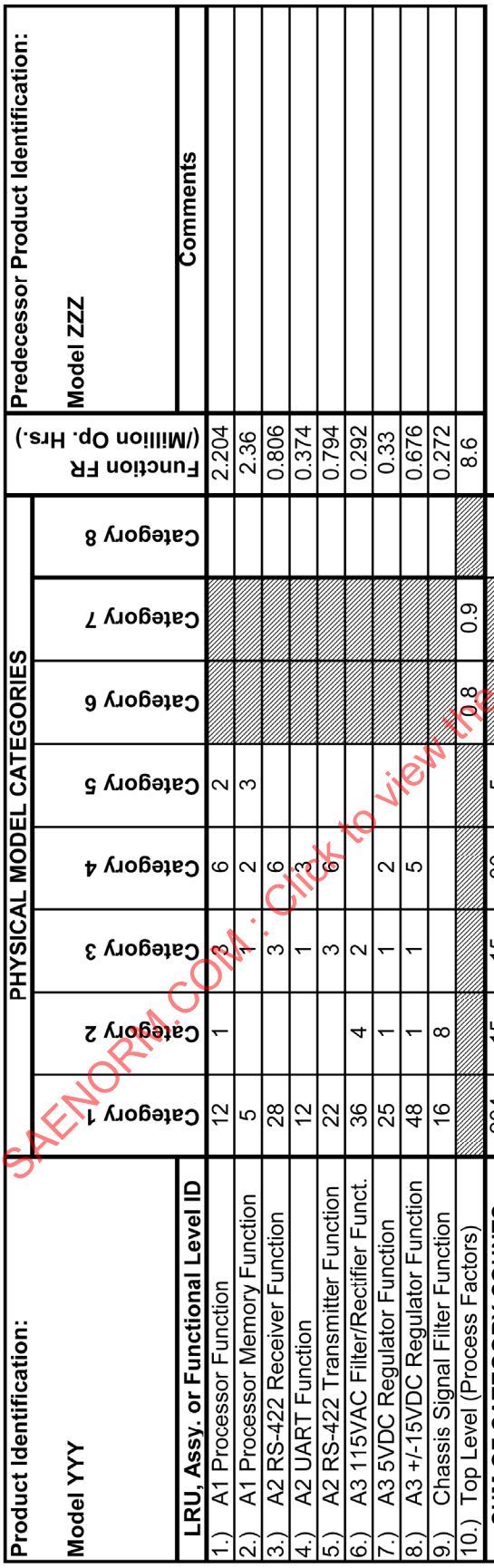
| Product Identification: Model YYY | | PHYSICAL MODEL CATEGORIES | | | | | | | | | Predecessor Product Identification: Model ZZZ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Characteristic Differences (Category - Description) | Category 1 | Category 2 | Category 3 | Category 4 | Category 5 | Category 6 | Category 7 | Category 8 | Category 9 | Comments |
| 1.) | Two PWB's combined into one | | | 0.9 | | | | | | | |
| 2.) | Reduced parts count on A4 | 0.8 | | | 0.6 | | | | | | |
| 3.) | A1 card moved to surface mount | | | | | | 0.8 | | | | |
| 4.) | Performing RET on new product | | | | | | | 0.8 | | | |
| 5.) | Combined A2 into ASIC | 0.89 | | 0.98 | 0.85 | 1.2 | | | | | |
| 6.) | | | | | | | | | | | |
| 7.) | | | | | | | | | | | |
| 8.) | | | | | | | | | | | |
| 9.) | | | | | | | | | | | |
| 10.) | | | | | | | | | | | |
| | PRODUCTS OF PHYSICAL MODEL IMPACTS= | 0.712 | 1 | 0.882 | 0.51 | 1.2 | 0.8 | 0.8 | 1 | 1 | |
| | PREDECESSOR PRODUCT FAILURE MODE DISTRIBUTION= | 10.0% | 10.0% | 10.0% | 20.0% | 20.0% | 20.0% | 10.0% | 0.0% | 0.0% | |
| | FAILURE RATE IMPACT PER CATEGORY= | 0.0712 | 0.1 | 0.0882 | 0.102 | 0.24 | 0.16 | 0.08 | 0 | 0 | |
| | FAILURE RATE RATIO= | 0.8414 | | | | | | | | | |

Precedessor Failure Rate (/Million Op. Hrs.)= 50.77
Projected Failure Rate (/Million Op. Hrs.)= 42.718

Predecessor MTBF (Op. Hrs.)= 19,697
Projected MTBF (Op. Hrs.)= 23,409



FIGURE A3 - EXAMPLE HIGH LEVEL SIMILARITY ANALYSIS SPREADSHEET



| Product Identification: Model YYY | PHYSICAL MODEL CATEGORIES | | | | | | | | Predecessor Product Identification: Model ZZZ | |
|---|---|---|---|---|---|---|---|---|---|---|
| LRU, Assy. or Functional Level ID | Category 1 | Category 2 | Category 3 | Category 4 | Category 5 | Category 6 | Category 7 | Category 8 | Function FR (/Million Op. Hrs.) | Comments |
| 1.) A1 Processor Function | 12 | 1 | 3 | 6 | 2 | | | | 2.204 | |
| 2.) A1 Processor Memory Function | 5 | | 1 | 2 | 3 | | | | 2.36 | |
| 3.) A2 RS-422 Receiver Function | 28 | | 3 | 6 | | | | | 0.806 | |
| 4.) A2 UART Function | 12 | | 1 | 3 | | | | | 0.374 | |
| 5.) A2 RS-422 Transmitter Function | 22 | | 3 | 6 | | | | | 0.794 | |
| 6.) A3 115VAC Filter/Rectifier Funct. | 36 | 4 | 2 | | | | | | 0.292 | |
| 7.) A3 5VDC Regulator Function | 25 | 1 | 1 | 2 | | | | | 0.33 | |
| 8.) A3 +/-15VDC Regulator Function | 48 | 1 | 1 | 5 | | | | | 0.676 | |
| 9.) Chassis Signal Filter Function | 16 | 8 | | | | | | | 0.272 | |
| 10.) Top Level (Process Factors) | | | | | | 0.8 | 0.9 | | 8.6 | |
| SUM OF CATEGORY COUNTS= | 204 | 15 | 15 | 30 | 5 | | | | | |
| FAILURE RATE FACTOR= | 1 | 1 | 1 | 1 | 1 | | | | | |
| EXPECTED CATEGORY FAILURE RATE (/Million Op. Hrs.)= | 0.002 | 0.03 | 0.05 | 0.1 | 0.7 | 4 | 6 | | | |
| TOTAL CATEGORY FAILURE RATE (/Million Op. Hrs.)= | 0.408 | 0.45 | 0.75 | 3 | 3.5 | 3.2 | 5.4 | | | |
| TOTAL PRODUCT FAILURE RATE (/Million Op. Hrs.)= | 16.708 | | | | | | | | | |
| PROJECTED MTBF (Op. Hrs.)= | 59,852 | | | | | | | | | |



FIGURE A4 - EXAMPLE LOW LEVEL SIMILARITY ANALYSIS SPREADSHEET

A.3.2.2.1 High Level Similarity Analysis Process Steps

Step 2H: Identify all characteristic differences between the new and predecessor end item or assemblies. Paragraph A.3.1.2 provides a description and example list of characteristic differences. Each characteristic difference is entered into the first column of the example spreadsheet shown in Figure A3.

Use of the spreadsheet in Figure A3 is affected by the number of predecessor end-items used, or if the analysis is being performed at an LRU, assembly or functional level. If multiple predecessor end-items are analyzed, a separate spreadsheet should be completed for each predecessor end-item. If an assembly or functional level analysis is performed, a separate spreadsheet should be completed for each predecessor assembly or function.

Step 3H: Evaluate each characteristic difference, identified in step 2H above, relative to the expected reliability difference between the new and predecessor item. This evaluation is quantified relative to the individual physical model categories defined in A.3.2.1.

In this step an entry is made for each category of each characteristic difference, as shown in Figure A3. If no impact is expected for a particular characteristic difference in that category then no entry is necessary (a “1” is assumed). Entries that are expected to improve reliability are less than one, and entries that are expected to degrade reliability are greater than one.

To further clarify the entry for the characteristic difference in Figure A3, “Combined circuits on A2 into ASIC,” describes the combination of a number of individual components into a single ASIC. The entries in Figure A3 indicate that there was an overall reduction of 11% in low complexity passive parts, 2% in interconnects, and 15% in low complexity semiconductors. The added ASIC increased the high complexity category parts count by 20%.

Step 4H: Incorporate the in-service failure data for the predecessor end-item or assembly into the spreadsheet of Figure A3. The in-service failure data, described in A.3.1.1, must be compiled in the form of percentages to quantify the failure mode distribution, by physical model category and an overall failure rate. For the failure mode distribution, the causes for all in-service failures, of the end-item or assembly, are assigned to the physical model categories. The failure quantity in each category is then divided by the total failure count to quantify the percent contribution of each category to the total end-item or assembly failure quantity. These percentages are entered into the row in Figure A3 labeled “Predecessor Product Failure Mode Distribution”. The overall failure rate for the end-item or assembly is entered into the appropriate space in the lower section of Figure A3.

Step 5H: Compile the results in the spreadsheet of Figure A3 to calculate the predicted reliability data. Calculations performed in the spreadsheet are described in the following paragraphs.

Calculate the values in the row labeled “Products of Physical Model Impacts” for each physical model category, as the product of the entries for all characteristic differences.

Calculate the values in the row labeled “Failure Rate Impact Per Category” for each physical model category, as the product of the “Products of Physical Model Impacts” and “Predecessor Product Failure Mode Distribution”.

Calculate the “Failure Rate Ratio” entry as the sum of all entries in the row labeled “Failure Rate Impact Per Category”.

Calculate the “Projected Failure Rate” for the new end-item or assembly as the product of the “Predecessor Failure Rate” and the “Failure Rate Ratio”.

The spreadsheet depicting the high-level similarity analysis implements equation A1, which is shown as follows:

$$\text{New Product Failure Rate } (\lambda) = \lambda_P * \sum_{N=1}^{7} (D_N * F_N) \qquad \text{(Eq. A1)}$$

where:

$\lambda_P$ = Field failure rate for the predecessor end-item or assembly

$D_N$ = Failure mode distribution percentage for category N

$F_N$ = Difference factor between the new and predecessor end-item or assembly for category N

N = Physical model category identifier which ranges from 1 to 7

The above equation is based on the assumption that there are no additional user-defined physical model categories. If there are additional categories, then the maximum value of N increases by the number of user defined categories.

Though not shown in the spreadsheet, individual category failure rates can be computed. This is accomplished by normalizing the “Failure Rate Impact per Category” entries to total 1.0 and multiplying a category normalized value by the “Projected Failure Rate”.

A.3.2.2.2 Low Level Similarity Analysis Process Steps

Step 2L: After the fielded product group(s) are selected, the category failure rates are determined. Generally, these category failure rates can be applied directly to the new product; however there may be instances where the failure rates must be factored, e.g., a new product in an environment different from that of the predecessor. In such instances, the failure rates may be factored, with a description of the factoring and its basis included in the assessment report.

The outputs of this step are the category failure rates with any factoring applied. They are entered into the spreadsheet of Figure A4 in the row labeled “expected category failure rates”.

If different predecessor data is being used for different new product functions, a separate spreadsheet will be required for each set of predecessor data. In a similar manner, if multiple predecessor products will be used, the data can either be compiled into a single spreadsheet or a separate analysis with separate spreadsheets can be used for each predecessor product.

Step 3L: Quantify the number of components, by type, for each of the functional levels identified in the first column of the spreadsheet of Figure A4. The component quantities are put into the appropriate component category, and entered into the spreadsheet.

Step 4L: Quantify and list the manufacturing and design process differences between the new and fielded equipment(s). Figure A1 shows a list of potential differences to be considered for the manufacturing and design processes.

The individual difference factors (multipliers) are themselves multiplied to determine a composite failure rate factor for the manufacturing failure rate, and a composite failure rate factor for the design failure rate. Figure A5 shows the identified process factors and their product for the example analysis.

The total process factors are entered into the first open spaces under the Category 6 (Manufacturing Process) and Category 7 (Design Process) columns of Figure A4.

The above description assumes that the manufacturing and design failure rates represent mature (constant) failure rates. If these failure rates are not constant, the constant failure rate may be replaced with another type, e.g., Weibull, but the algorithms and equations will need to be changed.

| Characteristic Differences | Impact of Mfg. Failure Rate |
|---|---|
| 1.) Surface Mount vs Leaded Assy. | 0.8 |
| 2.) Introduced HASS | 0.8 |
| 3.) 25% higher board count than average | 1.25 |
| 4.) | |
| 5.) | |
| 6.) | |
| 7.) | |
| 8.) | |
| 9.) | |
| 10.) | |
| **TOTAL=** | **0.8** |

| Characteristic Differences | Impact of Design Failure Rate |
|---|---|
| 1.) Introduced HALT | 0.8 |
| 2.) Internal design reviews missed | 1.125 |
| 3.) | |
| 4.) | |
| 5.) | |
| 6.) | |
| 7.) | |
| 8.) | |
| 9.) | |
| 10.) | |
| **TOTAL=** | **0.9** |

FIGURE A5 - EXAMPLE PROCESS DIFFERENCE FACTOR TABLES

Step 5L: Perform the assessment calculations with the spreadsheet shown in Figure A4. The calculations use equations A2 and A3 shown below and are described as follows:

- Calculate the row labeled “Sum of Category Counts” for categories 1-5 by adding the entries for each level identified in column 1.
- Calculate the row labeled “Total Category Failure Rate” for:
- Categories 1 through 5, by multiplying the “Sum of Category Counts” row by the “Expected Category Failure Rate” row.
- Categories 6 and 7 by multiplying the “Process Factors” row by the “Expected Category Failure Rate” row.
- Calculate the “Total Product Failure Rate” entry by adding all entries in the row labeled “Total Category Failure Rate”. This failure rate could then be used to calculate MTBF or other appropriate reliability metrics.

$$\text{Total Product Failure Rate } (\lambda) = \sum_{C=1}^{5} \sum_{L=1}^{n} Q_{L,C} * \lambda_C + (F_M * \lambda_6) + (F_D * \lambda_7) \quad \text{(Eq. A2)}$$

$$\text{Total Function Failure Rate} = \sum_{C=1}^{5} (Q_{L,C} * \lambda_C) + \left( \sum_{L=1}^{5} Q_{L,C} / P_T \right) * (F_M * \lambda_6 + F_D * \lambda_T) \quad \text{(Eq. A3)}$$

where:

$Q_{L,C}$ = Part quantities for function number “L” and component category "C"

$P_T$ = Total number of parts in the device, calculated by:

L = Denotes one of the assembly levels listed in the first column of the Figure A4 spreadsheet

C = Denotes one of the physical model categories as shown in Figure A4

n = Number of function levels in the assessment

$\lambda_C$ = Represents the expected category failure rate for category “C”

$F_M$ = Represents the Process Factor for the manufacturing process

$F_D$ = Represents the Process Factor for the design process

$\lambda_6$ = Represents the expected category failure rate for the manufacturing process - category 6

$\lambda_7$ = Represents the expected category failure rate for the design process - category 7

The above equations are based on the assumption that there are no additional user-defined physical model categories. Additional user-defined categories are treated in the same manner as the component categories (Category 1 through 5).

The functional level failure rates shown in Figure A4 do not incorporate the process failure rates for categories 6 and 7. Though not shown in the spreadsheet this can be accomplished by distributing the process failure rates between the functions. Two possible methods to accomplish this are listed as follows:

1. Distribute based on complexity i.e. parts count, lead count or component category total failure rate.

2. Distribute based on prior knowledge of problems areas encountered in similar products.

The method for distributing the process failure rate can be different between manufacturing and design. A combination of the two methods can also be used i.e. distribute based on parts count then adjust for prior knowledge.

### A.3.3 Use and Limitations

Results from the similarity analysis reliability assessment method can be directly applied to equipment design decisions, business decisions, system architecture decisions and safety assessment decisions. Applicability to safety assessment depends on the safety analysis requirements, and also on the level at which the reliability assessment was performed.

### A.3.4 Process Improvement

After adequate in-service history has been attained for the product, the field data are compared to the reliability assessment results. Inconsistencies are evaluated for potential process changes. These changes may effect the data collection and analysis process or directly impact the process contained in the Plan document.

# APPENDIX B - DURABILITY ANALYSIS

## B.1 SCOPE

This appendix includes information to help the user understand the durability analysis method of reliability assessment.

## B.2 DESCRIPTION AND USE OF DURABILITY ANALYSIS

Durability analysis is defined as the analysis of the equipment's response to the stresses resulting from operation, maintenance, shipping, storage, and other activities throughout its specified life cycle in order to estimate its expected life.

As the definition indicates, the results of a durability analysis are stated in expected time to failure, rather than as a failure rate or MTBF. Durability analysis results indicate the length of time an individual item is expected to last prior to failure, rather than the frequency with which a group of items is expected to fail. This concept is illustrated in Figure B1.

Typically, reliability analysis is aimed at assessing the random failures that will occur in the equipment during its useful life. These failures are usually assumed to be repairable, and may be due to a variety of causes, such as defects in the equipment, improper use, damage due to unusual conditions, inadequate maintenance, etc. Durability analysis, on the other hand, assesses failures due to systematic wear-out of certain elements of the design.

The major steps of durability analysis are:

1. Determination of operating and environmental conditions;
2. Stress analysis; and
3. Damage modeling.

Each of the above steps are discussed in this Appendix.



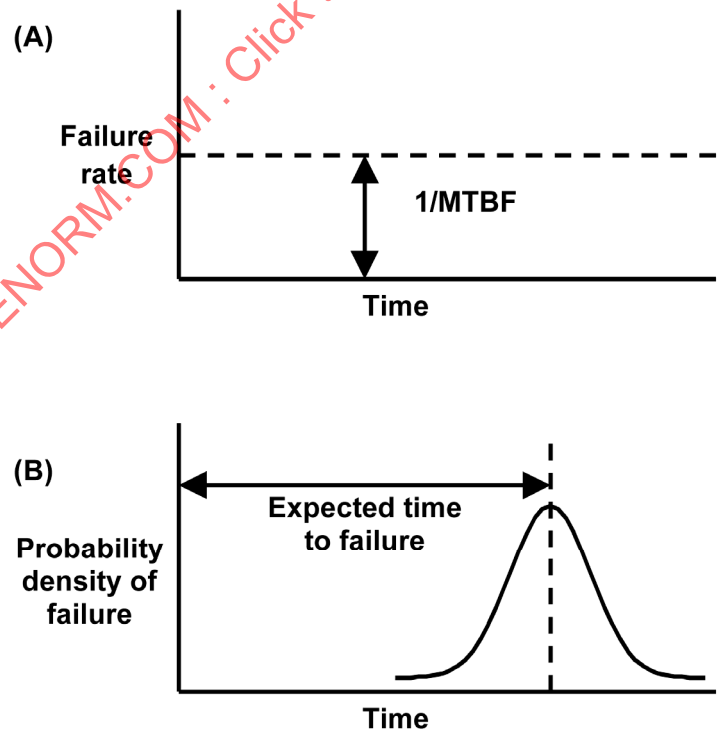



FIGURE B1 - ILLUSTRATION OF (A) MTBF, WHICH IS THE TYPICAL MEASURE OF RELIABILITY, AND (B) THE MEASURE OF DURABILITY

## B.3 DURABILITY ANALYSIS

### B.3.1 Determination of Operating and Environmental Conditions

Durability analysis is concerned with determining the specific responses of the equipment to the specific stresses that the equipment will encounter during its lifetime. For this reason, durability analysis begins with determining the types, magnitudes, and sources of all the conditions in which the equipment must be operated, stored, or handled.

Operating conditions include:

- Electrical stresses due to function of the equipment;
- Steady state temperature due to self-heating;
- Temperature variations due to turning the equipment on and off;
- Vibration due to operation;
- Moisture conditions due to condensation; and
- Any other stresses that may cause failures.

Environmental stress include:

- Ambient steady state temperature;
- Variations in ambient temperature;
- Ambient moisture;
- Ambient chemical contaminants;
- Mechanical shock due to handling;
- Mechanical vibration due to transportation; and
- Any other environmental conditions that may cause failures.



Some of the conditions described above may be obtained from the customer, and others may be obtained from design handbooks or similar publications. It may not be possible to quantify all the necessary information regarding environmental and operating conditions. In these cases, engineering judgment may be required. If a condition is known, or strongly suspected, to exist, it is usually better to estimate it than to ignore it.

Many of the relevant conditions may occur only in certain phases of the equipment's expected life, such as storage, shipping, etc. It is important to know or estimate credibly, the duration of each of the conditions.

### B.3.2 Stress Analysis

The conditions described above may result in life-limiting stresses in the equipment. Stress analysis is the determination of the magnitudes and locations of those stresses. In some cases, the stresses may be uniform throughout the equipment, e.g., temperature conditions may be uniform when the ambient temperature is stable and the equipment generates little or no heat during operation. In most cases, however, the stresses will vary both temporally and spatially. In almost all cases, the ability of the various elements of the equipment to withstand the stresses will vary.

Usually, stress analysis is conducted with some type of computer-aided analytical process, such as finite element or finite difference analysis. The results of this type of analysis are usually reported graphically, with the areas of greatest stress being highlighted in some easily detectable way.

### B.3.3 Damage Modeling

After the types, locations and magnitudes of the stresses are identified, their effect in causing wearout failures is determined. This is done using damage models. Damage models are mathematical equations that predict how long a given item can withstand a given stress before failure due to wearout. (Damage models also may be used in accelerated testing to estimate the behavior of an item in a longer time at a lower stress level, based on its behavior in a shorter time at a higher stress level.)

As the name implies, damage models are useful for predicting wearout failures due to the accumulation of damage caused by operating or environmental stresses. They are not applicable to failures due to overstress, or to failures that are caused by defects in materials or assembly.

The most rigorous damage models are those that describe the failure mechanisms at the structural, or atomic, level. They are called structural, closed form, constitutive, or physics-of failure models. An example of such a model is Fick's work in diffusion [1].

Another type of damage model is the empirical model. Empirical models are not based on descriptions of structural changes, but describe mathematically the data collected from testing or use. They can be viewed as curve fitting, although a good knowledge of physics-of-failure mechanisms is often applied to the exercise. Examples of this type of model are some of those developed for humidity testing.

Damage models range from the very simple to the very complex. Usually, the simpler models can be said to apply to a wider range of cases, while the more complex models are specific to a rather narrow set of applications. Also, some of the more complex models can be quite difficult to use. Engineering judgment is required to select the simplest model that gives satisfactory results. Perhaps the best advice in this regard is that given by Weibull [2]:

".....there may exist two or more true relationships of different shapes. Facing this abundance, the only reasonable way to act seems to be to choose the one which most easily gives answers to posed questions."

A variety of damage model forms is available for durability analysis, and all reasonable models should be considered. In this appendix, three general forms are presented: 1) the Arrhenius model, 2) the inverse power law, and 3) the Eyring model. Most of the popular damage models in use today are variations of one of these three models. They, and other models, are described in many publications, and references 3through 7 are listed as examples.

B.3.3.1 The Arrhenius Model

Svante Arrhenius [8] developed his model in 1889 to describe the inversion of sucrose. The model is a rate equation that describes the temperature dependence of the time required for an event to occur:

$$r = r_o e^{\frac{E_a}{kT}} \quad \text{(Eq. B1)}$$

where:

- $r$ = Reaction rate
- $r_o$ = Constant
- $E_a$ = Activation energy, in electron volts[1]
- $k$ = Boltzmann's constant ($8.617 \times 10^{-5}$ eV/°K)
- $T$ = Reaction temperature, in °K

The product of the reaction rate and the time for it to occur is constant over its temperature range of applicability, or

$$r_1 t_1 = r_2 t_2 \quad \text{(Eq. B2)}$$

for two different reaction temperatures $T_1$ and $T_2$. Thus for a given mechanism, with time-to-failure expressed as $t_f$, $rt_f$ is a constant, and

$$t_f = Ae^{\frac{E_a}{kT}} \quad \text{(Eq. B3)}$$

If the constant A and the activation energy are unknown, they can be determined by conducting an accelerated test at a temperature higher than that expected in use. This yields an acceleration factor for the Arrhenius equation:

$$AF = \frac{t_u}{t_t} = \exp\left[\frac{E_a}{k}\left(\frac{1}{T_u} - \frac{1}{T_t}\right)\right] \quad \text{(Eq. B4)}$$

where the subscripts u and t indicate "use" and "test" respectively.

Use of the Arrhenius equation is illustrated by the example of a thermocompression bond between two dissimilar metals. The bond strength is reduced over time by the formation of voids or brittle intermetallics via solid-state diffusion, with an activation energy of 0.9 eV. The use temperature is 25 °C, and an accelerated test is conducted at 100 °C. The mean time-to failure is 185 hours.

Equation B4 can be used to estimate the life of this bond in service, with

$t_u$ = Life of the bonds in use
$t_t$ = Mean life of the bonds in test = 185 hours
$E_a$ = 0.9
$k$ = 8.617 x 10-5 eV/°K
$T_u$ = 25 °C = 298 °K
$T_t$ = 100 °C = 373 °K

[1] Usually the activation energy is reported in electron-volts, but sometimes it is reported in calories per mole. 1 eV ≈ 23 cal/mole.