

INTERNATIONAL STANDARD



Methods for product accelerated testing

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IEC Secretariat
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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INTERNATIONAL STANDARD



Methods for product accelerated testing

INTERNATIONAL
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

METHODS FOR PRODUCT ACCELERATED TESTING

FOREWORD

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This commented version (CMV) of the official standard IEC 62506:2023 edition 2.0 allows the user to identify the changes made to the previous IEC 62506:2013 edition 1.0. Furthermore, comments from IEC TC 56 experts are provided to explain the reasons of the most relevant changes, or to clarify any part of the content.

A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text. Experts' comments are identified by a blue-background number. Mouse over a number to display a pop-up note with the comment.

This publication contains the CMV and the official standard. The full list of comments is available at the end of the CMV.

IEC 62506 has been prepared by IEC technical committee 56: Dependability. It is an International Standard.

This second edition cancels and replaces the first edition published in 2013. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) references have been updated;
- b) symbols have been revised;
- c) errors in 5.7.2.3 and Annex B, mainly, have been corrected;
- d) calculation errors in the examples of Annex B and Annex F have been corrected.

The text of this International Standard is based on the following documents:

Draft	Report on voting
56/2000/FDIS	56/2016/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

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INTRODUCTION

Many reliability or failure investigation test methods have been developed and most of them are currently in use. These methods are used to either determine product reliability or to identify potential product failure modes, and have been considered effective as demonstrations of reliability:

- fixed duration,
- sequential probability ratio,
- reliability growth tests,
- tests to failure, etc.

Such tests, although very useful, are usually lengthy, especially when the product reliability that has to be demonstrated is high. The reduction in time-to-market periods as well as competitive product cost, increase the need for efficient and effective accelerated testing. Here, the tests are shortened through the application of increased stress levels or by increasing the speed of application of repetitive stresses, thus facilitating a quicker assessment and growth of product reliability through failure mode discovery and mitigation.

There are two distinctly different approaches to reliability activities:

- the first approach verifies, through analysis and testing, that there are no potential failure modes in the product that are likely to be activated during the expected life time of the product under the expected operating conditions and usage profile;
- the second approach estimates how many failures can be expected after a given time under the expected operating conditions and usage profile.

Accelerated testing is a method appropriate for both cases, but used quite differently. The first approach is associated with qualitative accelerated testing, where the goal is identification of potential faults that eventually ~~might~~ can result in product field failures. The second approach is associated with quantitative accelerated testing where the product reliability may be estimated based on the results of accelerated simulation testing that can be related back to the use of the environment and usage profile.

Accelerated testing can be applied to multiple levels of items containing hardware ~~or~~ and software. Different types of reliability testing, such as fixed duration, sequential test-to-failure, success test, reliability demonstration, or reliability growth ~~or~~ improvement tests can be candidates for accelerated methods. This document provides guidance on selected, commonly used accelerated test types. This document should be used in conjunction with statistical test plan standards such as IEC 61123, IEC 61124, IEC 61649 and IEC 61710.

The relative merits of various methods and their individual or combined applicability in evaluating a given system or item, should be reviewed by the product design team (including ~~dependability~~ reliability engineering) prior to selection of a specific test method or a combination of methods. For each method, consideration should also be given to the test time, results produced, credibility of the results, data required to perform meaningful analysis, life cycle cost impact, complexity of analysis and other identified factors.

In this document the term "item" is used as defined in IEC 60050-192 covering physical products as well as software. Services and people are however not covered by this document.

METHODS FOR PRODUCT ACCELERATED TESTING

1 Scope

This document provides guidance on the application of various accelerated test techniques for measurement or improvement of ~~product~~ item reliability. Identification of potential failure modes that ~~could~~ can be experienced in the use of ~~a product/~~ an item and their mitigation is instrumental to ensure dependability of an item.

The object of the methods is to either identify potential design weakness or provide information on item ~~dependability~~ reliability, or to achieve necessary reliability/ and availability improvement, all within a compressed or accelerated period of time. This document addresses accelerated testing of non-repairable and repairable systems. It can be used for probability ratio sequential tests, fixed duration tests and reliability improvement/growth tests, where the measure of reliability ~~may~~ can differ from the standard probability of failure occurrence.

This document also extends to present accelerated testing or production screening methods that would identify weakness introduced into the ~~product~~ item by manufacturing error, which ~~could~~ can compromise ~~product dependability~~ item reliability. Services and people are however not covered by this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-192 – *International Electrotechnical Vocabulary (IEV) – Part 192: Dependability*, available at <http://www.electropedia.org>

~~IEC 60068 (all parts), Environmental testing~~

~~IEC 60300-3-1:2003, Dependability management – Part 3-1: Application guide – Analysis techniques for dependability – Guide on methodology~~

IEC 60300-3-5, *Dependability management – Part 3-5: Application guide – Reliability test conditions and statistical test principles*

IEC 60605-2, *Equipment reliability testing – Part 2: Design of test cycles*

IEC 60721 (all parts), *Classification of environmental conditions*

~~IEC 61014:2003, Programmes for reliability growth~~

IEC 61123:2019, *Reliability testing – Compliance test plans for success ratio*

IEC 61124:2012/2023, *Reliability testing – Compliance tests for constant failure rate and constant failure intensity*

~~IEC 61163-2, Reliability stress screening – Part 2: Electronic components~~

~~IEC 61164:2004, Reliability growth – Statistical test and estimation methods~~

IEC 61649:2008, Weibull analysis

IEC 61709, ~~Electronic~~ Electric components – Reliability – Reference conditions for failure rates and stress models for conversion

IEC 61710, Power law model – Goodness-of-fit tests and estimation methods

~~IEC 62303, Radiation protection instrumentation – Equipment for monitoring airborne tritium~~

~~IEC/TR 62380, Reliability data handbook – Universal model for reliability prediction of electronics components, PCBs and equipment~~

IEC 62429, Reliability growth – Stress testing for early failures in unique complex systems

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ~~IEC 60050-191:_____~~ IEC 60050-192 and the following, apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>

NOTE Symbols for reliability, availability and maintainability ~~and safety~~ measures follow those of ~~IEC 60060-191:1990~~ IEC 60050-192, where available.

3.1.1

activation energy

E_a

empirical factor for estimating the acceleration caused by a change in absolute temperature

Note 1 to entry: Activation energy is usually measured in electron volts per degree Kelvin.

3.1.2

detection screen

low stress level exposure to detect intermittent faults

3.1.3

event compression

increasing stress repetition frequency to be at considerably higher levels than it is in the field

3.1.4

highly accelerated limit test

HALT

test or sequence of tests intended to identify the most likely failure modes of the product in a defined stress environment

Note 1 to entry: HALT is sometimes spelt out as the highly accelerated life test (as it was originally named in error). However, as a non-measurable accelerated test, it does not provide information on life duration, but on the magnitude of stress which represents the limit of the design.

3.1.5

highly accelerated stress audit

HASA

process monitoring tool where a sample from a production lot is tested to detect potential weaknesses in a product caused by manufacturing

3.1.6

highly accelerated stress screening

HASS

screening intended to identify latent defects in a product caused by manufacturing process or control errors

3.1.7

item

subject being considered

Note 1 to entry: The item may be an individual part, component, device, functional unit, equipment, subsystem, or system.

Note 2 to entry: The item may consist of hardware, software, people or any combination thereof.

Note 3 to entry: The item is often comprised of elements that may each be individually considered. See "sub-item"; ~~definition 191-41-02~~ (IEV 192-01-02) and "indenture level"; ~~definition 191-41-05~~ (IEV 192-01-05).

Note 4 to entry: IEC 60050-191:1990 (now withdrawn; replaced by IEC 60050-192:2015) identified the term "entity" as an English synonym, which is not true for all applications.

Note 5 to entry: The definition for "item" ~~given in the first edition~~ in IEC 60050-191:1990 (now withdrawn; replaced by IEC 60050-192:2015) is a description rather than a definition. This new definition provides meaningful substitution throughout this document. The words of the former definition form the new Note 1 to entry.

Note 6 to entry: In this document people and services are excluded.

[SOURCE: ~~IEC 60050-191:—, definition 191-41-01~~ [1] IEC 60050-192:2015, 192-01-01, modified – Note 6 to entry has been added.]

3.1.8

life time

<of a non-repairable item> time interval from first use until user requirements are no longer met

Note 1 to entry: The end of life time is usually called failure of the component.

Note 2 to entry: The end of life is often defined as the time where a specified percentage of the components have failed, for example stated as a B_{10} or L_{10} value for 10 % accumulated failures.

3.1.9

precipitation screen

screening profile to precipitate, through failure, conversion of latent faults into ~~permanent~~ revealed faults

3.1.10

~~step stress~~

step-stress test

test in which the applied stress is increased, after each specified interval, until failure occurs or a predetermined stress level is reached

Note 1 to entry: The 'interval' could be specified in terms of number of stress applications, durations, or test sequences.

Note 2 to entry: The test should not alter the basic failure modes, failure mechanisms, or their relative prevalence.

[SOURCE: ~~IEC 60050-191:—, definition 191-49-10~~ IEC 60050-192:2015, 192-09-10]

3.1.11**test acceleration factor**

~~ratio between the item failure distribution characteristics or reliability measures (e.g. failure intensities) of an item when it is subject to stresses in expected use and those the item acquires when the higher level stresses are applied for achieving a shorter test duration~~

~~Note 1 to entry: For a test to be effectively accelerated, the acceleration factor is >1 .~~

~~Note 2 to entry: When the failure distribution Poisson is assumed with constant failure rate, then the acceleration factor corresponds to the ratio of time under stress in use vs. time under increased stress in test.~~

ratio of the stress response rate of the test specimen under the accelerated conditions, to the stress response rate under specified operational conditions

Note 1 to entry: Both stress response rates refer to the same time interval in the life of the tested items.

Note 2 to entry: Measures of stress response rate are, for example, operating time to failure, failure intensity, and rate of wear.

[SOURCE: IEC 60050-192:2015, 192-09-09]

3.1.12**time compression**

removal of exposure time at low or deemed non damaging stress levels from a test for the purpose of acceleration

3.1.5**highly accelerated stress test**

~~HAST~~

~~test where applied stresses are considerably increased in order to reduce duration of their application~~

3.2 Symbols and abbreviated terms

~~ADT — accelerated degradation testing~~

ADT accelerated degradation test(ing)

AF acceleration, acceleration factor

AF_{Test} overall acceleration in a test

~~AF — acceleration factor~~

CALT calibrated accelerated life testing

B_{10} life time, the time where 10 % of the items have failed

C confidence

CD compact disc player in a HiFi equipment

DL destruct limit

DSL design specification limit

FIT failure ~~to~~ in time (failure per 10^9 hours)

HALT highly accelerated limit test

HASA highly accelerated stress audit

HASS highly accelerated stress screening test

HAST highly accelerated stress test

L load

L_v life time ratio

LDL lower destruct limit

LDT lower destruct temperature

LOL	lower operating limit
LOT	lower operating temperature
LRTL	lower reliability test limit
MTBF	mean operating time between failures
MTTF	mean operating time to failure
OL	operating limit
OVL	operation vibration limit
P_A	acceptance probability
PDF	probability density functions
PWB	printed wiring board
~~RG~~	~~reliability growth~~
$R(t)$	reliability as a function of time; probability of survival to the time t

~~NOTE 1 IEC 60050-191:1990, definition 191-12-01 uses the general symbol $p(t, z)$. Time may be substituted by cycles, measure of distance, etc.~~

~~NOTE 2 In reliability growth testing, the same symbol normally used for the instantaneous failure rate can be used for variable failure intensity.~~

RTL	reliability test level
S	strength
SL	specification limit
SPRT	sequential probability ratio test
~~SPRT~~	~~sequential probability ratio tests~~
~~t_0~~	~~start of a period of in-determination of product destruct life test~~
t_0	time denoted time 0
t_L	~~duration of a predetermined~~ a specified time, e.g. life
THB	temperature humidity bias test
TTF	time to failure
UDL	upper destruct limit
UDT	upper destruct temperature
UOL	upper operating limit
UOT	upper operating temperature
URL	upper reliability test limit
UUT	unit under test
VDL	vibration destruct limit
$\lambda(S)$	failure rate as a function of a stress
$\lambda(t)$	failure rate as a function of time

4 General description of the accelerated test methods

4.1 Cumulative damage model

Accelerated testing of any type is based on the cumulative damage principle. The stresses of the ~~product~~ item in its life cause progressive damage that accumulates throughout the ~~product~~ item life. This damage ~~may~~ can, or ~~may~~ not, result in ~~a product's~~ an item's failure in the field.

The strategy of any type of accelerated testing is to produce, by increasing stress levels during testing, cumulative damage equivalent to that expected in the ~~product's~~ item's life for the type of expected stress. The determination of ~~product~~ item destruct limits, without reliability estimation, provides information on whether there exists a sufficient margin between those destruct limits and ~~product~~ item specification limits, thus providing assurance that the ~~product~~ item will survive its predetermined life period without failure related to that specific stress type. This technique ~~may or may~~ can, but not necessarily, quantify a probability of ~~product~~ item survival for its life, and just provides assurance that the necessary adjustments in ~~product~~ item strength would help eliminate such failure in ~~product~~ item use. Where sufficient margins are determined unrelated to the probability of survival, the type of test is qualitative. In tests where this probability of survival is determined, the magnitude of the stress is correlated to the probability that the ~~product~~ item would survive that stress type beyond the predetermined life, and this test type is quantitative.

Figure 1 depicts the principle of cumulative damage in both qualitative and quantitative accelerated tests.

In Figure 1, for simplicity, all stresses, operating limits, destruct limits, etc. are shown as absolute values. The specification values for an item are usually given in both extremes, upper and lower, thus the upper and lower (or low) specification limit, USL and LSL with the corresponding design limits (DSL), UDL and LDL, the upper and lower operating limits, UOL and LOL, and also the reliability test limits, URTL and LRTL. The rationale is that the opposite (negative stresses), ~~may~~ can also cause cumulative damage probably with a different failure mechanism, thus the relationship between the expected and specified limits can be illustrated in the same manner as for the high or positive stress. As an example, cold temperature extremes ~~might~~ can produce the same or different failure modes in ~~a product~~ an item. To avoid clutter, the positive and the negative thermal or any other stresses are not separately shown in Figure 1, thus the magnitudes of stresses are either positive or negative, and thus represented as absolute values only as upper or lower limits.

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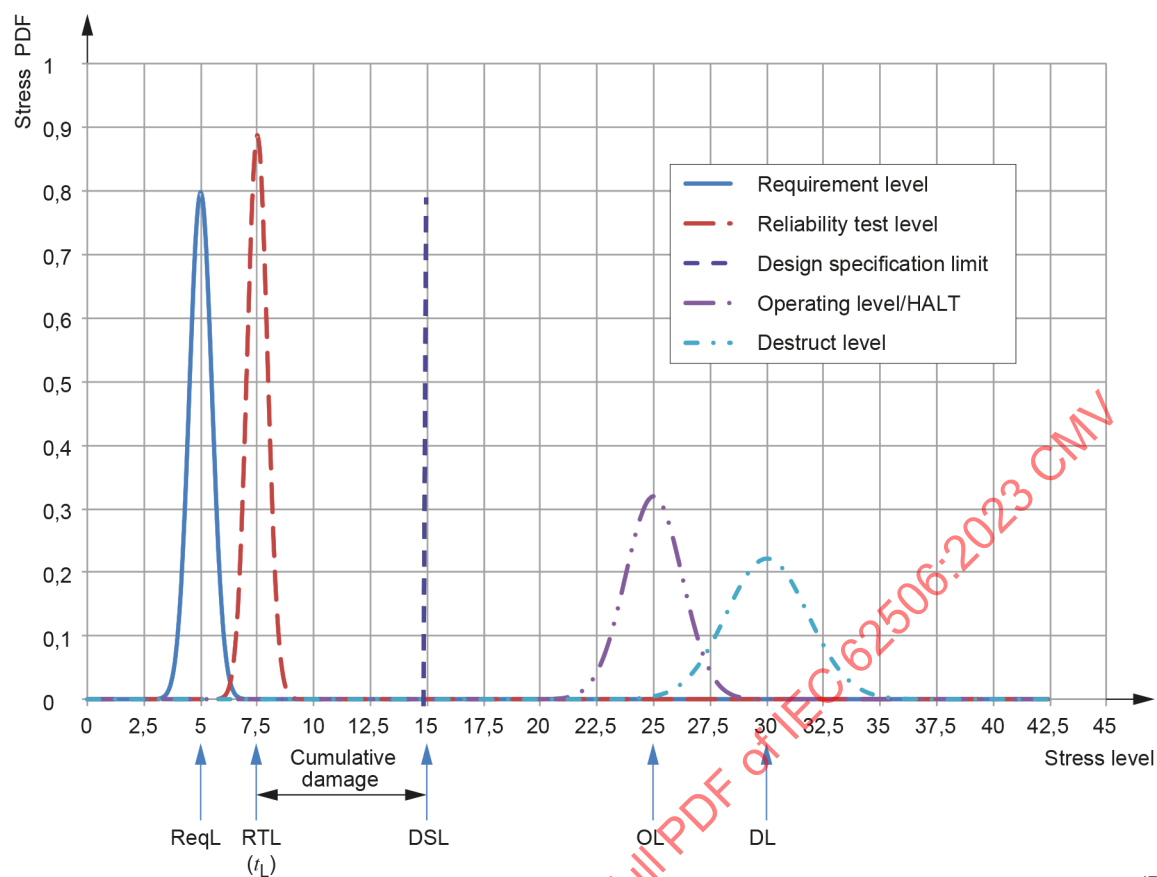


Figure 1 – Probability density functions (PDF) for cumulative damage, degradation, and test types

The graph in Figure 1 shows the required strength of ~~a product~~ ~~an item~~ regarding a stress for the duration of its life time, from beginning of life (e.g. time when the ~~product~~ ~~item~~ is made), t_0 , through the end of life, t_L . The strength and stresses in tests are also assumed to have a Gaussian distribution.

The different types of accelerated tests can now be illustrated using Figure 1 as a conceptual model.

Functional testing is carried out within the range of the requirement specification and at the level of the specification. In this area no failures should occur during the test; design is validated to allow operation within the upper and lower specification limits. Accelerated testing of Types B and C (4.2.3 and 4.2.4), i.e. accelerated degradation testing (ADT) or cumulative damage testing can be illustrated as the distance between the design specification ~~level~~ limit (DSL) and the level where the reliability demonstration test should be performed (RTL). When the degradation reduces the performance below the requirement specifications, the ~~product~~ ~~item~~ can be declared as failed, if this behaviour is defined as a failure. When testing the ~~product~~ ~~item~~ at time t_0 no failures should be expected for stress levels up to and including the design specification ~~level~~ limit (DSL).

The ~~product~~ ~~item~~ design specification should take into consideration certain degradation during the ~~product's~~ ~~item's~~ life which is resultant from the cumulative damage of the stresses expected in life, thus its limit is the design specification limit (DSL) which is higher than the requirement limit (RL) in order to provide the necessary margin. After ~~product~~ ~~item~~ degradation resultant from the cumulative damage caused by expected stresses, the reliability test provides information on the existing margin between the test level (the remaining strength) and the requirement. This margin is a measure of reliability at the end of required period, t_L .

The ultimate strength of the design is considerably higher than the design specifications and this is the level determined in the qualitative accelerated test where the goal is to identify design weaknesses which ~~could~~ can compromise ~~product~~ item reliability, i.e. the weaknesses that ~~could~~ can occur in the ~~product's~~ item's life span, as the ~~product~~ item degrades. Thus, the strength in the qualitative test is demonstrated at operating limit (OL).

The destruct limit is above (beyond) the operating limit, and is denoted as DL. This is where a permanent failure is observed. If the OL or DL are close to the DSL or the standard deviation of the OL or DL distributions are high, then the test will indicate a potential weakness in the design as indicated in Figure 1.

~~Product~~ Item reliability is a function of time, usually predetermined life time, t_L .

The cumulative normal distribution of the margin (difference of stress means divided by their common standard deviation) between the specified strength (use conditions) which is represented by the requirement and the reliability test level (RTL) determines ~~product~~ item reliability. The test level and its duration are chosen so as to cause cumulative damage during testing corresponding to the degradation due to cumulative damage in the ~~product's~~ item's life span. The calculated value produces ~~product~~ the item required reliability, which is then a quantitative measure.

A summary of listed tests and the mapping of their applications to the ~~product~~ item life cycle is presented in Table 1.

Table 1 – Test types mapped to the ~~product~~ item development cycle

Type	Design	Integration	Validation	Acceptance	Manufacturing	Services
A Qualitative	FMECA	HALT			HASS/HASA	
	Maturity Building		Maturity Confirmation			
B & C Quantative			Reliability Growth Test	Reliability Qualification Test	Reliability Production Acceptance Test	
	Maturity Assessment					
Product Breakdown structure Opportunity	Type B/C : Component					
	Type A : Component	Type A : Assembly an/or Subsystem				
		Type B/C : Assembly	Type B/C : System			

Table 1 provides the users of this document a synthesis in order to get a better understanding of the different methods as and when required during the whole life cycle ~~product~~ of the item.

4.2 Classification, methods and types of test acceleration

4.2.1 General

Based on the cumulative damage model, the information expected from the test and the ~~product~~ item use assumptions, the accelerated test methods may be divided into three groups:

- Type A: qualitative accelerated tests: for detection of failure mode ~~and~~ or phenomenon;
- Type B quantitative accelerated tests: for prediction of failure distribution in normal use;
- Type C: quantitative time and event compression tests: for prediction of failure distribution in normal use.

~~NOTE Both B and C types of test may lead to test time reduction. Type B test should be performed based on particular failure mechanism, and generally it may be applied to lifetime acceleration. Type C test requires research of usage or specific conditions' assumption before test. Type C test may be applied to failure rate acceleration.~~

4.2.2 Type A: qualitative accelerated tests

Type A accelerated tests are designed to identify potential design weaknesses and also weaknesses caused by the manufacturing process. They can therefore be induced at levels considerably higher than OL, as shown in Figure 1. The goal of this type of test is not to quantify ~~product~~ item reliability, but to induce or precipitate, during the test, the ~~product's~~ item's overall performance issues which are likely to take place in the field some time during the ~~product's~~ useful item's life time and result in ~~a product~~ an item failure. Improvement of the ~~product~~ item design or manufacturing processes is executed to preclude those failures, producing a stronger or more robust ~~product~~ item, expected to be more reliable in the field even under extreme or repetitive stresses as outlined in the design specifications.

Type A tests may be applied also to detect other weaknesses or latent failures not only for reliability but also for other dependability attributes.

~~Product~~ Item development processes using this type of test increase ~~product~~ item reliability through the mitigation of failure modes and by increasing ~~product~~ item robustness without demonstrating a reliability target or measuring reliability improvement. These tests are often made with such high stress levels that, ideally, failures should be observed (DL in Figure 1) well beyond design specification limits. The purpose is to identify the failure modes, the weak links in the design and the margin between the functional limits, operating limit (OL) and the destruct limit (DL), as shown in Figure 1. The margin between the specification limit and the operating limit ensures that the weaknesses are identified in HALT (see 5.1.1) and are not expected to occur as failures during the expected ~~product~~ item life, t_L .

NOTE Other tests of type A are marginal tests and overstress tests.

4.2.3 Type B: quantitative accelerated tests

Type B tests use cumulative damage methods to determine ~~product~~ item reliability projected to the end of the expected ~~product~~ item life. The necessary margin between the expected cumulative damage and the requirement produces a reliability measure. These tests are then accelerated to achieve the required cumulative damage in considerably shorter time than the ~~product's~~ item's expected life. Type B accelerated tests use quantifiable acceleration factors which are based on the physics of specific failures (or failure modes) and provide a relationship between the exposure time to the specific stresses during testing and in use environment. The failure, or failure mode distribution, is determined from information gathered through separate accelerated tests. Such test information provides the basis for a functional life model and can be used to quantify test acceleration for various reliability calculations, as necessary and/or applicable. In this way, ~~product~~ item reliability can be estimated through estimation of the reliability or probability of occurrence of individual failure modes for any level of expected stresses. If ~~needed~~ necessary for data analysis using other test types (e.g. reliability growth or reliability demonstration tests), the determined test acceleration factor can be used to recalculate times to failure data from accelerated tests so as to represent times to failure occurrences in the use environment, and use the results for reliability calculations. In Figure 1, these tests are shown as reliability test levels (RTLs).

Another way of getting information from this type of test is to test to failure samples of items for the specific failure modes and the specific environments. This permits determination of applicable failure distributions and appropriate acceleration factors which can then be used for calculation of the probability of occurrence of the particular failure mode. This information ~~may~~ can be useful for future tests as well as Weibayes tests (1 parameter Weibull; see IEC 61649). The stress level of the Type B tests can be illustrated in Figure 1 as being higher than the requirement, but below the stress level that would be applied in HALT. The stress level can be between the design specification limit and the stress level of DL. The duration of the stress application shall be sufficient to cause cumulative damage with a margin over the cumulative

damage produced by the expected life stresses during the ~~product~~ item life. ~~This margin then yields the measure of product reliability during the time t_L , $R(t_L)$.~~

Test time reduction is often achieved through an increase in operational or environmental stress beyond those specified for use. The increased level of these stresses produces a cumulative damage effect equivalent to that expected in the ~~product~~ item life, but in a considerably reduced time period.

The accelerated degradation test (ADT) is a method where the degradation of an item is measured as a function of time or stress cycles. The degradation is plotted and extrapolated until the parameter reaches an unacceptable level (failure). This method is very useful for failures that are not sudden failures, but develop gradually. The stress levels applied in the test may be the nominal or worst case operating limits expected in the field use or the test may be accelerated by increasing test stresses as described in [1]¹.

4.2.4 Type C: quantitative time and event compressed tests

4.2.4.1 Use of Type C tests

Type C tests are mostly used for estimation of the life time of components where wear-out in active use is the dominating failure mode, for example switches, keyboards, relays, connectors or bearings. The data from these tests are often analysed using the Weibull distribution, and often in the form of the so-called "sudden death test" (see IEC 61649).

Type C time compression tests are also often used to identify:

- system integration issues (such as software and hardware integration or interaction);
- failure modes that are specific to the operating state, for example operating cycles for any mechanical and electrical cycling event;
- failure modes specific for environments where the range of stress is broad, but there is a threshold defined such that stress exposures below the threshold will not contribute significant damage to the ~~product~~ item.

With the time compressions or event compression, the stress is accelerated by the duration or frequency of its application but not by the increase of its level.

Each of the above accelerated test methods is further described in Clause 5.

4.2.4.2 Time compression

Time compression is a test acceleration that can be applied in some circumstances, where the tests take into consideration only the time that ~~a product~~ an item is actually operational or operating in a state that produces significant damage (also known as removal of "non-damaging exposures"). The circumstances in which this type of acceleration may be applied are those where the operational stresses and their cumulative damage are significantly higher than those in other operational modes, for example non-operational or standby, ~~etc.~~ To apply this rationale, the accumulated damage during the lower stress periods should be insignificant compared with the damage accumulated during the high stress periods, which physically ~~may~~ will possibly not be easily justified (see IEC 60605-2).

4.2.4.3 Event compression

When a stress is repetitious, such as ON/OFF cycling, then the test can be accelerated by speeding up the repetition of stress (event compression). This is especially useful in cases where the test cannot be accelerated by increasing the stress level itself. In this manner, the number of operations remains the same as does the effect of the cumulative damage. Care

¹ Numbers in square brackets refer to the Bibliography.

should be taken that the higher repetition rate of the stress does not cause failure modes that would not occur in normal operation. Examples are self-heating in a plastic part, vibrations that do not dampen out before the next load and software sequences that do not finish before the next signal.

5 Accelerated test models

5.1 Type A, qualitative accelerated tests

5.1.1 Highly accelerated limit tests (HALT)

5.1.1.1 General

Each type of commonly applied accelerated test method is presented in this document with its advantages, disadvantages and necessary application cautions.

Type A tests are not only the classical HALT but there are also other highly accelerated test types such as the autoclave, thermal shock, marginal tests, over-stress tests and other quantitative accelerated tests (see JESD47B [2] and [3]).

NOTE 1 A classical HALT uses only thermal and vibrational stresses.

The model shown in Figure 1 illustrates the relationship between the specifications, the design limits and the test strategies of the HALT.

NOTE 2 The acronym HALT was inadvertently spelt out in the past as highly accelerated *life* test. By its nature of being a qualitative accelerated test, however, HALT does not measure the life of an item, even though the term "life" is implied by ensuring that the failures in HALT would not be experienced in the life of the tested item. The test effectively tests the strength limits of ~~a product~~ an item, thus the word "limit" is appropriately used in the spelt-out acronym.

When reliability demonstration or reliability growth tests are accelerated, there is a need to demonstrate a margin between the cumulative damage induced by the applied stresses during testing and the cumulative damages caused by stresses expected to take place during the life, or any other predetermined time for which reliability is to be demonstrated. The favourable test results for the applied margins provide information on ~~product~~ item reliability in that predetermined time as expressed by strength versus stress criteria. Demonstrated strength is shown through the test results, while reliability is the complement of the area common to both, load and strength curves, shown in Figure 2 (the area common to both ~~curves represents the area where a failure occurs~~ stress and strength distributions are associated with the probability of failure of the item, the larger this area, the greater the probability of failure will be).

In Figure 1 the requirement specifications are translated into design specifications. The figure further illustrates how the design margin is verified by the HALT.

In order to estimate the margin between the design specifications and the unit under test (UUT) it is necessary to increase the stress levels until failure occurs during Type A tests. The margins verified in these tests are illustrated by a HALT operating stress limit (OL), as well as a destruct limit (DL). This also indicates the margins for the variations in the materials and manufacturing processes during manufacturing.

5.1.1.2 Main principles of HALT

The methodology of HALT is to quickly precipitate failures to identify and mitigate design weaknesses in ~~a product~~ an item in order to increase robustness during the ~~product~~ item field use. This type of accelerated test is not intended to measure, but to increase ~~product~~ item reliability through the elimination of failure modes with the lowest margin between the field stress (load) and ~~product~~ item strength (Figure 2 and Figure 3). This type of accelerated test only identifies potential failure modes and guides the development and improvement processes for the chosen stressors. It is from the experience of HALT that most products are very robust for the applied stresses, but that a few components or design details are significantly weaker

than the rest. The idea of a HALT is to find those few components or design details and make them as strong as the rest of the ~~product~~ item.

Figure 2 illustrates the interference between the strength and stress distribution. It is assumed that the stresses in the field from different applications, climatic conditions, etc. can be modelled by a ~~stress~~ load distribution. It is shown here as a normal distribution. The strength of the ~~products~~ items will vary due to variations in raw materials and manufacturing processes. This can be modelled by a strength distribution which in Figure 2 is also shown as a normal distribution.

The area common to both ~~stress~~ load and strength distribution, ~~measures~~ is associated with the probability of ~~product~~ item failure. The larger this area, the greater the probability of failure will be. The graph in Figure 2 shows the classical design margin, stress versus strength criteria, but in the context shown in 5.1.1.2, it does not account for the cumulative damage model; therefore, it is ~~not~~ applicable to the initial short duration test that would measure the ultimate strength of the ~~product~~ item design. Also, if the extensive ~~product~~ item quality control maintains a very narrow strength distribution (which ~~may~~ can be a very expensive and time consuming measure), then the distributions would not overlap, meaning that the field failures for the specific failure mode would be unlikely.

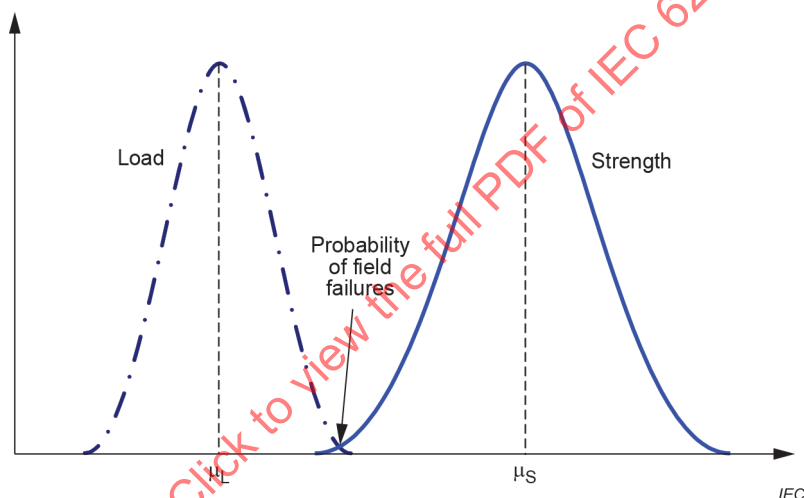


Figure 2 – Relationship of PDFs of the ~~product~~ item strength versus load in use

The manufacturing process, during production of the initial test units, is usually maintained under tight control, which may not be the case with the later continuous production runs. Figure 3 illustrates that the samples manufactured for testing are often of average strength or stronger, since they are often manufactured in a special prototype line with maximum management attention. Once the product is mass produced, the regular production items will be often weaker than the samples taken from the initial production. The rationale is shown in Figure 3. If the distribution of the first carefully produced samples were plotted as a function of stress, the low side of that distribution curve would fall at the place where the mean of the new distribution, μ_1 is located.

The narrow spread of this original distribution would make it far from the distribution of the expected load, shown as the distribution on the left. All of the items in that production run would have passed the test, i.e. there would be no failures detected. But with the later mass production, the strength mean becomes considerably lower, so that the overlap of the stress and the strength distribution becomes imminent; this would lead to failure of the units of weaker production under the field load. This means that the test would not adequately discover the potential weakness of the mass produced units. If the test level is higher (the mean approximately at the level μ_3 in Figure 3), and the product strength has a distribution that includes the regular production, such a test would provide a sufficient margin to ensure that the potential failures in use of the weaker units are detected and mitigated. In the cases where there is inadequate margin will cause failures in the field in later production. **1**

Figure 3 illustrates the importance of design margins. The design margin not only have to cover the reduction in strength due to ageing, wear and fatigue, it also has to cover the variations in strength caused by the raw materials, components and manufacturing and assembly processes. Figure 3 a) illustrates a case of insufficient design margin, Figure 3 b) a case with sufficient design margin. The load curve illustrates the loads used during testing, representing the loads in the field. The strength curve is a PDF curve that covers all produced items from early test samples to mass produced items. The test samples are often manufactured in a special prototype test laboratory with optimum manufacturing conditions and maximum management attention. They are therefore typical of average strength or better (light blue circles). Later when the items are mass produced variations in strength from raw materials, components and manufacturing processes often cause the produced items to be of lower strength (the left "tail" of the strength distribution – the dark blue circles). When looking at the acceptance test of the design in Figure 3 a) the test level is H1 – the maximum stress expected in the field. The test samples (light blue circles) pass this test and the design is approved. However, once the mass production starts, some items in the left tail of the strength distribution (dark blue circles) are produced, and some of these cause failures in the field. In Figure 3 b) a HALT test is made on the design. Once the design survives the stress level H1 the stress is increased to H2, H3 and H4. In Figure 3 a) failure would be seen already at H2, had a HALT test been made, but in Figure 3 b) no failures are seen even at stress level H4. The conclusion is therefore that the design in Figure 3 b) has a sufficient margin, while the design in Figure 3 a) has an insufficient margin. This would not have been detected if a HALT test had not been made.

This is the rationale behind the application of tests such as step-stress tests and HALT, to ensure an appropriate margin over the expected stresses in life ~~is ensured~~. In this way, these tests can be performed on a considerably smaller number of test samples than needed for conventional testing.

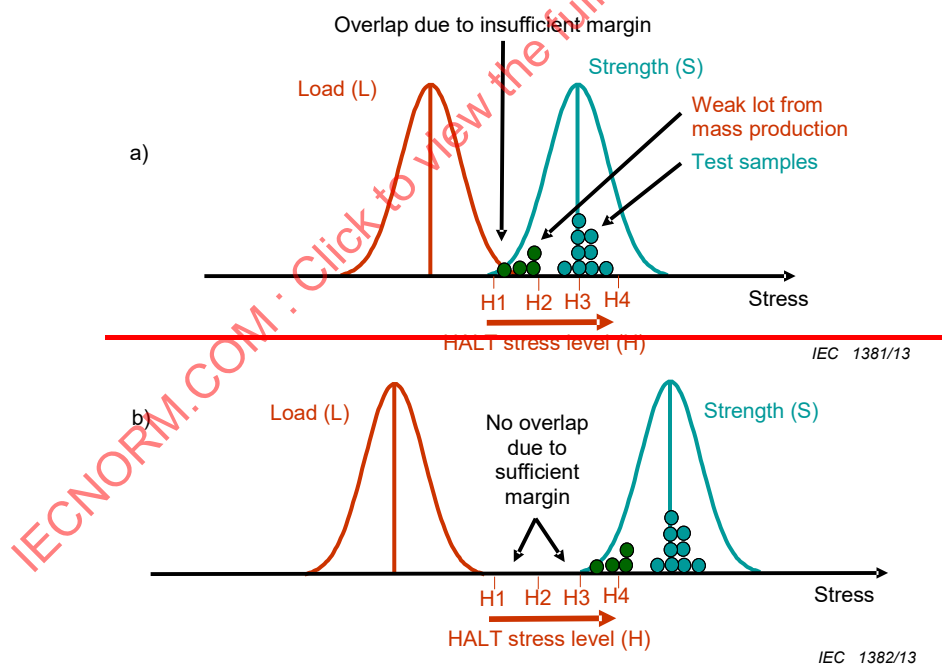


Figure 3 – How uncertainty of load and strength affects the test policy

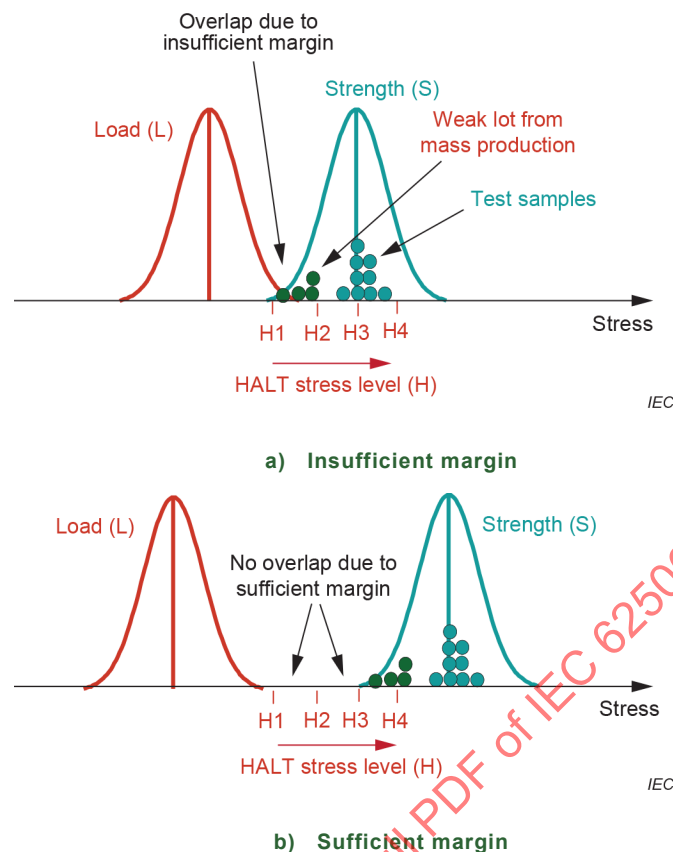


Figure 3 – How HALT tests detect the design margin

HALT is an explorative, qualitative design improvement test and should be accepted as such. It identifies the weakest link failure mode in the design for the related stress type(s). If this failure mode is related to the stress in the ~~product~~ item use environment, the stress levels can only be estimated by an engineering judgement, considering the margin between the load and strength curves and including the additional margin for the expected variations in both the manufacturing process and the expected use environment. The comparison between HALT and a conventional accelerated test is illustrated in ~~Table C.1~~ Table A.1. A step by step procedure can be found in Clause A.2 and examples in Table A.2, Table A.3 and Table A.4.

With the weakest link failing first, HALT is applied further to detect the second, third, and other consecutive weak links. This takes place until no more relevant failure modes are observed or until the technological limits of the tested system are reached.

HALT is designed to far exceed the ~~product~~ item use environment as well as the design specifications. The stresses are applied in short durations, and the goal is to precipitate transition of faults into failures, and strengthen the ~~product~~ item as much as it is economically and technically feasible. HALT identifies failure modes, but not their time dependency.

The UUT ~~has to~~ shall be functionally monitored during the test in order to detect the loss of its functions. If continuous monitoring is not possible, the ~~product~~ item functions have to be tested while the stress level is kept constant. A typical procedure for a HALT is shown in Annex A.

The stress magnitude is not the focus of HALT; the real focus of an effective HALT programme is on ~~product~~ item improvement activities and organizational response to failures. The ~~product~~ item improvement should be continued to the point of a cost-effective rugged ~~product~~ item where no part of the design is significantly weaker than the rest of the ~~product~~ item. The goal is to keep improving the ~~product~~ item to the level justified by the business case and utilization of cost-effective technology.

The operating and destruct limits for the ~~product~~ item can be pictured as distributions on a stress axis, as illustrated in Figure 4, for both stress extremes, high and low (LOL, UOL, LDL, and UDL).

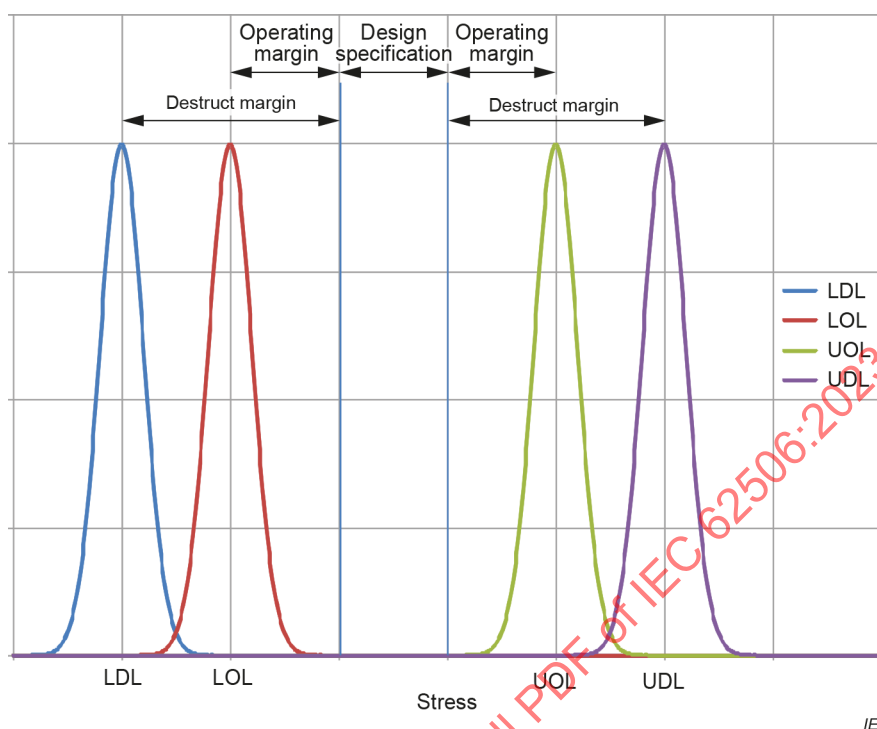


Figure 4 – PDFs of operating and destruct limits as a function of applied stress

Figure 4 is an example where both limits of the stress affect an item. This example ~~could~~ can be the thermal stress where both, high and low temperatures, affect the performance of the ~~product~~ item. It is possible that these effects ~~may~~ will not be symmetrical, as the limits for high and low temperatures ~~may~~ can be at a different distance from the nominal design stress. Even though these tests are performed on early prototypes they can provide information on design related failure modes. As shown in Figure 4, all of these limits can vary as indicated by the distributions. These distributions may have different standard deviations, and to determine HALT is to give an indication of the margins that allows the final ~~product~~ item to accommodate these variations without failures in the field.

Even though Figure 4 depicts the temperature stress, other stresses may also be successfully applied in a HALT. In the case of other stress types, it is possible that lower limits ~~may~~ will not exist as for example is the case for mechanical stresses, but they ~~may~~ can exist with other stresses such as electrical stress and humidity.

5.1.1.3 Stress types and application

The primary or typically applied stresses in HALT are as follows:

- temperature;
- thermal cycling;
- vibration/ or shock;
- voltage;
- combination of vibration/ or shock and thermal cycling.

Other ~~product~~ item-specific stresses can also be applied such as clock frequency for the microprocessor, voltage or power variations, contaminants or solvents, or a combination of these [3].

Verification of margins and ~~product~~ item improvements made in response to HALT serve to increase the likelihood that the ~~product~~ item will be robust and reliable in the field.

An example of typical stress levels is shown in Annex A. Ideally, the HALT stresses are applied as described in 5.1.1.2 until the predetermined maximum stresses are achieved. These maximum stresses are determined as follows:

- by the material limits and technological limits of the used materials and components;
- by the maximum stress achievable with the available methods and equipment.

It should be noted that the applied stress levels should not exceed the ultimate material limits where the physical or chemical characteristics ~~might~~ can change.

It is normal to expect that there are some fragile elements in the UUT that are not designed for the stress levels normally applied in HALT. Those fragile elements should if possible be protected during HALT or disregarded in the test data evaluation. Fragile elements may be protected for example by applying cooling air to them, by isolating them against cold air, by suspending them outside the UUT in order to isolate them from vibration and shock or even by moving them outside the HALT test chamber and extending their connections to the rest of the UUT. Fragile elements that have been protected during the HALT test then have to be tested by a separate test for example a component test or a survival test.

Each failure observed during the HALT should be investigated and root cause failure analysis should be performed (see IEC 62740 [4]). If the identified failure mode is likely to occur in the field where the stress level is expected to be considerably lower than in a HALT, a corrective action should be proposed and implemented in accordance with engineering as well as management decisions.

5.1.2 Highly accelerated stress test (HAST)

This type of testing may be considered to be a cross between the qualitative, Type A, and quantitative, Type B, tests. This test type is very popular in the electronic components industry where it is widely used as a more efficient (shorter) alternative to the much longer temperature humidity bias test (THB), i.e. a pressure cooker test, which has a duration of 1 000 h. The stresses in these tests consist usually of temperature and humidity where corrosion of vias (metal conductors) in dies and thin film resistors ~~may~~ can occur. The components are normally voltage biased during the test. Even though these tests do not yield numerical reliability estimates, they are used as effective re-qualification tests to provide certainty that reliability of the components is not compromised by any changes introduced in the components, see JESD22-A110 [5]. The duration of a HAST in the electronic component industry is usually about 100 h, and the stress levels for temperature and humidity are usually 130 °C and 85 % RH, respectively.

5.1.3 Highly accelerated stress screening~~/~~ or audit (HASS~~/~~ or HASA)

5.1.3.1 Principle Applicability and ~~extent~~ principle of HASS~~/~~ or HASA

HASS and HASA are not classified as tests. Yet, both are included in this document because they apply accelerated stress for defect detection~~/~~ or screening. HASS is used for screening of production units using stresses considerably higher than those expected in normal use or in shipping, but with lower levels than those that ~~might~~ can significantly reduce ~~product~~ item life in the field. These levels are determined based on the finding from the HALT programme. The screening may be performed on all (100 %) production units or on a sample. The purpose of screening is to detect any latent manufacturing defects that would eventually appear in the normal use of the ~~product~~ item. Detection of latent defects, followed by failure analysis and necessary corrective action (verified through a test designed to detect the specific failure mode), reduces the number of faults. The resulting field reliability improvement is due to the reduction in the number of field components with latent manufacturing defects and not due to a change in the inherent design reliability. HASS is ideally suited to pilot production or production ramp-up, i.e. when production rate is slow and 100 % screening can easily be accomplished.

HASS may continue during normal production for very critical items that are manufactured in small volumes.

The stress levels in HASS/ or HASA are used for defect precipitation screening. The precipitation screen consists of combined stresses with their levels barely inside the operational limits. The purpose of this screen is to precipitate manufacturing defects into intermittent or permanent failures. To detect the failures, it is recommended to monitor the functions of the UUTs during screening as it is possible that some operational abnormalities may will not be discovered in the post test operational checks. Further, it is not known when, during the precipitation screening, the possibly intermittent functional failure may can be detected. The precipitation screen may combine several different stress types and stress levels. As with HALT, intermittent failures can be verified by using a detection screen (see Clause A.2, Step 4). Constant monitoring should provide functional coverage that is as complete as possible. Coverage and effectiveness of the monitoring should be optimized prior to beginning of the screen development process. The monitoring process should facilitate root cause analysis.

A typical precipitation screen itself will require a relatively short stress application time such as from 3 min to 1 h of stress. Additional time will be required for the test and monitoring equipment set-up.

~~HASS is ideally suited to pilot production or production ramp-up, i.e. when production rate is slow and 100 % screening may easily be accomplished. HASS may continue during normal production for very critical products that are manufactured in small volumes.~~

HASA is a process monitoring tool where a sample from a production lot is exposed to the precipitation screen to detect possible defects. HASA is often performed before the production lot is released. HASA often supplants HASS when the manufacturing process reaches its maturity. HASA is further reduced and even eliminated when the effectiveness of production controls is established.

5.1.3.2 Selection of stresses and their magnitudes

Stresses should be selected so as not to compromise functionality, material properties, or the life of non defective hardware. The initial levels are determined from information gained in HALT.

The precipitation screen is performed with stress levels a little lower than the operating limits since the UUT have to be monitored for function during screening. Typically, the temperature stress is reduced by 5 °C and the vibration level by 2 g RMS (19,62 m/s²). Before the precipitation screen is used for HASS/ or HASA it should be verified that the precipitation screen does not significantly reduce the product item life in the field. This can be tested, for example, by exposing one sample to the precipitation screen 10 times.

5.1.4 Engineering aspects of HALT and HASS

5.1.4.1 Advantages of HALT and HASS

The advantages of HALT and HASS are as follows:

- verified and selectively increased design margins for reliability improvement;
- sample size for determination of a specific failure mode is small;
- quick determination of dominant failure modes for specific stressors and easily combined stresses (the duration of the test is typically three days);
- efficient trade-off analysis information and determination of necessary corrective actions;
- quick verification of corrective actions;
- efficient short-term production screening;

- elimination of weak or defective components (HASS) from the main population (quality and reliability improvement).

5.1.4.2 Disadvantages of HALT and HASS

The disadvantages of HALT and HASS are as follows:

- a) possibility of stimulating failure modes that would not normally be observed in ~~product~~ item use;
- b) potential for over-improvement of design margin (over-design);
- c) resultant reliability not known;
- d) no statistical confidence in the test result (over- or under-estimation of the design margins);
- e) testing does not address all interactive effects of multiple failure modes;
- f) impractical for very large ~~products~~ items, very small ~~products~~ items and ~~products~~ items with diverse fragility;
- g) limited number of stress types (primarily temperature, vibration, shock and thermal cycling);
- h) inability to evaluate the design limits for a stress influenced by synergy with other stress types not provided by the HALT types.

5.2 Types B and C – Quantitative accelerated test methods

5.2.1 Purpose of quantitative accelerated testing

The purpose of quantitative accelerated tests is to estimate one or more measures of reliability, for example failure rate, probability of failure or survival, or time to failure (TTF). Often the purpose of quantitative accelerated testing is to determine the life time of components with a limited life (wear-out), or to determine (quantify) and improve the reliability of systems and components. For this, Weibull analysis is very useful (see IEC 61649).

5.2.2 Physical basis for the quantitative accelerated Type B test methods

5.2.2.1 General

The goal of Type B accelerated testing is to measure the reliability and verify acceptable reliability performance of the ~~product~~ item within a short period of time. Thus, the goal in accelerated testing is to accelerate the damage accumulation rate for relevant repetitive stress and wear-out failure mechanisms (a relevant failure mechanism is one that is expected to occur under life-cycle conditions).

In order to accelerate tests, it is necessary to have a thorough understanding of the potential failure mechanisms and the operational and environmental stresses of the ~~product~~ item or system. This can also be achieved through failure mode analysis of the designed ~~product~~ item associated with the intended ~~product~~ item usage profile, for example using an FMEA (see IEC 60812 [6]). Effective measures can then be taken not only to prevent their manifestation under predetermined life or usage stresses, but also to precipitate them effectively during accelerated testing for ~~product~~ item improvement. Accelerated wear-out or reliability testing has been recognized to be a valuable activity to assess the reliability of high reliability electronics, electro-mechanical and mechanical systems. The application of elevated stresses is usually for the purpose of:

- a) making the design more robust and improving the manufacturing process through systematic step-stress testing and increasing the stress margins through corrective actions (reliability growth testing);
- b) conducting accelerated life tests in the laboratory to measure and verify in-service reliability.

The extent of acceleration, usually termed the acceleration factor (AF ~~or~~ A), is defined as the ratio of the life under use conditions to that under the accelerated test conditions. This acceleration factor is needed to quantitatively extrapolate reliability measures (such as time-to-failure and failure rates) from the accelerated test environment to the usage environment, with

some reasonable degree of confidence. The acceleration factor depends on hardware parameters (e.g. material properties, ~~product~~ item architecture) of the UUT, usage stress conditions, accelerated stress test conditions and the relevant failure mechanism. Thus, each relevant failure mode (assuming it is a result of one failure mechanism) in the UUT has its own acceleration factor and the test conditions (e.g. duty cycle, stress level, stress history, test duration) shall be tailored based on these acceleration factors.

The physics of failure approach means that each failure mode is addressed separately and the margin to the life time or to the required reliability is verified for each of them. ~~In some cases the result is kept qualitative.~~ With this approach, each of the failure modes has its own failure distribution and failure rate. In other cases, the result is combined to an estimated reliability for the whole ~~product~~ item.

When planning a test the potential failure modes in the item should be listed. The test is then planned with stress levels and durations so that the failure modes should be observed in the test if they are present in the ~~product~~ item. For this planning, empirical factors from previous ~~products~~ items, from the component suppliers or from literature, can be used to estimate the acceleration factor of the test. After the test is performed the actual failure modes are known, and the test can be analysed for each failure mode separately. It is recommended to use a test set-up where the empirical factors can be estimated from the test itself. See Annex E and Annex F.

Type B tests can be run by increasing the level of a variety of loads such as thermal loads (e.g. temperature, temperature cycling, and rates of temperature change), chemical loads (e.g. humidity, corrosive chemicals like acids and salt), electrical loads (e.g. steady-state or transient voltage, current, power), and mechanical loads (e.g. quasi-static cyclic mechanical deformations, vibration, and shock ~~impulse~~ or impact). The accelerated test environment may include a combination of these loads. Interpretation of results for combined loads and extrapolation of the results to the life-cycle conditions requires a quantitative understanding of the relative interactions of the different test stresses and the contribution of each stress type to the overall damage.

5.2.2.2 Advantages of the Type B test

The acceleration stress test provides quantitative information on the reliability of the tested ~~product~~ item:

- this test type can be designed
 - for selected failure modes (e.g. from FMEA) to assess, with reasonable confidence, overall reliability;
 - for combined stresses also to simulate the interactive effects of those stresses and a realistic assessment of the ~~product~~ item reliability;
- an acceleration test can be effectively carried out to enable the test to represent cumulative damage in use.

5.2.2.3 Disadvantages of the Type B test

- A risk that the stress acceleration ~~may~~ can exceed the physical properties of ~~product~~ item materials and cause unforeseen damage.
- A risk that the acceleration of combined stresses ~~may~~ can cause additional unforeseen damage to the ~~product~~ item that would not have happened in actual use.
- The base line for ~~acceleration~~ accelerated testing is not a single stress but is generally a multiple stress that varies with user and location. ~~This needs to be taken~~ It is necessary to take this into consideration when quantifying the results.

5.2.3 Type C tests, time (C_1) and event (C_2) compression

5.2.3.1 Type C_1 tests

5.2.3.1.1 General

Time compression is achieved by eliminating "OFF-time" (e.g. non-operating time or time with low stress levels) by compressing the duty cycle through addressing just the ON time. Furthermore, when ~~products~~ items are exposed to a wide range of stresses, it is typical that the highest stresses (the primary stresses) will induce the most damage, and that there are some levels of usage stress that, compared to the primary stresses, are assumed to produce negligible damage. Any exposure below a chosen damage threshold stress can be assumed to produce negligible damage and can be eliminated from the test programme. This is particularly true for mechanical fatigue and is often applied in accelerated structural fatigue testing (see IEC 60605-2).

An example of duty cycle compression is when the test duration is 24 h per day, whereas the ~~product~~ item in its actual use environment operates for only 8 h per day. This results in a time compression factor of 3. Each day of test time is equal to three days of actual use time.

5.2.3.1.2 Advantages of time compressed tests

~~Products~~ Items with a minimal or short operating use time compared with calendar time can be tested within a very reasonable test time relative to its required life (e.g. office equipment, cars, harvesting machinery). For example, a snow plough is used only in one season, once a year, and only when there is a reasonable accumulation of snow to justify its use. Even when used, it is expected to be on for 2 h to 3 h on average. There are several primary damaging stresses such as vibration, stress in the motor, wear-out of blades, ~~etc.~~ For the rest of the year, it is stored in a shed, and protected from extreme weather conditions. Thus a snow plough that has a required life of ten years, but effectively is used four times a month for three months, for durations of 2 h, can be tested for a required usage duration of 240 h. Therefore, a test of approximately 300 h would provide a good margin to prove the snow plough's reliability.

With a relatively short test duration at nominal stresses, there is no reason to increase the stresses, and therefore, there is no need to determine stress acceleration factors; otherwise there is a risk of overstressing the UUT.

5.2.3.1.3 Disadvantages of time compressed tests

Concentration exclusively on operational time means considering the operational environment only with its associated failure modes, while the failure modes occurring in the "non-operational" environments may be neglected. Such failure modes ~~could~~ can even be more damaging to the ~~product~~ item, since they are a result of stresses that are perhaps considerably lower than those when the ~~product~~ item is in use, but are applied for a considerably longer time to produce the same or greater cumulative damage than the stresses applied in use.

Considering the same example of the snow plough, there are 87 600 h in its ten-year lifespan when the snow plough is exposed to extreme cold temperature for approximately 20 000 h, leading to the failure mode of embrittlement of materials; very high temperatures for approximately 6 000 h, leading to ageing of plastic parts, paint, adhesives, thermal cycling; approximately 7 200 cycles causing multiple structural damage; and humidity, applied for a minimum of 30 000 h per year, causing corrosion. Testing only under operational conditions would disregard the influence of non-operating environments.

For ~~products~~ items where active time is considerably shorter than the passive (OFF time), it is necessary to combine time accelerated testing for the operational periods with tests that accelerate the passive periods, for example corrosion tests, humidity tests, ~~etc.~~ In some cases the ~~product~~ item can be preconditioned before the time compressed tests by applying some stresses from the passive periods, for example moisture, cold storage, solar radiation or mechanical loads like vibrations and shocks simulating the non-operating conditions. The

purpose of such preconditioning is to simulate the inter-relationship of the failure modes of active use with the failure modes expected in storage, which in turn highly affect the failure modes in use. As an example, corrosion of the snow plough would highly affect the influence of applied vibrations on the ~~product~~ item structure.

5.2.3.2 Type C₂ tests

5.2.3.2.1 General

The event compression tests apply repetitions of events with considerably higher rates than those applied in actual ~~product~~ item use. As an example, the ON/OFF cycling of the above-mentioned unit (the snow plough) can be compressed to a test of several hours, by applying the ON/OFF cycling repeatedly. Therefore, the 120 required ON/OFF cycles in the 10-year life with a sufficient margin to demonstrate reliability would be a very short test.

Type C₂ tests can be combined with the time compression tests for further test acceleration. This ~~may~~ can result in a very short test with "high reliability" demonstration, however, several important precautions shall be taken when carrying out this combined acceleration. For example, the rapid application of repetitious stresses ~~may~~ can influence test results by varying cumulative damage.

The event compression tests may also be combined with the stress acceleration tests to further shorten the test time. Caution should be exercised when preparing such tests, as the time compression ~~may~~ can influence the stress acceleration. For example, fast ON/OFF cycling results in a very short time in the OFF condition, which does not then allow the UUT to properly cool down. This can then result in additional thermal acceleration of the UUT's degradation and precipitation of failures. Also, this type of acceleration ~~may~~ can neglect the failures due to non-use, such as material deterioration.

5.2.3.2.2 Advantages of the Type C₂ test

The advantage of the Type C₂ test is that in a short time, by speeding up the stress repetition, the cumulative damage can be reproduced within a much shorter time than in regular use.

5.2.3.2.3 Disadvantages of the Type C₂ test

This type of testing ~~may~~ can also produce some negative effects by applying continuous stress and in a manner that precipitates failures that normally would not occur. For example, in mechanical parts with a wear-out mechanism induced by friction during operation, continuous friction ~~may~~ can produce heat that would further precipitate a failure that would normally be delayed by periods of cooling. Another example ~~could~~ can be the metal fatigue caused by stress repetition, if applied without allowing time for the material relaxation.

5.3 Failure mechanisms and test design

The importance of correct failure analysis shall be strongly emphasized. Understanding the failure mechanisms is essential for designing and conducting successful accelerated life test or other test as advocated in physics-of-failure based reliability design and prediction methodologies (provided that the predictions are done using the physics of failure approach). To achieve this, a rational method shall be identified to relate the results of accelerated tests quantitatively to the reliability or failure rates in use conditions, using a scientific acceleration transform. The amount of test-time compression achieved in an accelerated test ~~shall~~ need to be determined quantitatively, based on the physics of the relevant failure modes. Accelerated life tests attempt to reduce the time it takes to observe failures. In some cases, it is possible to do this without actually changing the equation for the instantaneous failure rate. However, if the hazard function changes, it is termed a "proportional hazard model." Mathematically, the differences between these two can be seen in the following two equations for a Weibull distribution in which $H_{AL}(t)$ is the cumulative hazard function for accelerated life, $H_{PH}(t)$ is the cumulative hazard function for the proportional hazard model, AF is an acceleration factor due

to some sort of stimulus and $(t/\eta)^\beta$ is the unmodified cumulative hazard for a Weibull distribution (t = time, η = characteristic life and β = shape parameter).

$$H_{AL}(t) = \left(\frac{AF \times t}{\eta} \right)^\beta \quad (1)$$

$$H_{PH}(t) = AF \times \left(\frac{t}{\eta} \right)^\beta \quad (2)$$

In $H_{AL}(t)$, there is a linear relationship between time and the acceleration factor. In $H_{PH}(t)$, the hazard function itself is being modified. By rearranging the equation for $H_{PH}(t)$, it can be seen that there is a non-linear relation between time and acceleration factor. The difference between these two types of accelerated tests is that $H_{AL}(t)$, requires knowledge only of the ratio of the actual test time to calendar time (non-accelerated time) caused by the applied environmental stimulus whereas $H_{PH}(t)$, requires knowledge of how the AF changes as a function of the parameter β . For the Weibull distribution, of which the exponential distribution is a special case, the resultant distribution for either of these two conditions is still a Weibull distribution.

Equation (1) is usually applied when the acceleration is made with the increased repetition rate of the applied repetitious stress such as operational cycling. Equation (2) is preferred when the acceleration is applied to the physical states of the unit under test such as thermal acceleration (~~Brown's motion~~), where the acceleration factor itself depends on the distribution.

To summarize the above rationale, it can be said that the stress acceleration provides reduction in time to failure by increasing the stress levels beyond those expected in the normal use of the item.

5.4 Determination of stress levels, profiles and combinations in use and test – Stress modelling

5.4.1 General

It is equally important to understand the operational and environmental stresses that generate the failure mode based on physics of failure. This stress modelling serves as the base point from which acceleration occurs. How this baseline is handled is extremely important when the stresses will vary depending on ~~product~~ item use.

5.4.2 Step-by-step procedure

The following procedure ~~shall be applied~~ is applicable:

- identify the relevant stress factors from the field, including storage and transportation (see the IEC 60721 series);
- determine which stress types ~~have to~~ that will be accelerated, which will be nominal and which can be omitted, for example because they are covered by other tests;
- determine if the stresses can be applied simultaneously to include stress interactions or whether they will have to be applied sequentially, for example in a test cycle (see IEC 60605-2);
- determine if the acceleration factor (~~AF~~) can be estimated from the test or estimate the acceleration factors based on relevant acceleration equations and relevant empirical factors;

- e) determine the sample size (see IEC 61649, IEC 61123 and IEC 61124);
- f) perform the test (see IEC 60300-3-5);
- g) perform failure analysis;
- h) analyse the test – each failure mode separately (see IEC 61649, IEC 61710 and IEC 61124);
- i) report test result (see IEC 60300-3-5).

5.5 Multiple stress acceleration methodology – Type B tests

In cases where two or more stresses are the cause of reactions affecting the component or ~~product~~ item life (reliability), the test acceleration is made by increasing each individual stress using models appropriate for those stresses. In these cases, failure rates representing each of the failure mechanisms are individually accelerated and the overall reliability (R) or failure probability (F) ~~shall~~ ~~should~~ be estimated separately. This can generally be expressed as follows:

$$R = \prod_{i=1}^{N_S} R_i \quad (3)$$

where

R_i represents the influence of a stress i on the reliability of the UUT when stresses are independent;

R represents the reliability of the UUT;

N_S is the total number of independent stresses.

The specific case of competing risks is described in IEC 61649:2008, Annex G.

If the time to failure of all the components or items can be modelled by the exponential distribution this can be simplified as follows:

$$\lambda_{item}(Stress) = \lambda_U + \sum_{i=1}^{N_S} \lambda_i(Stress_i) \quad (4) \quad 2$$

where

~~λ_U is the unknown failure rate.~~

$$AF \times \lambda_{item} = \sum_{i=1}^{N_S} AF_i \times \lambda_{item}(Stress) \quad (4)$$

In the case of Weibull distribution where all of the failure modes distributions have the same shape parameter, the scale parameter of an item under combined stresses is as follows:

$$\frac{1}{\eta_{item}^\beta(Stress)} = \frac{1}{\eta_U^\beta} + \sum_{i=1}^{N_S} \frac{1}{\eta_i^\beta(Stress_i)} \quad (5)$$

$$\frac{1}{\eta_{\text{Item}}^{\beta}(\text{Stress})} = \frac{1}{\eta_U^{\beta}} + \sum_{i=1}^{N_S} \frac{1}{\eta_i^{\beta}(\text{Stress})} \quad (5)$$

where

- β is the shape parameter of the Weibull distribution;
- η_{Item} is the item scale parameter for the combined individual stress;
- η_U is the base scale parameter;
- η_i are the individual stress scale parameters.

For different shape parameters, the resultant distribution may be different to Weibull and the complexity of the relationships increases beyond the scope of this document.

It is to be noted that the Weibull rationale may be used only when accelerating single failure modes because it expresses dependency of times to failure, as Weibull modelling is not applicable to the mix of different failure modes. Times to failure are not related in the case of different failure modes, not even if applied to a single component.

Equation (4) presents a rather accurate way of expressing the overall item failure rate with applied stresses. It assumes that the part or component failure rate is a sum of a basic failure rate, resultant from undetermined failure modes related to the part inherent defects, and of failure rates attributed to the failure modes sensitive to particular stresses and accelerated by them. Then, failure rates representing individual stresses can be determined by separate stress tests. Individual stress accelerations then apply to each of these stress-relevant failure modes.

If each stress type accelerates one and only one failure mode, the acceleration factor will influence each failure mode separately. With the assumption that the exponential distribution is applicable, which is often the case when assemblies and systems are tested for multiple different failure modes, the item failure rate as accelerated is:

$$A \cdot \lambda_{\text{Item}} = \lambda_U + \sum_{i=1}^{N_S} A_i \cdot \lambda_{\text{Item}}(\text{Stress}_i) \quad (6)$$

$$AF \times \lambda_{\text{Item}} = \sum_{i=1}^{N_S} AF_i \times \lambda_{\text{Item}}(\text{Stress}) \quad (6)$$

Dropping the λ_U , which is small in regards to all failure modes' rates of occurrence, and Having in mind that more than one stress may accelerated can accelerate the same failure mode, the test acceleration from Equation (6) becomes Equation (7):

$$\lambda_A = A_{\text{Test}} \cdot \lambda_0 = \sum_{i=1}^{N_S} \left(\left(\prod_k A_k \right)_i \cdot \lambda_i \right) \quad (7)$$

$$\lambda_A = AF_{\text{Test}} \times \lambda_0 = \sum_{i=1}^{N_S} \left(\left(\prod_k AF_k \right)_i \times \lambda_i \right) \quad (7)$$

where

λ_0 is the failure rate that the item has in its use conditions;

λ_A is the accelerated test failure rate;

~~A_i is the acceleration factor for each of the increased stresses in test;~~

~~$\left(\prod_k A_k\right)_i$~~ $\left(\prod_k AF_k\right)_i$ is the product of acceleration factors of stress, i , affecting the failure mode k ;

λ_i is the failure rate of the item corresponding to the specific stress;

N_S is the number of stresses;

~~A_{Test}~~ AF_{Test} is the acceleration factor of the failure rate of the item in use conditions to produce the overall accelerated, test failure rate.

$$A_{Test} = \frac{\sum_{i=1}^{N_S} \left(\left(\prod_k A_k \right)_i \cdot \lambda_i \right)}{\lambda_0} \quad (8)$$

$$AF_{Test} = \frac{\sum_{i=1}^{N_S} \left(\left(\prod_k AF_k \right)_i \times \lambda_i \right)}{\lambda_0} \quad (8)$$

If the failure rate λ_i is defined in terms of reliability at a predefined time t_0, t_1 , $R_i(t_0, t_1)$ then the test acceleration is:

$$A_{Test} = \frac{\sum_{i=1}^{N_S} \left(\left(\prod_k A_k \right)_i \cdot \left[-\frac{\ln(R_i(t_0))}{t_0} \right] \right)}{\lambda_0} \quad (9)$$

$$AF_{Test} = \frac{\sum_{i=1}^{N_S} \left(\left(\prod_k AF_k \right)_i \times \left[-\frac{\ln(R_i(t_1))}{t_1} \right] \right)}{\lambda_0} \quad (9)$$

If all stresses influence all failure modes, the resulting acceleration factors (~~A_i~~ AF_i) can be multiplied. Then the easier or simpler way of calculating the total part failure rate ~~could~~ can be in a form of its base failure rate modified by multiple compounded environmental stresses:

$$\lambda_{Item}(Stress) = \lambda_U \prod_{i=1}^{N_S} A_i \quad (10)$$

$$\lambda_{\text{item}}(\text{Stress}) = \lambda_0 \times \prod_{i=1}^{N_S} A F_i \quad (10)$$

Equation (10), although widely used in the industry, assumes that each applied stress accelerates the base failure rate, and the next applied stress accelerates the total failure rate accelerated by the previous stress, and so on. This simplistic approach ~~may~~ can lead to overestimation of effects of multiple stresses, as the failure mechanisms are different, and some are not accelerated by all of the stresses.

The result of overestimation of acceleration is the overestimation of the probability of failure or leads to tests that are unreasonably short and inadequate.

The best way to calculate realistic test acceleration is to investigate what stresses do influence the same failure modes in which case they can be multiplied.

5.6 Single and multiple stress acceleration for Type B tests

5.6.1 Single stress acceleration methodology

5.6.1.1 General

With this methodology, test acceleration is accomplished with a single stress only. These models are life stress models, where the damage per unit time of test is appropriately accelerated by increasing the level of stress.

The three most frequently used relationships are:

- inverse power law model, used for test acceleration when stresses other than constant temperature are considered, such as electrical, mechanical, chemical (corrosion) ~~and others;~~
- Arrhenius reaction rate model, used for constant temperature stresses, based on the effect that the absolute temperature has on a failure mechanism;
- Eyring model which is used in cases where the acceleration is achieved with temperature and moisture stress levels. ~~The model is derived from quantum mechanics.~~

With all acceleration models, test data can be analysed using established analytical models to determine characteristic accelerated life parameters. Using the acceleration factors, the parameters corresponding to use environments are determined and used for reliability projections as ~~needed~~ necessary. The acceleration models should, if possible, be verified by plotting the test data.

5.6.1.2 Inverse power law

5.6.1.2.1 General

The inverse power law is applicable to:

- dynamic stresses such as shock (any pulse type) and vibration (sinusoidal and random);
- climatic stresses such as thermal cycling, temperature changes (shock and thermal cycling), humidity, solar radiation, or any other climatic stresses with cumulative damage.

The inverse power law model [7] is very simple to understand and use, and is very easily adaptable to any failure distribution. Graphical solutions (best fit by eye) are possible, and the parameters can also be determined using maximum likelihood methodology.

With the inverse power law, the characteristic that represents ~~product~~ item reliability related to time, such as characteristic life, mean life, mean time to a failure, is represented as:

$$L(S) = C^{-1} \times S^{-m} \quad (11)$$

where

S is the stress;

C is the constant (> 0) to be determined;

m is the parameter dependent on stress behaviour, also to be determined;

$L(S)$ is the life or other predetermined time duration as a function of stress.

The power law model is simple when expressed or plotted in logarithmic form, where it becomes a straight line with the slope representing the value of parameter m , and the value of the intercept with the y-axis is a function of the constant C :

$$\ln[L(S)] = -m \times \ln(S) - \ln(C) \quad (12)$$

The inverse power law is applicable to all distributions regularly used in reliability.

The test acceleration factor is then:

$$A_{S_IPL} = \frac{L(S_{Use})}{L(S_{Test})} = \frac{C^{-1} \times S_{Use}^{-m}}{C^{-1} \times S_{Test}^{-m}} = \left(\frac{S_{Test}}{S_{Use}} \right)^m \quad (13)$$

$$AL_{S_{IPL}} = \frac{L(S_{Use})}{L(S_{Test})} = \frac{C^{-1} \times S_{Use}^{-m}}{C^{-1} \times S_{Test}^{-m}} = \left(\frac{S_{Test}}{S_{Use}} \right)^m \quad (13)$$

where

$AL_{S_{IPL}}$ is the acceleration of stress by inverse power law;

$L(S_{Use})$ is the life as a function of stress in actual use;

$L(S_{Test})$ is the life as a function of stress applied in test.

In the Equation (13) the subscripts "Test" and "Use" denote accelerated test condition and non-accelerated use condition, respectively.

Parameter C in the test acceleration cancels out, but the parameter m shall be determined for the item and the stress type.

If not readily known, the parameter m can be determined through tests performed on the same component or item at various stress levels to failure (Annex E and Annex F). The test data is analysed then to determine the distribution and the distribution parameters. The parameter of that distribution that corresponds to the life is then plotted as a function of stress in log-log coordinates, and the slope of the straight line determines the value of the parameter m while the negative intercept will produce the value of the constant C .

This process that appears easy when described ~~may~~ can become a very tedious process for items that are more complex than a single component, as the test ~~may~~ can involve long periods of time and a large number of samples. However, using test acceleration factors that are loosely estimated ~~may~~ can lead to large errors in design of accelerated tests.

When extrapolating the stress-life curve well beyond the test points the predicted stress life curve ~~may~~ can represent a more conservative estimate of life since the actual stress-life curve for the specific failure mode ~~may~~ can exhibit a lower slope.

The inverse power law is usually applicable to thermal shock, electrical and mechanical stresses (static and dynamic) and to humidity.

When accelerating a component life test with a specific stress, failures should be understood and grouped together for the same failure modes to ensure that the applied stresses are generating the same failure mechanism. For example, an accelerated test of a chip ceramic capacitor with nickel electrodes by voltage increase ~~may~~ can exhibit two different failure mechanisms: dielectric breakdown, and movement of oxygen vacancies, both resulting in shorting of the capacitor. The two ~~may~~ can appear as the same failure mode as the two mechanisms would not be distinguished if the failures were not analysed. One of the indicators of presence of two different failure mechanisms ~~could~~ can be a resultant bimodal Weibull distribution (see IEC 61649).

Confidence limits on parameters, life functions and reliability for each of the distributions can be determined with appropriate statistics, as described in for example IEC 61649. Care should be exercised when applying statistical limits for the stress-life curve as, due to small sample size, the resultant extrapolated stress-life curve ~~may~~ can be incorrect.

5.6.1.2.2 Advantages of the inverse power law model

The primary advantage of this model is its simplicity and easy determination of the parameters from a test, provided that there is an easy separation between failure modes. Another advantage is that it is widely used so that the specific parameter values can be found in relevant literature.

5.6.1.2.3 Disadvantage of the inverse power law model

The model disadvantages are as follows:

- the simplicity of the model ~~may~~ can lead to errors in fitting life-related parameters of different distributions;
- often, due to time and cost constraints, it is not possible to determine the inverse power law parameters, hence common average values that can be misleading are used;
- tests to failure, to be statistically defensible, require a large number of samples to be tested to failure at each of the chosen stresses. Components at lower stresses ~~may~~ can require a long test time, and should those at the same time have a high level of reliability, the sample size may ~~need~~ have to be large, and the test ~~may~~ can be lengthy;
- caution should be exercised when accepting an assumed value for the parameter m , borrowed from a seemingly similar ~~product~~ item.

5.6.1.3 Arrhenius model

5.6.1.3.1 General

The Arrhenius model [7] is based on expressing the reaction rate as a function of the component type and its failure mode and the absolute temperature, T . This model assumes that the reaction rate is exponentially dependent on the absolute temperature.

The reaction rate is expressed as follows:

$$\rho(T) = K \times e^{-\frac{E_a}{k_B \times T}} \quad (14)$$

where

K is the constant (not a function of temperature);

E_a is the activation energy (eV);

k_B is Boltzman's constant = $8,617\ 385 \times 10^{-5}$ eV/K;

T is the absolute temperature (K);

$\rho(T)$ is the reaction rate as a function of the absolute temperature.

A function that represents reliable life is expressed as a function of temperature:

$$L(T) = C \times e^{\frac{D}{T}} \quad (15)$$

To represent the above equation as a straight line:

$$\ln[L(T)] = \frac{D}{T} + \ln(C) \quad (16)$$

where

T is the variable absolute temperature measured in degrees K (absolute temperature);

D is the slope of the straight line ($= E_a/k_B$);

$\ln(C)$ is the intercept of the straight line with the Y axis.

The acceleration factor is then found for the use with respect to test environment as the ratio of the two reaction rates:

$$A = \frac{\rho(T)}{\rho(T_0)} = \frac{K \cdot e^{-\frac{E_a}{k_B \cdot T}}}{K \cdot e^{-\frac{E_a}{k_B \cdot T_0}}} = e^{\left[\frac{E_a}{k_B} \left(\frac{1}{T_0} - \frac{1}{T} \right) \right]} \quad (17)$$

$$AF = \frac{\rho(T)}{\rho(T_0)} = \frac{K \times e^{-\frac{E_a}{k_B \times T}}}{K \times e^{-\frac{E_a}{k_B \times T_0}}} = e^{\left[\frac{E_a}{k_B} \left(\frac{1}{T_0} - \frac{1}{T} \right) \right]} \quad (17)$$

The failure rates as a function of absolute temperature, T , can be correlated to the failure rate at a specified absolute temperature, T_0 , as follows:

$$\lambda(T) = C \times e^{-\frac{E_a}{k_B \times T}} \quad (18)$$

The failure rate λ_0 at a specified temperature T_0 is:

$$\lambda_0(T_0) = C \cdot e^{-\frac{E_a}{k_B \cdot T_0}} \quad (19)$$

$$\lambda(T_0) = C \times e^{-\frac{E_a}{k_B \times T_0}} \quad (19)$$

Division of Equations (18) and (19) will provide the following relationship:

$$\lambda(T) = \lambda_0(T_0) \times e^{\left[\frac{E_a}{k_B} \left(\frac{1}{T_0} - \frac{1}{T} \right) \right]} \quad (20)$$

where

T_0 and T are the absolute temperatures in use and test environment, respectively.

An example of use of the Arrhenius model for the determination of the value of failure rate λ_0 which, at the temperature of 25 °C (298 K), was 1×10^{-8} failures/h, as a function of absolute temperature, T , is shown in Figure 5.

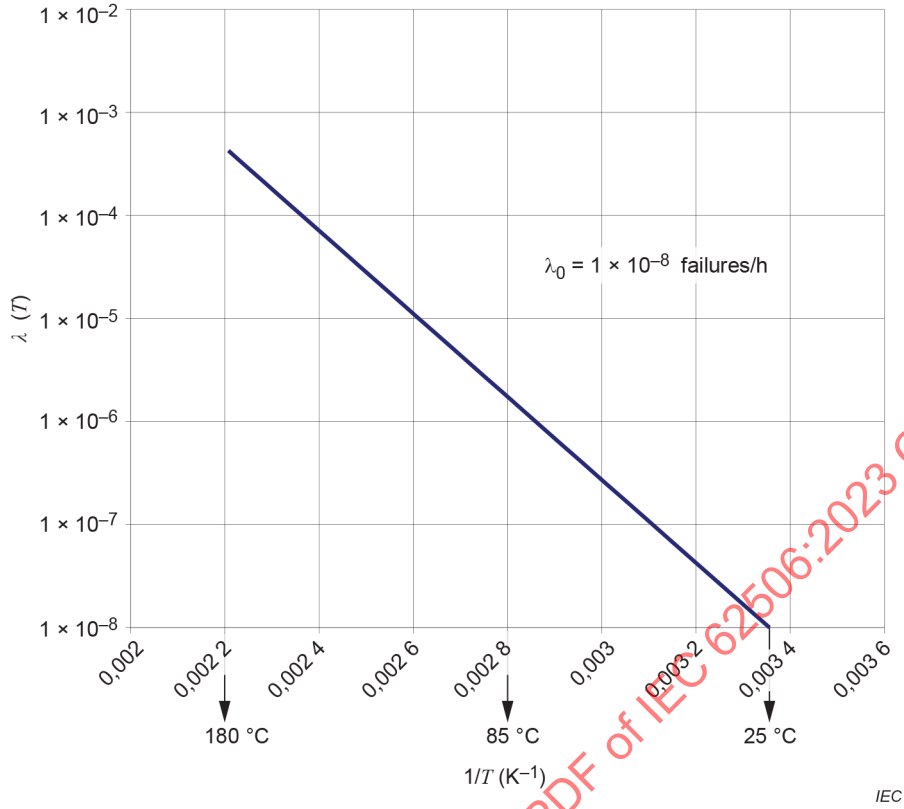


Figure 5 – Line plot for Arrhenius reaction model

The parameter E_a (activation energy) should be known for application of the Arrhenius model. The activation energy can be estimated as described in Annex C, but this is very time consuming. Component manufacturers estimate the activation energy for the relevant failure modes each time they qualify a new component technology. The estimate is often made on test structures and not on functioning components. The estimated activation energy is then applied to all components using the qualified technology. Therefore, the component supplier will usually be able to state the activation energy for the dominating failure modes of a given component.

Activation energy can be determined from the plot in Figure 5 by solving the equation used for the failure rate plot for E_a as follows:

$$E_a = k_B \cdot \frac{\{\ln[\lambda(T)] - \ln(\lambda_0)\}}{\frac{1}{T_0} - \frac{1}{T}} \quad (21)$$

$$E_a = k_B \cdot SLOPE$$

$$E_a = k_B \times \frac{\{\ln[\lambda(T_F)] - \ln(\lambda_0)\}}{\frac{1}{T_0} - \frac{1}{T_F}} \quad (21)$$

$$E_a = k_B \times SLOPE \quad (22)$$

$$\begin{aligned}
 \text{SLOPE} &= - \frac{\ln[\lambda(T)] - \ln(\lambda_0)}{\frac{1}{T_0} - \frac{1}{T}} \\
 \text{SLOPE} &= \frac{\{\ln[\lambda(T_F)] - \ln(\lambda_0)\}}{\frac{1}{T_0} - \frac{1}{T_F}} \quad (23)
 \end{aligned}$$

where

$$\lambda_0 = 1 \times 10^{-8} \text{ failures/h;}$$

$$\ln(\lambda_0) = -18,421;$$

$$T_0 = 25 \text{ °C} = (25 + 273) \text{ K} = 298 \text{ K}$$

$$\ln(\lambda_F) = -7,764 5;$$

$$T_F = 180 \text{ °C} = (180 + 273) \text{ K} = 453 \text{ K;}$$

$$E_a = 0,8 \text{ eV.}$$

Figure 6 shows the determination of the activation energy.

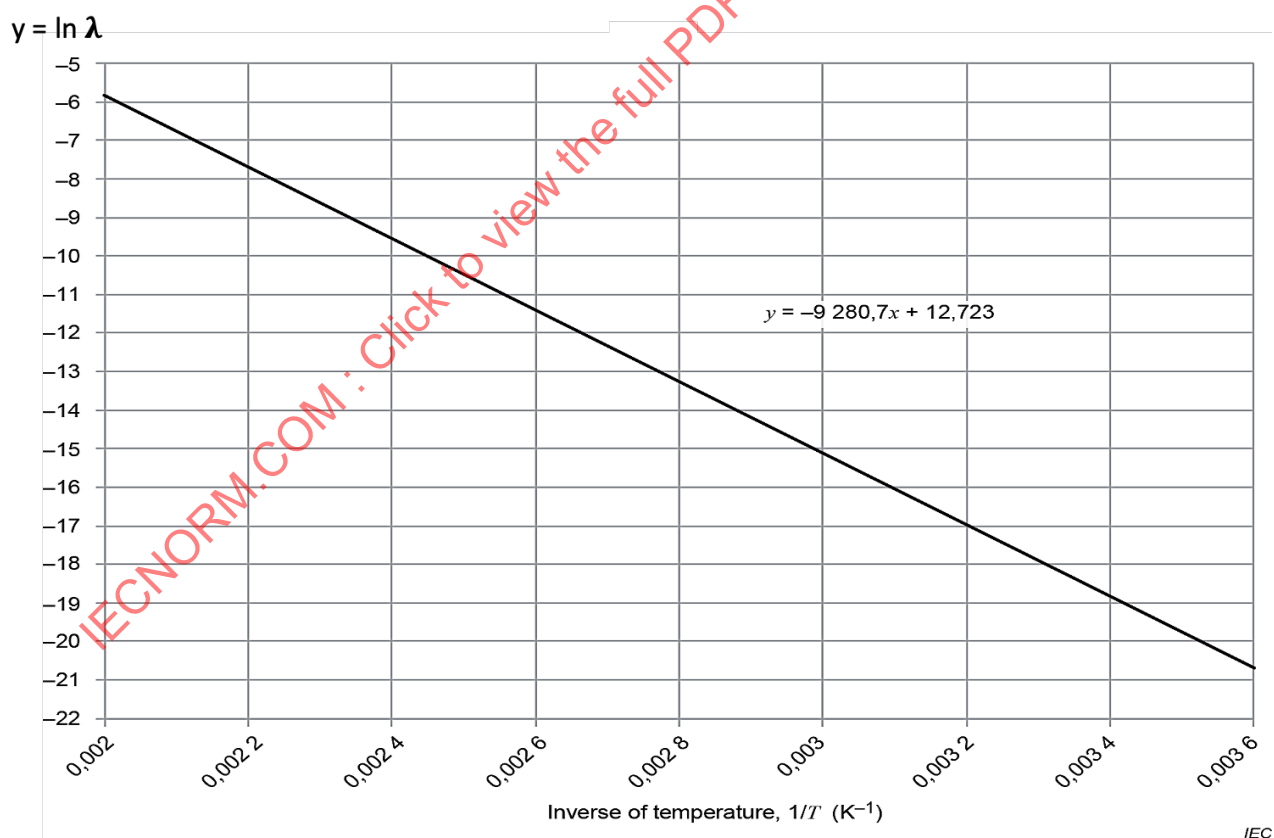


Figure 6 – Plot for determination of the activation energy

The Arrhenius method is applicable to a multitude of statistical distributions used in reliability analysis.

Confidence limits on parameters, life functions and reliability for each of the distributions can be determined with appropriate statistics.

5.6.1.3.2 Model applicability

This model is applicable to the circumstances where the thermal exposure in form of constant high temperature is expected to cause cumulative damage of materials thus changing their physical properties. Change of physical properties may then be demonstrated as a change in electrical and other specific properties.

The model is not applicable for damages caused by low temperatures. For these, it is advised that tests to failure be used to establish the specific model.

5.6.1.3.3 ~~Model advantages~~ Advantages of the Arrhenius model

The Arrhenius model is simple to use and, when the failure mode is truly only dependent on the absolute temperature, can produce realistic test acceleration.

5.6.1.3.4 ~~Model disadvantages~~ Disadvantages of the Arrhenius model

The model is easy to apply for single components provided that their failure rates are indeed dependent on and activated by temperature. For assemblies made of various electronic and mechanical parts, the model ~~may~~ can be hard to apply, as the components will often have different thermal activation energies for different failure modes (see JESD85 [8] and IEC 61649:2008, Annex G). Acquiring relevant values of activation energy is not simple for various tested items. Sometimes it requires extra specific experiments to get it. For more details see Annex C.

5.6.1.4 Eyring model

5.6.1.4.1 General

As with the Arrhenius model, the Eyring model is primarily used when thermal stress is a factor in the acceleration process. Unlike the Arrhenius model, the Eyring model is also used for stresses other than temperature, such as humidity, or some chemical reactions [7].

The function related to expected life is shown as follows:

$$L(S_E) = \frac{1}{S_E} \times e^{-\left(A - \frac{B}{S_E}\right)} \quad (24)$$

where

A and B are the function parameters that need to be determined through test or approximated by values from literature, ~~e.g. IEC 60605-7 [14]~~. Parameter B may be a constant, but more often it is a function of some stress, normally temperature;

S_E is the stress as used in this model (usually absolute temperature measured in degrees Kelvin);

$L(S_E)$ is the measure of life such as MTTF, characteristic life, half life, ~~etc.~~

The acceleration factor AF with this model is:

$$A_{S-E} = \frac{L(S_{E_Use})}{L(S_{E_Test})} = \frac{\frac{1}{S_{E_Use}} \cdot e^{-\left(A - \frac{B}{S_{E_Use}}\right)}}{\frac{1}{S_{E_Test}} \cdot e^{-\left(A - \frac{B}{S_{E_Test}}\right)}} = \frac{S_{E_Test}}{S_{E_Use}} \cdot e^{B \left(\frac{1}{S_{E_Use}} - \frac{1}{S_{E_Test}} \right)} \quad (23)$$

$$AF_{SE} = \frac{L(S_{E_Use})}{L(S_{E_Test})} = \frac{\frac{1}{S_{E_Use}} \times e^{-\left(A - \frac{B}{S_{E_Use}}\right)}}{\frac{1}{S_{E_Test}} \times e^{-\left(A - \frac{B}{S_{E_Test}}\right)}} = \frac{S_{E_Test}}{S_{E_Use}} \times e^{B \left(\frac{1}{S_{E_Use}} - \frac{1}{S_{E_Test}} \right)} \quad (25)$$

where

S_{E_Use} and S_{E_Test} are stresses in use and test, respectively;

B is a constant that needs to be determined through test or approximated by values from the literature.

The Eyring model can be applied to all distributions used in the reliability analysis.

Confidence limits on parameters, life functions and reliability for each of the distributions can be determined with appropriate statistics.

5.6.1.4.2 — Model advantages Advantages of the Eyring model

The model is relatively simple, yet it is applicable for stresses other than thermal. For a known parameter B , rather accurate test acceleration can be achieved.

5.6.1.4.3 — Model disadvantages Disadvantages of the Eyring model

As with the Arrhenius model, knowledge of the parameter B is critical for correct test acceleration. For products items with moderate complexity, accurate test acceleration may can become questionable because of different components and materials having a different value for the constant B .

5.6.2 Stress models with stress varying as a function of time – Type B tests

5.6.2.1 General

The time varying stress models are used to account for precipitation of failure modes in order to shorten the test time. These models can be used as a presentation of product item usage profile and those are the cumulative damage or cumulative exposure model.

5.6.2.2 Step-stress model

5.6.2.2.1 General

The model most frequently used is the step-stress model, where the units under test are subject to a succession of increasing stress levels that are applied for a predetermined time, and at the predetermined stress levels [9].

The stress levels are constant in each of the intervals.

The model can be presented mathematically using the life characteristic for an assumed distribution. As an example, the step-stress mathematical representation is as follows.

If reliability of a test unit for a test duration t and the stress S represented as a Weibull distribution is:

$$R(t, S) = e^{-\left(\frac{t}{\eta(S)}\right)^\beta} \quad (26)$$

where

$R(t, S)$ is the reliability as a function of time, t , and stress, S ;

β is the shape parameter of the Weibull distribution;

$\eta(S)$ is the scale parameter, a function of stress, S ;

then the probability of failure is:

$$F(t, S) = 1 - R(t, S) \quad (27)$$

In the Equations (26) and (27) with an example of the inverse power law model, the characteristic life is:

$$\eta(S) = C^{-1} \times S^{-m} \quad (28)$$

For successive stresses (stress levels) S_i , where $i = 1, 2, 3 \dots$

$$F_i(t, S_i) = 1 - e^{-\left(C \times S_i^m \times t\right)^\beta} \quad (29)$$

Data should be analysed using the appropriate distribution (in the case of the above example Weibull), using a cumulative exposure model, which makes a correlation between the failure distributions at the two successive levels. The failure distribution of the test units in each step will be specific to that step; however, the zero time of each particular step coincides with the total accumulated test time prior to that step.

Denoting an equivalent ageing time as τ_i , to account for ageing at the previous stress level:

$$\tau_i = (t_i - t_{i-1}) \times \left(\frac{S_i}{S_{i-1}}\right)^m + \tau_{i-1} \quad (30)$$

Probability of failure in the segment, i , then is:

$$F_i(t, S_i) = 1 - e^{-(C \times S_i^m \times (t - t_{i-1}) + \tau_{i-1})^\beta} \quad (31)$$

Distribution parameters may be then determined by maximum likelihood or other methods.

Confidence limits can also be set for the probability of failure, reliability, or any other ~~product~~ **item** life measure as described in the related standards on confidence limits, depending on the established distribution.

5.6.2.2.2 ~~Model advantage~~ Advantages of step-stress model

The method is effective to discover potential ~~product~~ **item** weaknesses in the short time period. The associated mathematics is not too complicated, so that the life characteristic of ~~a product~~ **an item** as related to the particular stress can be calculated.

5.6.2.2.3 ~~Model disadvantage~~ Disadvantages of step-stress model

The method does not account for ageing of the test units for the time that the previous stress steps are applied. Nor is the time involved enough typically to produce time dependent failure modes such as wear, or creep or high cycle fatigue. The primary driver is stress intensity. Further, this does not take into account potential fatigue or material changes resulting from the repetitive stress. This potential fatigue ~~may can~~ precipitate appearance of the failure modes earlier than they would normally appear without the fatigue factor and thus erroneously predict an early time to failure. The effect of the stress is usually logarithmic, so care should be taken not to use a stress level that will cause immediate failure of the UUTs.

The method also does not suggest how to handle appearances of failure modes unrelated to the applied stress, and how to account for them.

Care should be taken to not exceed the short time destruct limit of the UUT.

5.6.3 Stress models that depend on repetition of stress applications – Fatigue models

5.6.3.1 General

Fatigue can be defined as a gradual deterioration of item materials or item structure when those are subjected to repeated loads. Those loads can be mechanical, dynamic, thermal cycling, voltage cycling, etc. With cycling loads (such as thermal cycling, bending, ~~and others~~) the fatigue is proportional to more than one parameter, usually to the load extremes (the difference between extremes) number of repetitions and to a rate of change.

To represent the relationship between the number of load repetitions and the level of the load, testing is done on a number of items at different stress levels in a series of tests. The endured stress is plotted against the number of applied stress cycles or applications for which the failures have not occurred. The stress levels are reduced and the number of stress applications is increased. This continues to a point where seemingly, the stress is low enough that the item can endure an "infinite" number of applications. The stress value at this point is often known as the fatigue limit. Not all materials have a fatigue limit; exceptions are, for example, some types of aluminium alloys and plastics.

5.6.3.2 Calculating life time according to Miner's rule

The Palmgren-Miner linear-cumulative-fatigue-damage-theory (Miner's rule) is used to calculate the resultant pitting or bending fatigue lives for gears that are subjected to loads which

are not of constant magnitude but vary over a wide range. According to Miner's rule, failure occurs when:

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \dots + \frac{n_i}{N_i} + \dots + \frac{n_m}{N_m} = 1 \quad (32)$$

where

n_i is the number of cycles at the i -th stress level;

N_i is the number of cycles to failure corresponding to the i -th stress level;

n_i/N_i is the damage ratio (fraction of life) at the i -th stress level.

Replacing number of cycles by the life times:

$$\frac{l_1}{L_1} + \frac{l_2}{L_2} + \dots + \frac{l_i}{L_i} + \dots + \frac{l_m}{L_m} = 1 \quad (33)$$

where

l_i is the time at the i -th stress level;

L_i is the life at the i -th stress level;

$\frac{l_i}{L_i}$ is the damage ratio at the i -th stress level.

If the time at each of the stress level is expressed as a fraction of time of the total life, L :

$$\begin{aligned} l_1 &= \alpha_1 \times L \\ l_2 &= \alpha_2 \times L \\ l_i &= \alpha_i \times L \end{aligned} \quad (34)$$

where

α_i is the time at the i -th stress level;

L is the life to failure under the applied set of loads.

If the same ratio for lives applies as to the number of cycles, then:

$$\begin{aligned} &\frac{\alpha_1 \times L}{L_1} + \frac{\alpha_2 \times L}{L_2} + \dots + \frac{\alpha_i \times L}{L_i} + \dots + \frac{\alpha_m \times L}{L_m} = 1 \\ &L = \frac{1}{\frac{\alpha_1}{L_1} + \frac{\alpha_2}{L_2} + \dots + \frac{\alpha_i}{L_i} + \dots + \frac{\alpha_m}{L_m}} \end{aligned} \quad (33)$$

The loads are defined by the time ratio, α_i , and the load ratio, β_i , and additionally a speed ratio ω_i is needed for the calculation of the permissible lifetimes L_i .

where

β_i is the ratio between the instantaneous load and the base (overall) load;

ω_i is the instantaneous speed/nominal load. **3**

$$\frac{\alpha_1 \times L}{L_1} + \frac{\alpha_2 \times L}{L_2} + \dots + \frac{\alpha_i \times L}{L_i} + \dots + \frac{\alpha_m \times L}{L_m} = 1 \quad (35)$$

$$L = \frac{1}{\frac{\alpha_1}{L_1} + \frac{\alpha_2}{L_2} + \dots + \frac{\alpha_i}{L_i} + \dots + \frac{\alpha_m}{L_m}} \quad (36)$$

The stress versus number of cycles diagram is plotted from the fatigue tests and is known as the S-N curve. From a series of S-N curves, and with the assumption of the inverse power law of stress levels the parameter m , described in 5.6.1.2 is can be determined.

5.6.4 Other acceleration models — Time and event compression

5.6.4.1 General

Other acceleration models can be found in IEC 61163-2 [10] and in [7].

5.6.4.2 Time and event compression tests

In event compressed tests events that determine the reliability of life of the item are repeated more often than in the field (in use). Examples can be the number of copies in a copy machine or the number of couplings for a circuit breaker. The repetition frequency should not be so large that it changes the operating conditions, for example the test item has to cool down and stabilize in normal "idle" conditions before the next event. For factors not determined by the number of events, see below.

In time compressed tests, the time periods where the load from use and environment are low are left out of the test, leaving only the time periods that influences most the reliability or life of the item. But it has to be checked if loads and environmental conditions that are omitted does not add up to a significant contribution to the deterioration of the item. Such environmental conditions can typically be "off" periods where moisture and corrosion are dominant (the heat during use will often reduce corrosion by reducing the relative humidity in the item). Such "off" periods are typically determined by calendar time and not operating time. Separate tests may be needed to take these loads into account, for example moisture tests or corrosion tests. These considerations also apply to event compressed tests. **4**

5.6.4.3 Step-by-step procedure for event compression and time compression tests (Type C tests)

- Step 1: determine which factors can be event compressed and how much without changing failure modes;
- Step 2: determine if the test need be added to cover the failure mechanisms that are not determined by the number of events or are left out for time compression.
- Step 3: determine which periods in the mission profile can be time compressed or event compressed and how much (IEC 60605-2);
- Step 4: estimate the acceleration factor(s) for the potential failure modes (see 5.6);
- Step 5: determine the sample size (see IEC 61649);

Step 6: perform the test (see IEC 60300-3-5);

Step 7: perform failure analysis;

Step 8: analyse test results for each failure mode separately (see IEC 61649);

Step 9: report results (see IEC 60300-3-5).

5.7 Acceleration of quantitative reliability tests

5.7.1 Reliability requirements, goals, and use profile

5.7.1.1 General

This material is discussed at length and in detail in other dependability standards and literature, but, for completeness some brief explanations are included in this document.

5.7.1.2 ~~Product~~ Item and component use profile

Often the manufacturers choose to test ~~a product~~ an item in an accelerated test that simulates environmental stresses as they are experienced in the field. Some of the reasons for such tests ~~may can~~ be to verify that the previous tests (e.g. HALT) did not miss a failure mode that could appear in life or to estimate field reliability of that ~~product~~ item. There are instances where, due to space or performance constraints, one or more components in that ~~product may~~ item can be insufficiently derated which ~~may will possibly~~ not provide adequate stress versus strength margin. In these instances, ~~product~~ item reliability ~~may can~~ be highly dependent on the manner of its use, operational and environmental stresses, their combination and sequence.

~~A product~~ An item use profile consists of the following:

- operational and environmental stresses, their magnitude and sequence;
- the duration and number of sequence segments.

These use profiles can be chosen from one of the following evaluation conditions: average use profile, aggressive use profile, and a spectrum of use profile conditions.

These operational stresses and sequences should be known down to the assembly, critical components, and those components that may ~~need~~ have to be subjected to accelerated reliability testing.

5.7.1.3 Reliability goals or requirements

The overall reliability goal should be expressed in terms that are acceptable and understandable to the organization or to the customer (see IEC 60300-3-4 [11]). This goal may be expressed as a percent failed ~~products~~ items at the end of a specific time period (i.e. warranty) ~~and/or~~ multiple periods. The goal may also be expressed as a warranty ~~and/or~~ maintenance cost. At times it is found appropriate to express the goal reliability in terms of a mean time to failure (MTTF) or mean operating time between failures (MTBF).

Regardless of how the goal is specified, it ~~must~~ has to be understood that the goal reliability is related to the manner the item is going to be used, and that the same "number" or "reliability measure" is different for different use profiles (operational stresses of location). Conversely, the MTTF or MTBF of that item is only an average value representing the specific stress combinations. For that reason, any claimed reliability values of an item should be accompanied with the explanation of the expected use and relative degree of severity.

In cases where two or more stresses are applied to ~~a product~~ an item consisting of several components, the test acceleration is done by increasing each individual stress using models appropriate for those stresses. In these cases, failure rates representing each of the failure mechanisms are individually accelerated and the overall component reliability (R) or failure probability (F) ~~has to~~ shall be estimated separately. This can be expressed in general form for a combination of n independent stresses as:

$$R_{\text{equipment}} = \prod_{i=1}^n R_i \quad (37)$$

For the failure probability:

$$\underline{F_{\text{equipment}} = 1 - \prod_{i=1}^n (1 - F_i)} \quad (35)$$

$$R_{\text{equipment}} = 1 - \prod_{i=1}^n (1 - F_i) \quad (38)$$

The problem of competing risks is described in IEC 61649:2008, Annex G.

If an item consists of m components or piece parts which at any given time are subject to a set of n stresses that influences all the failure modes simultaneously, then its reliability R_p in a segment of time (part of a use profile where a specific stress combination exists) t_k is:

$$R_{\text{item}}(\text{Stress } t_k) = \prod_{j=1}^m \left[\prod_{i=1}^n R_p(\text{Stress}_i \times t_k) \right]_j \quad (39)$$

If there are w segments in total use profile with different stress combinations, then the total reliability of that item for a life or other predetermined time, t_0 is:

$$R_{\text{item}}(\text{Stress } t_0) = \prod_{k=1}^w \left\{ \prod_{j=1}^m \left[\prod_{i=1}^n R_p(\text{Stress}_i \times t_k) \right]_j \right\} \quad (40)$$

Where

$$t_0 = \sum_{k=1}^w t_k \quad (41)$$

These equations are conservative, i.e. they ~~may~~ can seriously underestimate the reliability of the equipment.

The total average failure rate of such an item is also a function of applied stresses and uses profile, and can be written as:

$$\lambda_{a_Item}(Stress, t_0) = -\frac{\ln[R_{Item}(Stress, t_0)]}{t_0} \quad (39)$$

$$\lambda_{aItem}(Stress, t_0) = -\frac{\ln[R_{Item}(Stress, t_0)]}{t_0} \quad (42)$$

For any other stress conditions or use profile, the average failure rate of the item will be different.

Reliability requirements for repairable items shall be viewed in terms of expected preventive maintenance, that is, parts of the item should be viewed separately for reliability and the time duration for which the requirements are prepared should correspond to the expected maintenance time.

5.7.2 Accelerated testing for reliability demonstration or life tests

5.7.2.1 Applicable test types

Since many tests are calendar time consuming many tests need to be accelerated. Practically, Most tests can be accelerated to shorten the test time. Certain reliability tests that can be accelerated are reliability demonstration, improvement, or assurance tests which can be:

- success tests, fixed duration;
- tests with failures, fixed duration;
- tests to failure (usually for components or small assemblies and individual failure modes);
- reliability improvement or growth tests, which are usually prepared for a predetermined time period;
- sequential probability ratio tests (SPRT) (see IEC 61124).

Engineering evaluation tests which are usually performed in view of a suspect failure mode can also be accelerated provided there is some knowledge of acceleration factors for those test items and the expected or suspect failure modes.

5.7.2.2 Reliability testing of a product or an item — Cumulative damage model

When a reliability test programme is prepared in view of the reliability for the specific use profile then the results of the test programme are valid for that specified use profile only. If reliability estimates for other use profiles are needed required for the same product item, this can be achieved by additional testing or adjusting the test results by mathematically modelling the test results to the new use profile. This modelling can be done in cases where there is a known relationship between the stresses and the use profile applied in the test and to the new adjusted use profile (see IEC 61709).

In case there are multiple differences between the two use profiles, there is more chance of model inaccuracy in adjusting the reliability estimate for the new profile. These differences rapidly increase with complexity of the system under evaluation.

Product Item and component reliability in regards to operational and environmental stresses as a function of predetermined time (life time) t_0 , can be expressed as follows:

$$R(t_0) = R_{LI}(t_0) \times \prod_i R_{S_i}(t_0) \times \prod_i R_{E_i}(t_0) \quad (40)$$

$$R(t_0) = R_U(t_0) \times \prod_i R_{S_i}(t_0) \times \prod_i R_{E_i}(t_0) \quad (43)$$

In the above Equation (43), $R_E(t_0)$ denotes the reliability of the item regarding environmental stresses for the time duration t_0 , while $R_S(t_0)$ denotes the reliability regarding operational stresses. Factor $R_U(t_0)$ is used to represent the unknown interaction or synergism of individual environmental and/or operational stresses as determination of individual stress duration and magnitude assumes stress independency, which in most cases ~~may~~ will possibly not be a valid assumption.

Equation (43) can be generalized to be written in the form:

$$R_{\text{Item}}(t_0) = \prod_{i=1}^{N_S} R_{\text{Stress}_i}(t_i) \quad (44)$$

If $R_{\text{Item}}(t_0)$ is the ~~product~~ item reliability goal or the ~~product~~ item reliability requirement that needs to be demonstrated in test, then a reliability value may be allocated to each of the multiples in the expression for the ~~product~~ item reliability. Simplified for illustration the allocated individual reliabilities may be assumed to be the same.

$$R_{\text{Item}}(t_0) = (R_{\text{Stress}_i}(t_i))^{N_S} \quad (45)$$

$$R_{\text{Stress}_i}(t_i) = \sqrt[N_S]{R_{\text{Item}}(t_0)} \quad (46)$$

The allocated values to reliability regarding individual stresses differ depending on the ~~product~~ item intended use and usage profile and its sensitivity to a particular environment. Besides the magnitude of stresses expected in the actual use, it is their cumulative effect that affects ~~product~~ item reliability. The test duration is then calculated based on the duration of each of the stresses applied in actual use, while the test acceleration is achieved by increasing the magnitude of each of the individual stresses or by their time acceleration.

When the purpose of the test is to estimate reliability in the field, an average user stress profile should be used. This profile can be estimated for given climatic conditions as for example Central Europe (see the IEC 60721 series). Different locations ~~may~~ can have different prevalent or extreme stresses. As an example, in some countries such as Northern Scandinavia, Canada and Russia, low temperature ~~may~~ can be one of the highest stresses, while New Mexico, Africa and India it ~~may~~ can be high temperatures. In Singapore and Japan the most pronounced stress ~~may~~ can be humidity and in New Delhi it ~~may~~ can be air pollution. Regarding the manner of use, the test can simulate an average user or an extreme user (e.g. where less than 1 % of the customers ~~heavily~~ load the ~~product~~ item more severely). It is not advisable to transfer a test result from one environmental and user profile to another. Therefore many companies supplement the environmental test with survival tests where the purpose of the test is to determine if the ~~product~~ item will survive a few extreme loads that are not expected to be repeated so often that they would influence the long term reliability of the ~~product~~ item. Such environmental tests are described in the IEC 60068 series [12].

Often, ~~products~~ items are tested with a stress cycle in order to expose the ~~product~~ item to several stresses in combination or sequentially. Ideally, the stresses should be applied combined and intermittent in order to simulate the field conditions as well as possible. But in practice this is seldom possible. In order to use the test equipment in an optimum way and make it easier to locate the stress type and level that caused the failure the test is often made using a test cycle, for example of one week duration (see IEC 60605-2).

In the following it is assumed that the item is tested for each of the expected stresses, operational and environmental, having in mind their levels and cumulative duration in actual use and the corresponding total use period, t_0 .

If the stress in the cumulative damage is proportional to duration of a stress, then reliability regarding each individual stress can be expressed as:

$$R_i(k, \mu_{L-i}) = \Phi \left[\frac{k \times \mu_{L-i} - \mu_{L-i}}{\sqrt{(a \times k \times \mu_{L-i})^2 + (b \times \mu_{L-i})^2}} \right] \quad (43)$$

where

R_i is the reliability allocated to the item regarding the specific stress during the duration of its application;

k is the multiplier of the actual stress duration, assuming the cumulative damage models; 5

μ_{L-i} is the mean duration of that load (stress) application in use; 6

a and b are the multipliers of strength and load mean values that would produce their respective standard deviations;

Φ is the symbol for the cumulative normal distribution.

By the cancelling out the mean loads, Equation (43) is reduced to the following format: 7

$$R_i(k, \mu_{L-i}) = \Phi \left[\frac{k-1}{\sqrt{(a \times k)^2 + b^2}} \right] \quad (44)$$

Plotted as a function of k for given values of a and b , reliability as a function of k is shown in Figure 7.

In Equation (43) it is assumed that each of the stresses can be modelled by a normal distribution. Preferably information on the exact distribution (factors a and b) should be used. If there is no information of the exact distributions, the standard deviations may be assumed to be as large as 10 % of the mean value. The reduced Equation (43) becomes:

$$R_i(k) = \Phi \left[\frac{(k-1) \times 10}{\sqrt{k^2 + 1}} \right] \quad (45)$$

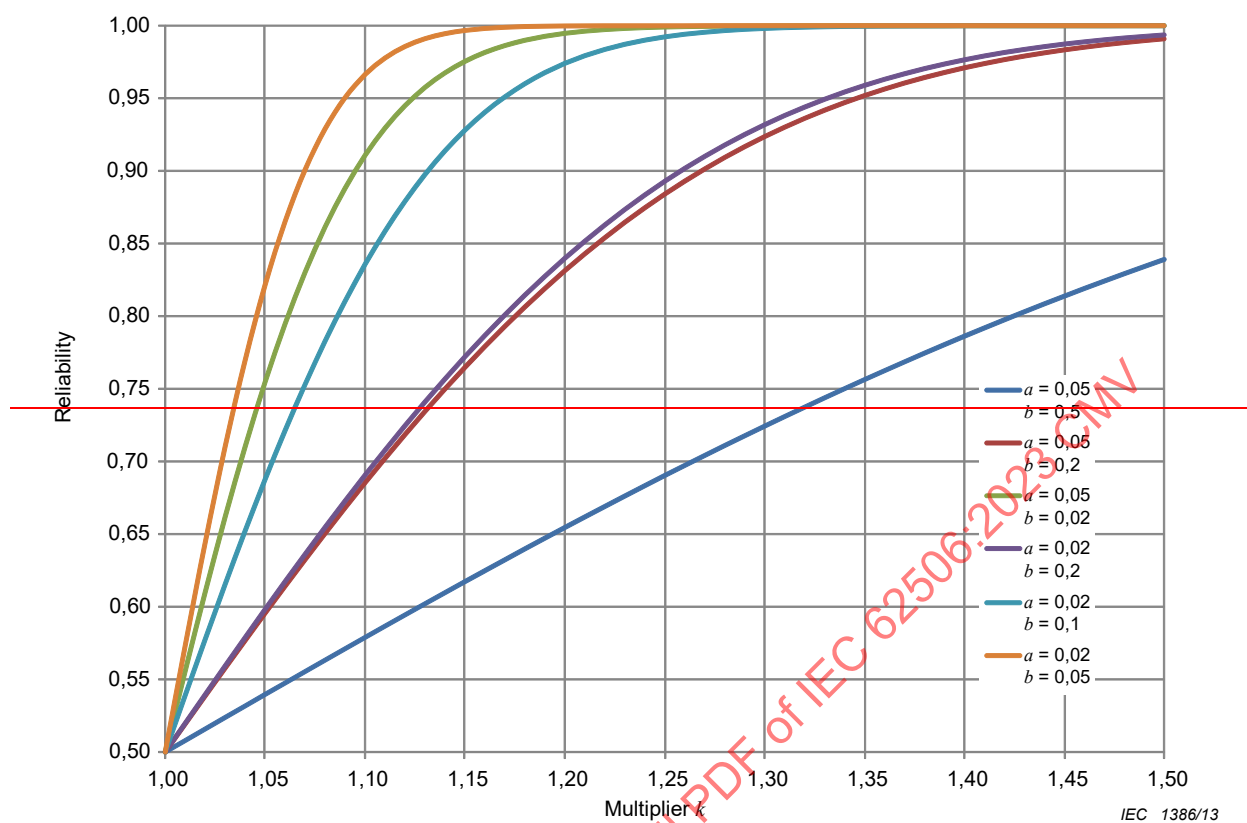
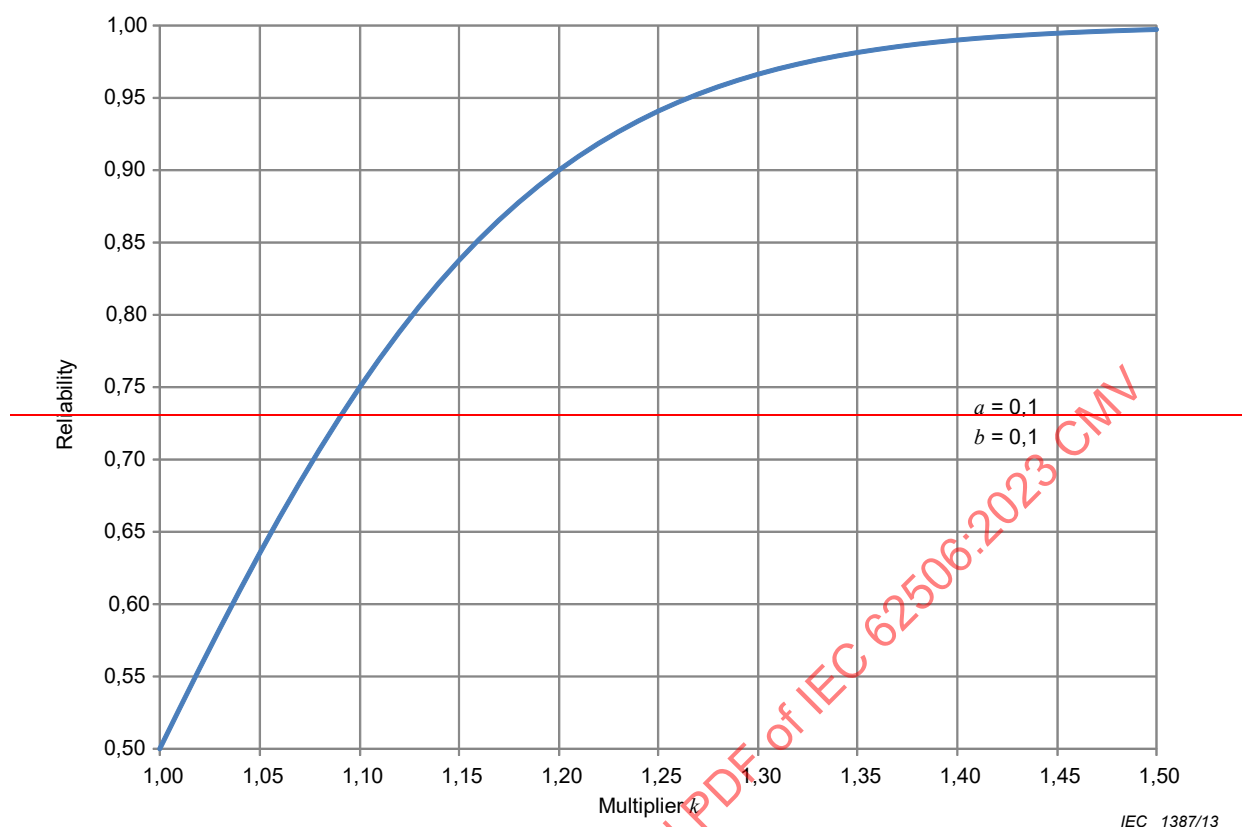


Figure 7 – Multiplier of the test stress duration for demonstration of required reliability for compliance or reliability growth testing

A specific plot for the chosen values of $a = 0,1$, and $b = 0,1$ is shown in Figure 8.



NOTE k is sometimes called the "lifetime ratio".

Figure 8 — Multiplier of the duration of the load application for the desired reliability

The duration of each stress application as determined above would result in a stress application longer (approximately 1,4 or 1,5 times) than the duration of the stress application in use.

To make testing possible, the stress levels are then accelerated by applying the appropriate acceleration factors. The stress acceleration type and the ~~product~~ item specific acceleration factors for the various expected stresses need to be known. These ~~need to~~ can be obtained through tests-to-failure at different stress levels for the specific components (see Annex E and Annex F).

The above programme can be prepared in different forms:

- as a success test, test with no failures;
- as a test with an allowed number of failures;
- as a fixed duration test, but without reliability requirement, thus the reliability of the ~~product~~ item will be estimated based on the number of failures in the test;
- as a reliability growth/ or improvement test based on an assumed growth rate (see IEC 61014 [13]).

~~When it is a success test, the results are simply and easy to interpret.~~ In a success test, the result is a minimum reliability estimate. Without failures, the test demonstrates the reliability requirement with applied (minimum) confidence intervals.

If this test is to allow a certain number of failures, then the determination of its duration should account for the allowed number of failures. The test then becomes the "fixed number of failures" test.

If the test is a reliability growth test, then the total test duration (or sample size in view of accumulated test time) is prepared for the expected total numbers of test failures, ~~+~~, having in mind the total duration of the applied stresses, required confidence and the required demonstrated reliability (see ~~IEC 62429~~ IEC 61014 [13]).

5.7.2.3 Accelerated tests assuming non-constant failure rate or failure intensity

It is assumed that the failure rate or failure intensity follow the so called bath-tub curve (see Figure 7). In the early failure period the failure rate or failure intensity is declining with time.

This is covered by IEC 61163-1 [14] and IEC 61163-2 [10]. In constant failure rate period the failure rate or failure intensity is assumed to be constant. In the wear-out period the failure rate or failure intensity is increasing. This often define the life time of the item. The end of life can be defined as the time when the failure probability has reached a specified value for example 10 % stated as the B_{10} value (see IEC 61649). An indication of whether the failure rate is decreasing, constant or increasing can be tested using IEC 61649 for non-repaired items. For repaired items IEC 61710 has to be used. In both cases a value of $\beta < 1$ indicates the decreasing failure rate or failure intensity.

$\beta = 1$ indicates constant failure rate or failure intensity, and $\beta > 1$ indicates increasing failure rate or failure intensity.

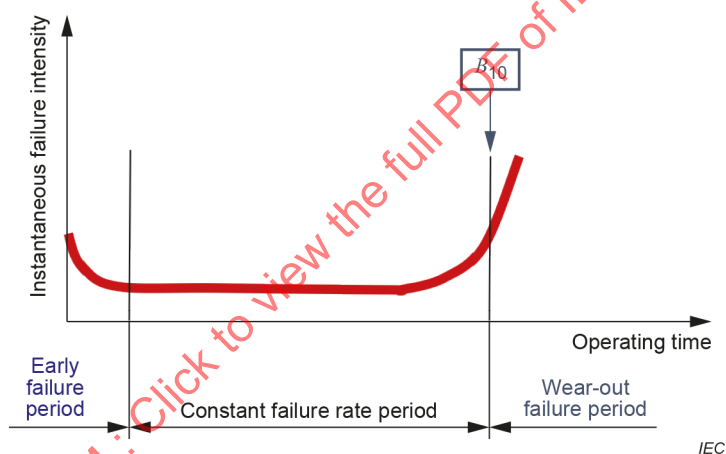


Figure 7 – Bathtub curve

NOTE 1 Some standards define the life time as the time where the instantaneous failure intensity has increased a number of times. This document uses the definition of B_{10} , the time when 10 % of the items have failed (accumulated probability of failure). The instantaneous failure intensity therefore increases before the life time point. See also Figure 10.

Often tests are aimed at estimating the life time of the item for example by estimating the B_{10} value. Here it is a special problem that the failure rate or failure intensity curve often has a tail to the left from the B_{10} value. This means that a small percentage of wear-out failures can occur before the B_{10} value. Because of the limited sample size for most accelerated tests the probability of observing the early wear-out failures are small. An important issue in planning accelerated tests is therefore to estimate the probability of wear-out failures before the B_{10} value. It is important to note that the definition of B_{10} only states that at the B_{10} time the accumulated probability of failure is 10 %. This makes no assumption if the 10 % was caused by early failures, the constant failure period or wear-out failures.

When the failure rate or failure intensity can be assumed constant the test can be analysed based on the accumulated test time as described in IEC 61124. For example 77 items tested each for 1 000 h would mean an accumulated test time of 77 000 h. To estimate the equivalent hours of operation at operating conditions (in the field) the accumulated test hours then shall be multiplied with the acceleration factor (AF). **8**

NOTE 2 Other measures of operation like cycles, mileage or copies made can replace hours as a measure of the test duration.

When the failure rate or failure intensity cannot be assumed constant, accumulated test hours cannot be used to analyse the test. In that case 77 items tested for 1 000 h each would have to be analysed as 77 independent tests each truncated after 1 000 h. In this case the 1 000 h shall be multiplied with the acceleration factor (AF) to estimate the equivalent duration of the test under field conditions.

Commercial software programs often include test planning features. It is important before using such programs to check if the program assumes constant failure rate or failure intensity and whether it assumes repaired or non-repaired items or allows replacement of failed test items during the test. If the program assumes non-constant failure rate or failure intensity it is important to note which β value is used or specified when using the Weibull distribution. For including previous knowledge using the Bayes theorem see IEC 61710.

5.7.2.4 Success tests

A success test is planned to end with zero failures. Since no failures were observed, success tests demonstrate a minimum reliability for a defined confidence level. No knowledge about the real reliability (or shape parameter) can be determined using the success test.

If the failure rate or failure intensity is assumed to be constant, a lower 60 % confidence limit of an MTBF value can be estimated (see IEC 60605-4 [15]).

The physics of failure interpretation of a success test is that during the observed test time, there were, with a certain probability, no active failure modes.

The equations for a success test are the following:

$$P_A = 1 - R(t)^n \quad (47)$$

$$R(t) = (1 - P_A)^{1/n} \quad (48)$$

$$n = \ln(1 - P_A) / \ln(R(t)) \quad (49)$$

where

$R(t)$ is the reliability at time t ;

P_A is the confidence level;

n is the sample size.

NOTE Equation (47) is often referred to as "success run".

It should be noted that these equations do not use accumulated test time, but the test time for each individual item in the test (t). The reliability $R(t)$ is estimated without assumptions about the failure rate or failure intensity.

5.7.2.5 Physics of failure tests

This test is planned to evaluate or verify the reliability based on the physics of failure model i.e. focusing on determining which failure mechanisms (if any) are active during the planned life time of the item under the expected operating and environmental conditions.

Step 1: From an engineering evaluation determine the worst expected failure mode and find from previous tests, in handbooks or literature the relevant acceleration equation (see 5.6) and the relevant empirical factors (e.g. activation energy (E_A) or m factor for the inverse power law).

Step 2: Determine the acceleration factor (AF) between the accelerated test conditions and the operating conditions in the field (see Annex B). If possible tests should be performed at two or three different stress levels to verify the acceleration factor (see Annex E and Annex F).

Step 3: Determine the test time t required to simulate the operating time in the field at the time where the reliability needs to be estimated for example at life time.

Step 4: Determine the required sample size for a reliability $R(t)$ and a confidence level of P_A using Equations (47) to (49).

Step 5: Perform the test of n samples for the test time t at each stress level (one to three different stress levels).

Step 6:

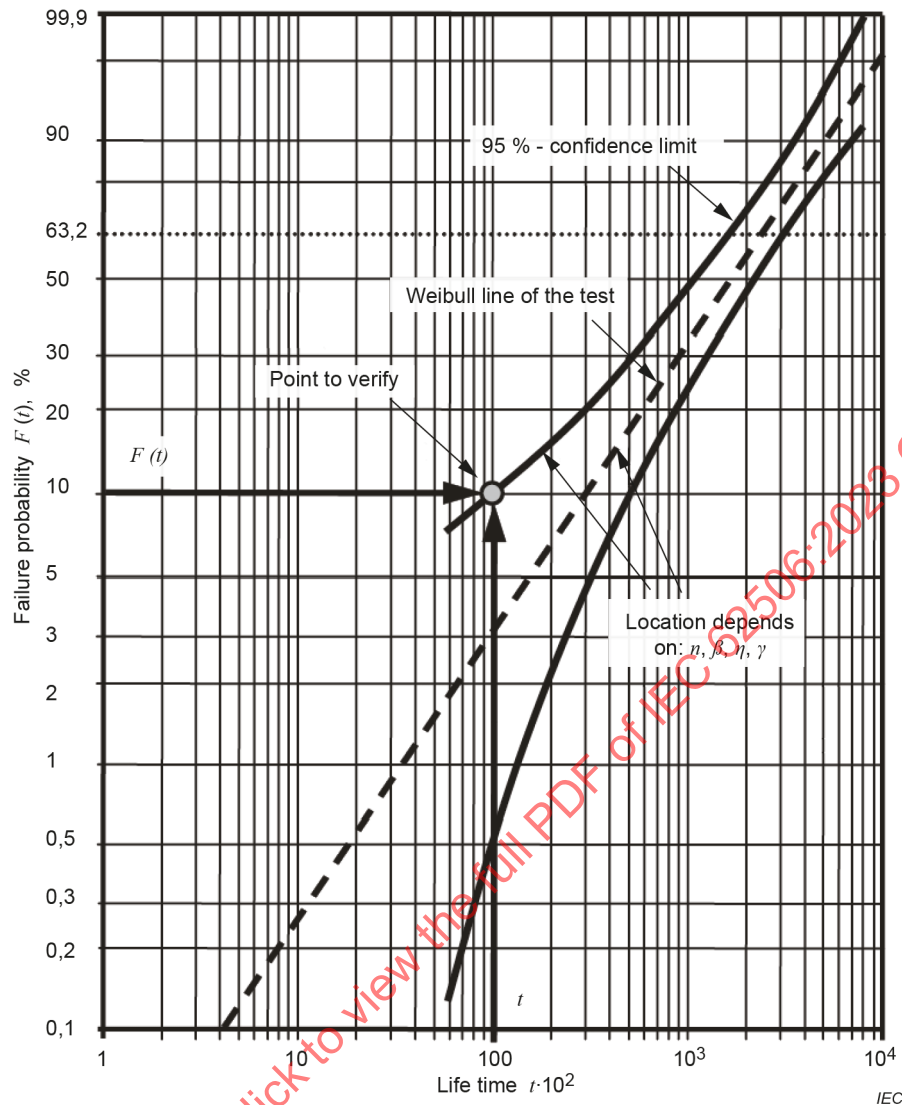
- a) If no failures were observed it can be stated with confidence P_A that the failure mode(s) assumed in step 1 are not active in the tested items up to time t . In this case the accelerating factor cannot be verified.
- b) If failures were observed during the test, perform a failure analysis. If the failure mode is the same as assumed in step 1, the probability of failure or reliability at time t may be estimated using IEC 61649 for non-repaired items and IEC 61710 for repaired items. If more than one stress level was used during the test, the empirical factors in the acceleration factor equation may be estimated (see Annex E and Annex F), and a better equivalent operating time in the field can be estimated. If the failure mode is different from the one assumed in step 1 the reliability for this failure mode can be estimated using IEC 61649 for non-repaired items and IEC 61710 for repaired items. If more than one stress level was used during the test, the empirical factors in the acceleration factor equation may be estimated (see Annex E and Annex F), and an equivalent operating time in the field can be estimated. If only one stress level was used, empirical factors from handbooks may be used to estimate the acceleration factor (AF) for that failure mode and estimate the operating time in the field equivalent to the test time t .

Step 7: Consider if, based on an engineering evaluation, the second worst failure mode should be tested in a similar way, returning to step 1. Depending on the acceleration factor the second largest failure mode may be covered by the initial test with an acceptable confidence. **9**

A variant of this test method, the so called CALT test is described in Annex D.

5.7.2.6 Test planning based on the Weibull distribution

This test is also a success test, since it is planned to end with zero failures. The principle of the test is illustrated in Figure 8 below. For further information see [16] and IEC 61649. If a reliability of 90 % at 10 000 h has to be verified with 95 % confidence in a test, the procedure can be illustrated in a Weibull plot as shown in Figure 8 below.



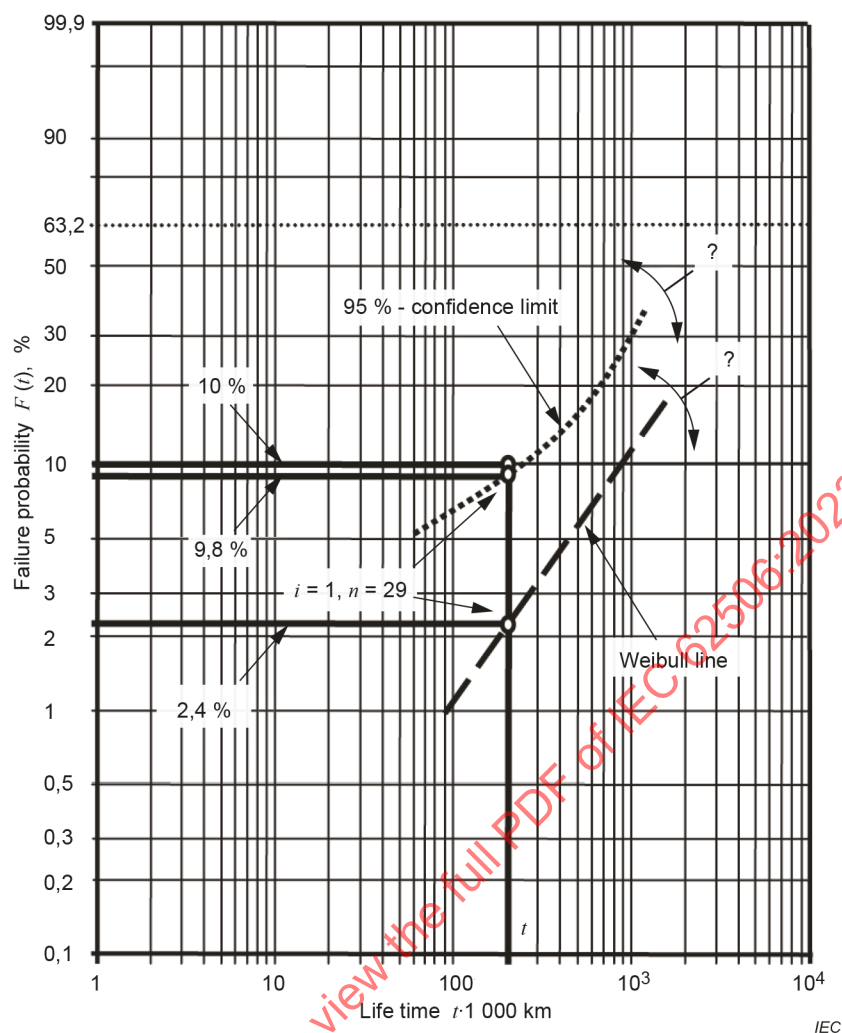
SOURCE: Reference [9], reproduced with the permission of the authors.

Figure 8 – Test planning with a Weibull distribution

The point to verify in a Weibull plot is 10 % failures at 10 000 h.

The Weibull curve is drawn with the assumed slope (β) and its 5 % and 95 % confidence limits are drawn so that the 95 % confidence line goes through this point (10 000 h, 10 %). This means that if the test of n items each for 10 000 h result in no failure, a reliability of 90 % (10 % failures) have been estimated with 95 % confidence. The rationale for this conclusion is that if a failure had occurred at exactly 10 000 h this failure had to be plotted in the point (10 000 h, 10 %).

The value of β can be obtained from previous tests of similar items, from literature or based on engineering judgement. An example is shown in Figure 9 below. **10**



SOURCE: Reference [9], reproduced with the permission of the authors.

Figure 9 – Example of a test based on the Weibull distribution

The procedure for planning the test is described below, illustrated with a practical example.

A reliability of $R(20\,000\text{ km})$ of 90 % is required with a confidence level of $C = 95\%$.

Step 1:

In Table G.1 of Annex G, find the sample size n where the 95 % median rank for the first failure ($i = 1$) is close to 10 %. To find the 50 % median rank use the approximation median rank = $(i - 0,3)/(n + 0,4)$ (see IEC 61649), where i is the failure rank order and n is the sample size. The median rank for $n = 29$ for $i = 1$ is found to be 9,8 %.

Step 2:

Test 29 items, each for 20 000 km. If no failure is observed the reliability $R(20\,000\text{ km})$ has been estimated with 95 % confidence.

NOTE If the test estimate $R(20\,000\text{ km}) = 90\%$ with 95 % confidence it will estimate $R(20\,000\text{ km}) = 97,6\%$ with 50 % confidence (best estimate), since the point 20 000 km, 2,4 % is on the Weibull line, which is the best estimate.

5.7.2.7 Life time ratio

The life time is often defined as the time where a stated percentage of failures have occurred for example B_{10} value for 10 % failures (see IEC 61649). This means that the failure rate or failure intensity will start to increase before the wear-out period as illustrated on Figure 10. The small sample size reduces the probability of including items that fail before the life time in the test. In order to compensate for this the test can be continued beyond the required life time of the item. **11**

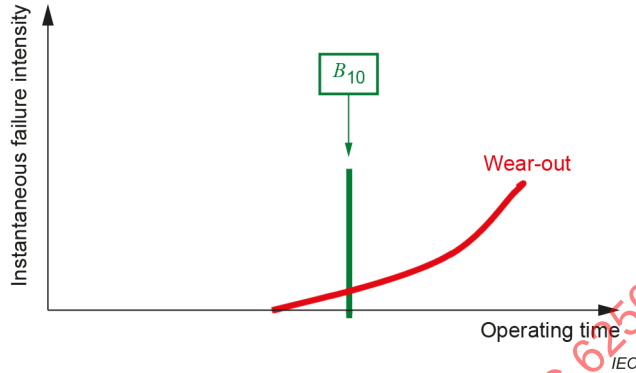


Figure 10 – Life time and "tail" of the failure rate or failure intensity

The extension of the test beyond the end of the specified life time are measured as the life time ratio L_V . The L_V value is defined as:

Life time ratio (L_V):

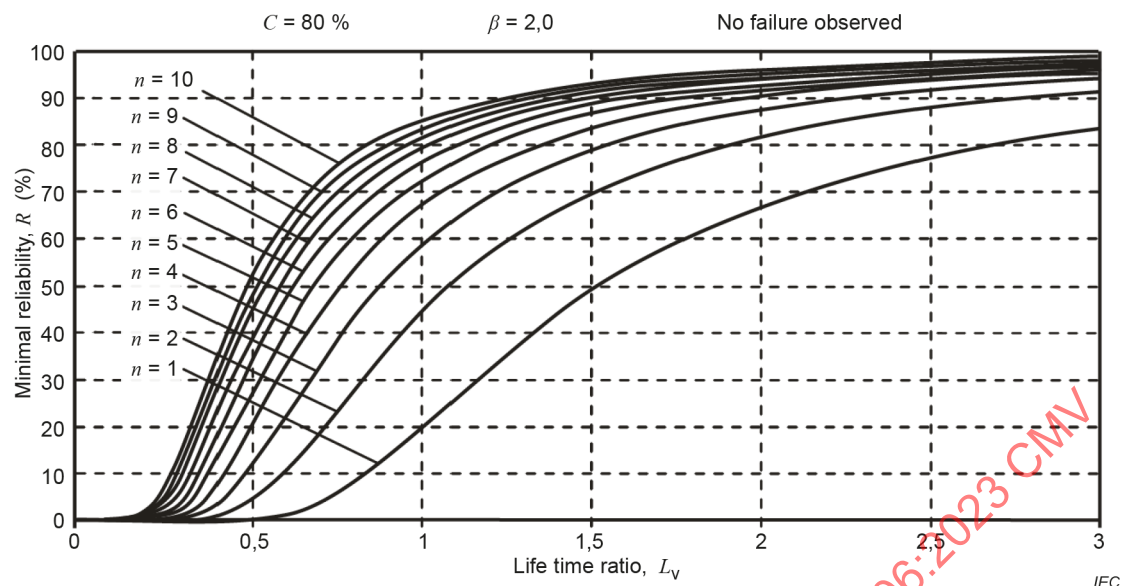
$$L_V = \frac{t_{\text{Test}}}{B_X} \quad (50)$$

where B_X is the specified life, for example B_{10} .

Success run formula with life time ratio:

$$R(t) = (1 - P_A) \frac{1}{L_V^\beta \times n} \quad (51)$$

The necessary input for the success test with life time ratio is the Weibull shape parameter β , which should be assumed conservatively i.e. with a value in the lower range. The assumption can be made for example based on predecessor items or tests. Using an L_V value in the test can increase or decrease the test time as shown in Figure 11 below.



SOURCE: Reference [9], reproduced with the permission of the authors.

Figure 11 – Reliability as a function of life time ratio L_v and number of test items

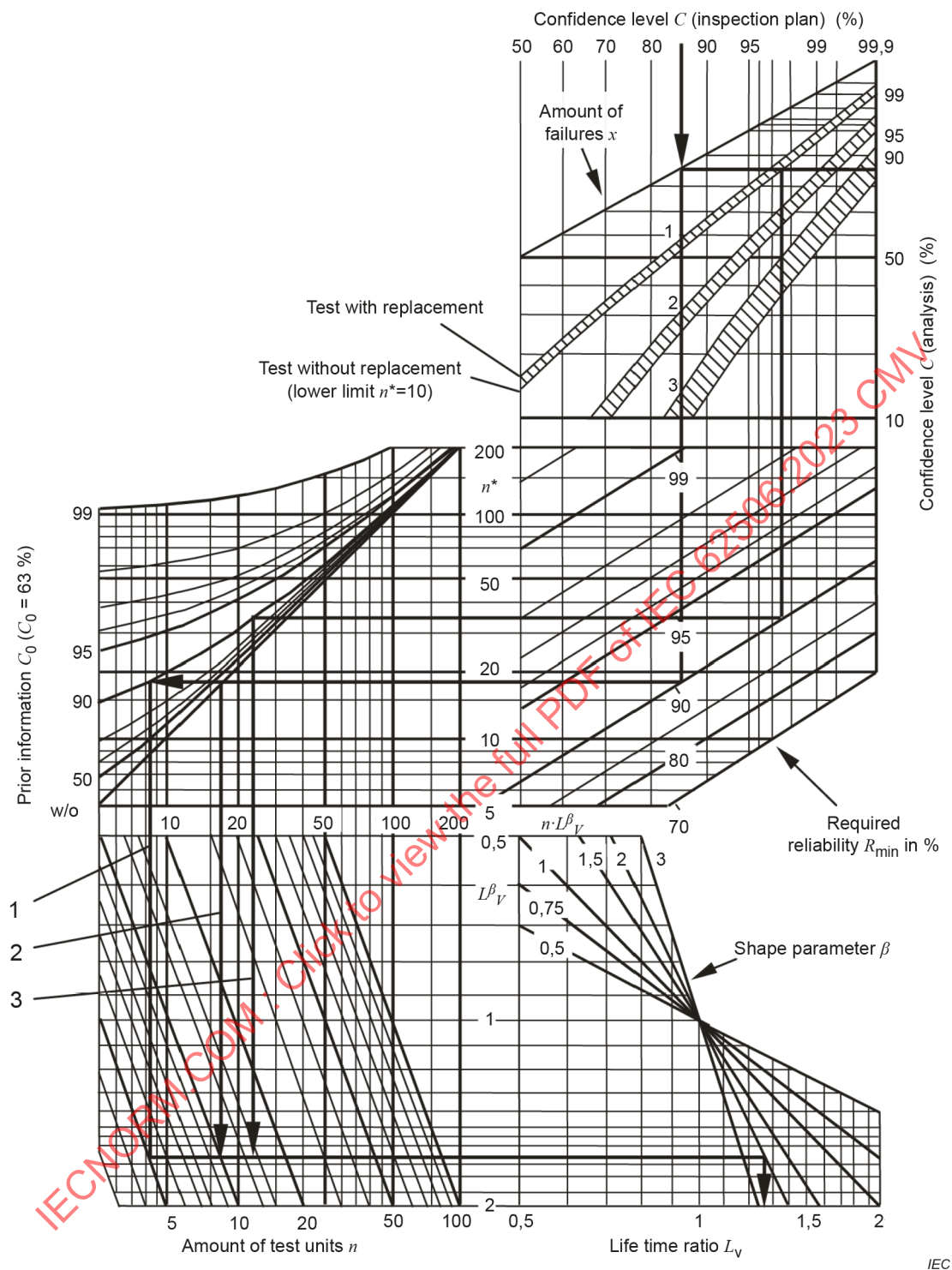
This test is also a success test, since it is planned to end with zero failures.

A practical example can be found in Clause B.4. More diagrams can be found in [16].

5.7.2.8 Consideration of failures and prior knowledge in success tests (Bayes)

This is also a special kind of a success run, where a small amount of failures is allowed and prior knowledge is used to reduce the sample size.

In case of more than one failure the following nomogram (from [16]) can be used. This nomogram gives the necessary life time ratio (L_v) as a function of β , the sample size n , the number of failures x and the prior information (see IEC 61710).



SOURCE: Reference [9], reproduced with the permission of the authors.

Figure 12 – Nomogram for test planning

A life test shall be made on an item. A life time of $B_{10} = 20\,000$ h is specified ($R(20\,000\text{h}) = 0,9$).

Knowledge about the items from previous items are: $R_0 = 0,9$ (with 63,2 % confidence) and the Weibull shape parameter $\beta = 2$.

The verification should be made with $P_A = 85$ % and $n = 5$ test items.

According to Figure 12 the life time ratio is $L_v = 1,25$. Therefore the test time $t_{\text{test}} = 25\,000\text{ h}$ (line (1)).

If some of the assumptions are changed the following modification to the test can be made using Figure 12:

- if no prior information exists then $n = 10$ test items should be used (line (2));
- if one failure occurs during the test the number of test items increases to $n = 14$ (line (3)).

For more information see [16].

5.7.3 Testing of components for a reliability measure

Mass produced electronic components are subject to accelerated stress testing to determine their reliability measure (failure rate or other) under the use stress. To determine the appropriate acceleration factors, test structures for new component technologies are tested at several stress levels to failure, and the appropriate failure modes and empirical factors for the acceleration models are determined. The qualification method is described in JESD47B [2]. The selection of stresses and their levels is made dependent on the expected failure modes of the components.

Larger components manufactured in smaller volumes can often be reliability tested using accelerated test methods and statistical tools like IEC 61649 or IEC 61124. Based on the ratio of parameters of the specific distribution (i.e. characteristic lives in Weibull distribution), acceleration factors are established for the particular stresses which are then used to predict their reliability at other stress levels of the same stress types. If more than one distribution parameters are different for the different levels of the same stress, then it ~~may~~ can be expected that the physical characteristics ~~may~~ can change too. As an example, if the characteristic life as well as the shape parameter in Weibull distribution is different at different stress levels, it ~~may~~ can be an indicator that perhaps the stress level was too high and has changed the physical characteristics of that component or that the manufacturing process was flawed. If that happened within the component rating it ~~could~~ can mean that the component rating needs to be re-evaluated.

Usual ~~environments~~ environmental stresses for component testing are as follows:

- temperature;
- vibration;
- humidity;
- thermal cycling;
- salt exposure.

Some examples of operational stresses include

- voltage,
- current,
- force,
- friction.

An example of accelerated testing for a component is shown in Annex B.

The accelerated test time is relevant for the estimated life of the components. It is testing to failures that provides meaningful results while testing with no failures—~~may~~ **can** provide information only if the test approximates a component life with a margin. The traditional total accumulated test time of multiple components (the total test time is a sum of all the times accumulated on single components)—~~may~~ **can** lead to meaningless results in predicting the reliability beyond the actual test duration for a single component. As an example, 32 000 km on 100 tyres with zero failures—~~could~~ **can** lead to an erroneous conclusion that 36,8 % of the tyres would last 3 490 000 km. The calculated failure rate is only valid to 32 000 km of the test. It is possible, however, to estimate failure rates beyond the duration of test through WeiBayes analysis, assuming a known Weibull slope (see IEC 61649).

While obvious for the tyre example, this fact is not too obvious for other components. Electronic components are normally tested by the manufacturers for 1 000 h, and usually on 77 components **from each of three different lots**. If that test is accelerated, it—~~may~~ **can** provide information only for the equivalent life time (normalized to use level). The fact that the multiple components were tested does not improve the test results, only the degree of confidence (see JESD47B [2] and JESD85 [8]).

5.7.4 Reliability measures for components and systems ~~/items~~

5.7.4.1 Electronic components

With electronic components, the preferred reliability measure is the instantaneous failure rate determined for standard profile conditions (see IEC 61709).

This allows the instantaneous failure rate to be re-calculated for the actual stresses of the operational use profile of the—~~product~~ **item**. The re-calculations are done using appropriate acceleration models (see IEC 61709).

This information is provided at a given environment (such as temperature as well as other specified stresses).

The stated failure rate is often the average failure rate over the—~~useful~~ **life time** of the component, assuming exponential time to failure. However, some electronic and electro-mechanical components have a limited life (wear-out). For these components, ~~there is a need to estimate the end of their useful life~~ **it is necessary to estimate their life time**. Components with limited life include, for example: power transistors, opto-couplers, LEDs and laser diodes, wet electrolytic capacitors, varistors, light bulbs, relays, switches, connectors and batteries (see IEC/TR 62380 61709).

5.7.4.2 Mechanical components

With mechanical components, the preferred reliability measure is the percent failures determined for standard profile conditions. Often this is stated as the operating time for a given percentage of failures as for example 10 % (often denoted as B_{10} or L_{10} life) or 1 % failures (often denoted as B_1 or L_1 life). For the estimation method, see IEC 61649.

This allows the reliability to be re-calculated for the actual stresses of the operational use profile of the—~~product~~ **item**. The re-calculations are done using appropriate acceleration models.

If expressed in terms of failure rate, the failure rate is often calculated as the equivalent failure rate calculated from the estimated probability of survival and is valid for the specified stresses; however, this gives no information about the expected life time of the component.

5.7.4.3 Assemblies, systems (items)

The more complex items made of components (electrical and mechanical, including software) would be best represented by expressing probability of survival or probability of failure. These

measures allow combinations of different failure distributions and are more appropriate when including software.

5.8 Accelerated reliability compliance or evaluation tests

Reliability compliance tests, sequential probability ratio test (SPRT) and fixed duration tests are designed with the assumption of a constant failure rate, as the complexity of items and their failure modes would not accommodate any other distribution unless the tests were used for the determination of item reliability with regard to individual failure modes, which is the case for components (piece parts).

Given the high reliability (or MTTF ~~or~~ MTBF) of the ~~products~~ items, these tests traditionally have cost or schedule prohibitive duration and need to be accelerated. As the test designs are the same for repaired or replaced items as for those that are not repaired, in this Subclause 5.8 the term MTBF is used for both MTTF and MTBF.

There are many descriptions, mathematical derivations, plot fitting and explanations of this test type in the literature, however the actual tests, what they consist of and what stresses are to be applied, as well as the rationale behind them, are not readily available. ~~Understanding that a test is only as good as the stresses it represents, the rationale of item reliability that needs to be demonstrated is the same as for the fixed duration tests shown in Equation (37), and the duration of applied stresses (not accelerated) when testing needs to be in accordance with Equation (38).~~

The average failure rate that shall be demonstrated through the test is determined from the appropriate reliability equation. In its simplest form, the failure rate, assuming exponential distributed time to failure, is as follows:

$$\lambda_0 = -\frac{\ln[R(t_0)]}{t_0} \quad (52)$$

where

t_0 is the expected operating time.

The failure rate is then accelerated using proper acceleration factors for each of the applied ~~environments~~ environmental stresses and becomes:

$$\lambda_A = A_{\text{Test}} \times \lambda_0 = \sum_{i=1}^{N_S} \left(A_i \left(\prod_k A_k \right) \times \lambda_i \right) \quad (47)$$

$$\lambda_A = AF_{\text{Test}} \times \lambda_0 = \sum_{i=1}^{N_S} \left(AF_i \left(\prod_k AF_k \right) \times \lambda_i \right) \quad (53)$$

where

λ_0 is the failure rate that the item has in its "in use" conditions;

λ_A is the accelerated test failure rate;

~~A_i~~ AF_i is the acceleration factor for each of the increased stresses in test;

λ_i is the failure rate of the item corresponding to the specific stress;

N_S is the number of stresses.

The total equivalent test acceleration factor is then ~~(Krasich acceleration model for constant failure rate [10])~~ the acceleration model for constant failure rate:

$$A_{Test} = \frac{\sum_{i=1}^{N_S} \left(A_i \left(\prod_k A_k \right) \cdot \lambda_i \right)}{\lambda_0} \quad (48)$$

$$A_{Test} = \frac{\sum_{i=1}^{N_S} \left(A_i \cdot \left(\prod_k A_k \right) \left[-\frac{\ln(R_i(t_0))}{t_0} \right] \right)}{\lambda_0} \quad (49)$$

$$AF_{Test} = \frac{\sum_{i=1}^{N_S} \left(AF_i \left(\prod_k AF_k \right) \times \lambda_i \right)}{\lambda_0} \quad (54)$$

$$AF_{Test} = \frac{\sum_{i=1}^{N_S} \left(AF_i \times \left(\prod_k AF_k \right) \times \left[-\frac{\ln(R_i(t_0))}{t_0} \right] \right)}{\lambda_0} \quad (55)$$

The reciprocal of the accelerated failure rate from Equation (52) will yield the MTBF, m_0 , which can be determined from tests:

$$m_0 = \frac{1}{\lambda_a} = -\frac{t_0}{\ln(R_0(t_0))} \quad (50)$$

$$m_0 = \frac{1}{\lambda_0} = -\frac{t_0}{\ln(R_0(t_0))} \quad (56)$$

Other parameters of the SPRT and fixed duration tests are then applied in accordance with normal SPRT test design (discrimination ratio, producer's and customer's risk, etc.).

The main difference between the accelerated reliability compliance and the conventional test is the minimum test time. This minimum test time shall not be shorter than the required minimum test time, determined for the accelerated test which, in turn, is a function of required reliability, the applied stresses and the test acceleration. The sample size, therefore, shall be limited so that the minimum test time, corresponding to zero failures on the acceptance line, is equal to or longer than the minimum required accelerated test duration for the demonstration of required reliability.

The SPRT is designed in the same way as the non-accelerated test; the accept and reject criteria are established, the test plan is prepared in accordance with the accepted producer and consumer risk, discrimination ratio, except the lower test MTTF is the reciprocal of the accelerated failure rate. The other exception is that the ~~environments~~ environmental stresses are accelerated and applied in the same way as they are applied in the fixed duration tests.

An example of the accelerated SPRT is shown in Annex B.

5.9 Accelerated reliability growth testing

When reliability growth testing is accelerated, each of the stresses that are expected to be present in the ~~product~~ item life is accelerated in accordance with the acceleration criteria. The stresses can be applied individually, in which case it is preferred that they are distributed for example in a test cycle, so that the cumulative effect is simulated. The preferred manner is to apply as many stresses as possible simultaneously so as to include their possible interaction.

The duration of each applied stress is such that it represents its life application with the margin necessary for reliability demonstration (as shown in fixed duration tests). Time to failure is then the test time multiplied by the appropriate acceleration factor. When the stresses are applied simultaneously, then it is important to determine the cause of failure so that the proper time to failure can be established. Recalculated for the use time, the failure times are then organized in increasing order and one of the analysis methods used for reliability growth test type is applied (see IEC 61164 [17]).

When analysis is carried out in this manner, the order of stress application does not skew the test results, as the failures are re-calculated per their "real time" of occurrence.

Annex B provides examples of reliability growth test acceleration and data analysis.
~~Acceleration testing guidelines~~

5.10 Guidelines for accelerated testing

5.10.1 Accelerated testing for multiple stresses and the known use profile

When the accelerated testing is prepared for the various combinations of multiple stresses, it is important to simulate the conditions of use to the best degree possible.

The stresses, both environmental and operational, are usually not applied as they occur in life, which is in different combinations in each of the specific sequences. The test stresses are combined where possible for the test, but are also performed as a single stress. The thermal cycling and thermal exposure can be easily combined into one test, with the addition of operational cycling, voltage changes, applied sound power, etc. Vibration tests can be done also combined with thermal cycling, but the short duration of vibration compared with the thermal cycling and exposure makes it technically difficult. Some tests, such as pothole shocks, acoustic noise, dust accumulation, hazardous or explosive chemicals and lubricants, are very difficult to combine with others. In such cases, the environmental exposures are distributed so that they can cause cumulative damage in sequence. This is done usually by splitting up the duration of certain tests into two or even three segments, or even changing the sequence between the exposures.

5.10.2 Level of accelerated stresses

A reasonable general rule is that accelerated stress levels should not exceed the levels at which the physical or chemical properties of the test item ~~might~~ can change.

For some tests where the intention is to understand the stress limits of the ~~product~~ item, this guideline does not apply. With these tests, however, it is not recommended to relate the results to any reliability demonstration value, due to the inaccuracies of any acceleration model beyond

the inherent assumptions. Examples of such tests are step-stress or failure mode sensitivity investigations.

5.10.3 Accelerated reliability and verification tests

Item performance tests are often confused with certain accelerated reliability demonstrations. It is not unusual for a customer to present the procedures along with reliability requirements. Some even claim that if the ~~prescribed~~ ~~specified~~ tests are performed, reliability requirements would be met.

Verification tests are designed to verify the ability of an item to perform in accordance with the specified environmental extremes, with adequate durability and reliability. If a specific reliability demonstration test is required dictating a particular set and length of tests with a required sample size it usually does not represent a true reliability test and no demonstrated reliability can be claimed if that test was a success (without a failure). Even though those tests ~~might~~ ~~can~~ represent some duration in life, there can be no correlation made between performance verification and ~~product~~ ~~item~~ reliability.

Completion of ~~validation~~ ~~verification~~ tests proves that the item conforms to the design specifications so that it can perform when subject to the listed extreme stresses. The sample size typically is inadequate for any reliability demonstration or robustness to manufacturing variation, and the fact that the small item samples are subject to limited test sequences does not allow any statements about their reliability for all stresses expected to be experienced in their use.

6 Accelerated testing strategy in product development

6.1 Accelerated testing sampling plan

For a qualitative accelerated test (Type A test) the sample size is determined by the number of stresses and the number of identified failure modes. ~~It can be necessary~~ for an item ~~may have~~ to be removed from the test either because the destruct limit has been found or because the item is ~~needed~~ ~~necessary~~ for failure (mode) analysis. In some cases the item may be repaired and the test continued. Therefore a number of spare modules and spare parts should be available during the HALT ~~test~~. But it is recommended not to count on a repair being possible. Therefore the test should be planned for at least one sample per stress type. For a classical HALT this means one for cold temperature, one for high temperature, one for vibration, one for temperature cycling and one for combined temperature cycling and vibration. In total this is five. To account for more than one failure mode another two to five samples are recommended, so the total recommended sample size is seven to ten items. If that number of items is not available repairs ~~must~~ ~~can~~ be made during the test.

For a quantitative accelerated test (Types B and C tests) the number of items are mainly determined by whether the purpose of the test is to estimate the average constant risk (exponential failure distribution assumed) or the purpose is to estimate the time to failure (life time) for the items.

For the exponential case the advantage is that the accumulated test time can be increased by increasing the sample size as the accumulated test time is calculated as sample size multiplied with test time. In this case it is assumed that testing one item for 1 000 h gives the same result as testing 1 000 items for one hour each. Obviously this is not the case. Therefore both the sample size and the test time ~~have need~~ to be chosen so as to have a realistic picture of the failure mode (time to the different failure modes) as well as the differences of strength from item to item (number of samples in the test). A typical sample size for an accelerated component test is 77 samples for 1 000 h (see JESD47B [2]). For the exponential case, test plan standards like IEC 61123 and IEC 61124 can be used. If a weak distribution is suspected the sample size should be so large that at least one weak item is with high probability expected in the test. The accumulated test time can be multiplied with the estimated acceleration factor in order to

estimate the equivalent number of operating hours in the field. The average failure rate can be estimated using IEC 60605-6 [18].

For the case where the purpose of the test is to estimate the time to failure (life time), the test time ~~have to~~ shall be long enough to give enough time to estimate the time to failure for the different failure modes. Each failure mode has to be calculated separately (see IEC 61649 and IEC 61710). For a test analysed using the Weibull distribution at least five to ten failures should be expected. Since a Weibull test is often stopped once one third of the tested items have failed the sample size should be 15 to 30 items. If more than one failure mode is expected these numbers should be ~~multiplied~~ increased with the expected failure modes. If a weak distribution is suspected the sample size should be so large that at least one weak item is with high probability expected in the test. For example if a weak population of 5 % is suspected the sample size should be at least 30 items. In order to reduce the test time and the number of items that fail (e.g. are destroyed) during the test, sudden death test can be used (see IEC 61649).

6.2 General discussion about test stresses and durations

Often the test methods of the IEC 60068 series [12] are used. These standards give different test severities but no guidance on which severity to use. Some guidance can however be found in the IEC 60721 series.

When comparing test conditions with field conditions it will seldom be possible to simulate the field conditions since they vary with user, climatic conditions, etc. Therefore representative or worst case conditions ~~have to~~ should be chosen. Some tests operate with the term "severe user" which is a user defined so that only a small percentage, for example 1 % of the users, operates the ~~product~~ item under higher stress conditions.

When testing for life time, for example using a test of Type C, the test is usually extended to more loading cycles or longer time than the ~~product~~ item is expected to encounter in the field in order to take into account the variations in the stress and strength distribution and ensure a proper confidence in the estimated reliability. This is called multipliers of the stress duration or life time ratio L_v (see 5.7.2.7 and Annex B).

Since the conditions of usage vary from user to user, geographically and over time the test conditions have to be simplified. For practical reasons the stress types are often applied in sequence instead of simultaneously. If the stress types are tested on different samples the test will not detect the effect of interactions between the stress types. Therefore it is recommended to combine stresses when possible. However, this usually requires more complicated and expensive test equipment. When stress types are applied sequentially it is important to combine the stresses to test cycles where the different stress types are applied in sequence for example during one day or one week. This test cycle is then repeated the required number of times. It will often also be a consideration that the test is reproducible. This is important for test laboratories that test equipment for approval. An example is a drop test of ~~a product~~ an item. If the test is performed so that the ~~product~~ item always hits in the same angle, the test will be very reproducible, but will not simulate the conditions in the field, where the angle at which the ~~product~~ item hits will be random.

6.3 Testing components for multiple stresses

Normally components are tested for each stress type separately (see JESD47B [2]). However, in some cases, a combined test is used in order to test for the combined effect of stresses. One example is preconditioning of components by exposing them to three times a thermal cycle equal to the soldering profile. Even though the component is not soldered in this preconditioning, the temperature cycling affects the interior of the components in a way similar to the soldering process. Another example of a combined test is thermal cycling after a moisture sensitivity level test to see if delamination in the components propagates (see ~~JEDEC JESD-A113 [23] and JEDEC STD A104-B [28]~~ JESD22-A113 [19] and JESD22-A104 [20]). Often the component testing will target a specific failure mode in order to verify that the failure mode is not present in the component, or the time to failure is acceptable. Component tests are often

made on test structures instead of on functioning components in order to save test effort and qualify the technology used for a family of components. For components accelerated tests of Types B and C are recommended, unless the component test is done as a part of root cause investigation in which case Type A tests ~~could~~ **can** be recommended.

6.4 Accelerated testing of assemblies

Assemblies are often tested for each stress type separately. But since there are more interactions possible in an assembly than in a component, combined stresses are more important for assemblies. Often assemblies have a size and a function suitable for a HALT test since HALT tests often do not work well with small items (components) or large items (systems). For assemblies accelerated tests of Types A, B and C should be considered. Often the maximum applicable stress in a Type B or C test is determined by the weakest component in the assembly.

6.5 Accelerated testing of systems

Systems are often tested with combined stresses using tests of Types B and C. Often these stresses are combined in a test cycle. If the components and assemblies have been tested previously, the test on system level will mainly test the integration of the components and the assemblies. Usually the system will also include embedded software and this ~~have to~~ **shall** be taken into account in the test (see IEC 62429). In many cases the exponential time to failure assumption is made since the sample size is small and ideally there should be no failures or only a few failures in the test. Often tests on system level are used for reliability growth testing (see IEC 61014 [13] and IEC 61164 [17] ~~and IEC 62303~~).

6.6 Analysis of test results

For qualitative accelerated testing (Type A tests) the result is the failure mode and the stress conditions at which they were observed. A thorough failure analysis is required to find the root cause of the failure and estimate by an engineering evaluation if the failure mode ~~could~~ **can** occur at lower stress levels in the field due to the variations of the strength and stress distributions (see 5.1.1.2). The purpose of the HALT test is to identify the few weaknesses in the ~~product~~ **item** that need to be improved for the whole ~~product~~ **item** to be sufficiently robust. The tests of Type A do not give an estimate of life time or failure rate for the ~~product~~ **item**.

For quantitative accelerated tests (Types B and C) the acceleration factor ~~has to~~ **shall** be estimated to link the test time with the equivalent time in the field. Each failure mode ~~has to~~ **shall** be analysed separately. Therefore a failure analysis is required for all failures. Failures need to be classified as relevant or non-relevant. The non-relevant failures are those failures that cannot happen in the field, this includes failures caused by error of the test equipment or from the operation of the test equipment. Once an estimate has been made for each failure mode observed, the failure probability and time to failure can be added to estimate the failure probability of the ~~product~~ **item** as a function of time (see 5.2.2.1) **based on the relevant failures**. Statistical tools that can be used for analysis include IEC 61123, IEC 61124, IEC 60605-6 [18], IEC 61649, ~~IEC 62303~~ and IEC 62429.

7 Limitations of accelerated testing methodology

There are several major limitations to accelerated reliability testing methodologies shown in the following list (which is not exhaustive):

- Determination of acceleration factors is very complex and **can be** cost and time prohibitive. Thus, accelerated testing duration and reliability results (values), which are dependent on acceleration factors, have limited precision.
- It ~~may~~ **can** be very difficult at times to speculate which stresses contribute in combination to a specific failure mode and to what degree. Therefore the acceleration factor for combined influences also ~~may~~ **can** be over or underestimated.

- Items to be tested ~~may~~ can be too large, or too expensive. In either case, the sample size may be limited for a reasonable confidence level in test.
- Test equipment, which includes automated test monitoring, ~~may~~ can be too complex to be affordable or manageable.
- Some means of test acceleration ~~may~~ will possibly not be attainable because of large thermal masses of the tested items or because of limited stress rating. Thus testing can also become time and cost prohibitive due to lack of efficient acceleration.
- In HALT, the number of test samples is frequently ~~not larger than one~~ small, and ~~may~~ will possibly not be representative of the average strength of all of the items, so that its destruct design limits ~~may~~ can also be different, pointing to wrong conclusions. An opposite case is also possible, where the test unit ~~may~~ can be of higher strength than that of the average samples.
- In components testing, usually the curves are constructed based on times to failures, and those are used for determination of test acceleration and for information on components reliability. When the components are small and have failed catastrophically (burned or greatly changed physical properties), it often is not possible to determine in which failure mode they did fail, therefore, the results ~~may~~ can be fitted with the wrong distributions, resulting in the wrong reliability information.
- Accelerated testing of items yields information on only stresses and their combination that are considered for test preparation. The test results cannot be used if the ~~product~~ item is used in a different manner or in different environments. A re-test would be required.
- The results of quantifying reliability through acceleration ~~may not~~ cannot always be predictive on an individual ~~product~~ item since it ~~may~~ can operate at different stress levels than was tested.

Annex A (informative)

Highly accelerated limit test (HALT)

A.1 HALT procedure

Table A.1 illustrates the differences between classical accelerated tests and HALT tests.

Table A.1 – Comparison between classical accelerated tests and HALT tests

Test type	Sample size	Test time	Number of failures	Analysis
Classical test	Large (typically 30 to 60)	Very long (months)	Zero or few failures (typically less than 5)	The test is planned so all observed failures should be relevant for field conditions
HALT test	Small (typically 10)	Very short (days)	Several failures (typically 10 or more)	Each failure shall be analysed to evaluate whether it is relevant for field conditions

Figure A.1 illustrates how FMEA (see IEC 60812 [6]) gives input to HALT and receive results from HALT. One advantage of HALT is that it can identify failure modes that were not expected when making the FMEA.

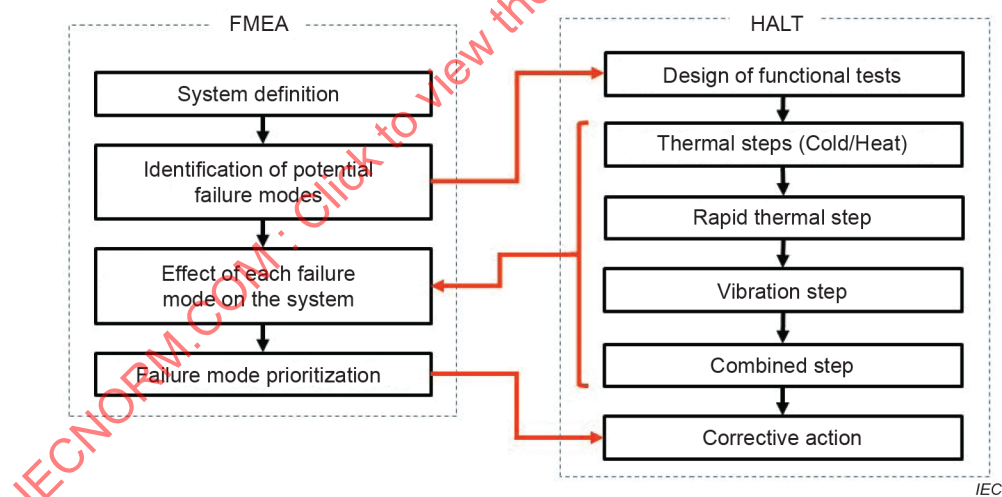


Figure A.1 – How FMEA and HALT supplement each other

A.2 HALT step-by-step procedure

A typical procedure for HALT is as follows:

- Step 1: Determine the stress level where the test will be stopped if the unit under test (UUT) has not failed.

Step 2: Set-up: mount the UUT in the HALT chamber and make the necessary connections for power supply, signals in and out, connections to monitor the function of the UUT, etc. The stress level on the UUT should be monitored by sensors (e.g. temperature sensors, accelerometers ~~etc.~~). Care should be taken that the connections can survive the stresses applied in test. In some cases part of the UUT that need not be exposed to high stresses, are placed outside the chamber, so HALT is not applied to them.

The item should be mounted to the HALT vibration fixture so that the desired vibrations or shock profiles are applied to the UUT without being significantly dampened. The fastening or fixture should not protect the UUT from rapid air movements in the chamber. In some cases it ~~may~~ **can** be necessary to remove enclosures to allow free access of the chamber air to the interior of the UUT. It ~~may~~ **can** also be necessary to remove plastic enclosures or parts ~~or~~ components that cannot survive the high temperature or vibration acceleration during the test.

Step 3: Initial testing: the UUT ~~must~~ **shall** be functionally operational prior to HALT. The monitoring devices also need to be tested for their proper functionality. Connections to the UUT also need to be checked for their integrity and capability to withstand the stresses in the HALT chamber, for example high air flow.

Step 4: Increase the applied stress to the desired level. If the UUT is continuously monitored, the stress level ~~can~~ **may** be increased continuously. If continuous monitoring is not possible, the stress levels ~~have to~~ **shall** be increased in steps, allowing the UUT to stabilize at each level before it is functionally tested to gather the possible failure information (if a failure did occur). The stress level is then reduced to see if the function of the UUT is resumed, possibly after a reset. If the functionality resumes, then the stress level where the UUT stopped functioning is the operating limit (OL).

Step 5: The stress level is increased until the UUT can no longer resume functioning even when the stress level is decreased. This stress level is the destruct limit (DL). In some cases the function can be resumed when the stress is removed even though there is a permanent damage (e.g. a crack). Therefore a so called detection screen is used where the UUT is subjected to a weak vibration level during the functional testing to activate intermittent failures. The UUT is then inspected and if necessary removed from the test chamber so that enough information can be collected to determine the failure mode, and if possible the root cause of the failure. In some cases the UUT will be permanently removed for failure analysis. In that case a new UUT should be mounted and the test continued. Where possible the fault in the UUT should be repaired, and the weak part of the design should be strengthened (e.g. by support or filling material) or protected (e.g. by directing cool air to the position or isolating the item against cold air as relevant). In some cases the part of the weaker design can be protected from the high stress or even moved out of the test chamber with connections to the rest of the UUT inside. In this way the test should be allowed to continue to find the next weakest part of the design.

Step 6: Continue until **the DL has been found or** the limit determined in Step 1 has been reached.

Step 7: Repeat the procedure from Step 2 to Step 6 with another type of stress (e.g. hot air).

NOTE The traditional HALT uses the following sequence of stresses: low temperature, high temperature and cycling between high and low operating temperatures.

Step 8: Repeat Step 2 to Step 6 with cycling between UOL and LOL. **Thermal cycling should avoid failure modes observed at temperature stress steps, therefore the operating levels UOL and LOL are used.**

Step 9: For the traditional HALT now repeat Step 2 to Step 5 with vibration ~~or~~ shock pulses.

Step 10: For the traditional HALT combine thermal cycling (Step 8) and vibration (Step 9).

Step 11: Repeat Step 2 to Step 5 for the combined stresses.

Step 12: Perform failure analysis to determine which failure modes ~~may~~ can occur at lower stress in the field use. Estimate the margin of the design taking into account the worst field conditions and the variations in the manufacturing processes.

Step 13: Report result. When the design improvements are implemented, it is recommended for the UUT ~~is~~ to be retested, if possible, to verify improvement (IEC 60300-3-5).

Depending on the type of ~~product~~ item and its sensitivity, the order of test stresses can be changed.

A.3 Example 1 – HALT test results for a DC/DC converter

Examples in Table A.2, Table A.3 and Table A.4 are from [21].

The DC/DC converter is designed for installation in an aeroplane.

Table A.2 –Summary of HALT ~~test~~ results for a DC/DC converter

Exposure	Result	Remarks	Possible cause	Action
Low temperature	LOT –70 °C (start-up) LOT –76 °C (operation) LDT Not found	Weakness: start-up unstable	Unstable start-up of 5 V and 3,3 V at low temperature Characteristics changed – Ripples	None Limit of technology
High temperature	UOT +125 °C UDT Not found	Weakness: 12 V disappeared	Internal temperature limit causes shutdown	Limit set in software
Vibration	OVL 294,3 m/s ² RMS 588,6 m/s ² RMS VDL 588,6 m/s ² RMS	Loose screw Unstable voltage	Screw too loose Hand-solder failed	Apply Loctite ² Solder processes
Temperature cycling ~~–70 °C to +125 °C~~ –65 °C to +120 °C 4 min to 10 min dwell time	No weaknesses found after more than 20 cycles			
Combined vibration and temperature cycling 40 g RMS, 50 g RMS and 60 g RMS ~~–70 °C to +125 °C~~ –65 °C to +120 °C		3 components fell off PWB Problems with 5 V DC		Review ~~of~~ ~~production~~ fixing processes Further investigation required
SOURCE: Reference [21], reproduced with permission of the authors.				

NOTE To enable the DUT to be tested during the test the levels in the combined vibration and temperature cycling test has been reduced.

² Loctite is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

A.4 Example 2 – HALT test results for a medical-product item

The medical-product item is designed for diagnostic use at a hospital.

Table A.3 – Summary of HALT results for a medical system

Exposure	Result	Remarks	Possible cause	Action
Low temperature	LOT –35 °C (module) LOT 0 °C (PC) LDT Not found	–20 °C. Output unstable. –35 °C. System stops		Error not found but similar problems seen in production at +10 °C
High temperature	UOT +59 °C +60 °C +70 °C UDT Not found +60 °C +70 °C UDT Not found	Stops after switching task. Fan does not start. 3,3 V shorted. Keyboard error		Oscillator failure To be analysed Component failure To be analysed Component failure
Vibration	OVL 49,05 m/s ² RMS OVL 196,2 m/s ² RMS OVL 490,5 m/s ² RMS VDL 294,3 m/s ² RMS	Keyboard error Output not updated Lines on screen No keyboard response Front end error Module stopped		Component as at +70 °C Reworked component Loose capacitor? Capacitor and cable loose Crystal defect 4 transmitters defect Short in filter
Temperature cycling ~~–20 °C to +85 °C~~ 5 °C to +55 °C. 10 min dwell time	No weaknesses found after 6,5 cycles			
Combined vibration and temperature cycling 30 g RMS, 40 g RMS and 50 g RMS ~~–20 °C to +85 °C~~ 5 °C to +55 °C	98,1 m/s ² RMS and temp. cycle 294,3 m/s ² RMS temp. cycle 294,3 m/s ² RMS and +80 °C 490,5 m/s ² RMS and –20 °C 490,5 m/s ² RMS temp. cycle 490,5 m/s ² RMS temp. cycle	Module stopped Keyboard error Module stopped Language change Unable to start Two functions unstable		Troubleshooting Component and reset failed No test possible SW – battery? Module defect Filter failed Further examination required
SOURCE: Reference [21], reproduced with permission of the authors.				

NOTE To enable the DUT to be tested during the test the levels in the combined vibration and temperature cycling test has been reduced.

When the top 10 list of field failures were compared to the failures found during the HALT test it was seen that all failures except one had also been found during the HALT test. The failure that was not found was due to this part of the ~~product~~ item not being tested in the HALT chamber [21].

A.5 HALT test results for a Hi-Fi equipment

The modules were designed for use in a Hi-Fi equipment for domestic use.

Table A.4 – Summary of HALT results for a Hi-Fi equipment

Exposure	Result	Remarks	Possible cause	Action
Low temperature	LOT –55 °C LDT Not found	Noise during change from radio to CD		None
High temperature	UOT Not found UDT Not found	Test stopped at +110 °C due to test cable failure		None
Vibration	OVL 245,25 m/s ² RMS 294,3 m/s ² RMS VDL 343,35 m/s ² RMS	5 components failed 1 component failed		Mounting of components
Temperature cycling ~~–55 °C to +100 °C~~ 30 min dwell time 10 cycles		Incipient stress symptoms at solder joints of heavy components (not critical after 10 cycles)		Solder joints analysed
Combined vibration and temperature cycling 10 g RMS, 20 g RMS, 30 g RMS, 40 g RMS and 50 g RMS ~~–55 °C to +110 °C~~ –50 °C to +100 °C		Problems regarding CD playing at low temperature		Mounting of 2 components
SOURCE: Reference [21], reproduced with permission of the authors.				

NOTE To enable the DUT to be tested during the test the levels in the combined vibration and temperature cycling test has been reduced.

For more detailed information see [21].

Annex B (informative)

Accelerated reliability compliance and growth test design

B.1 Use environment and test acceleration

To successfully design an accelerated reliability test it is necessary to have a good knowledge of the intended use environment, environmental and operational profile of the ~~product~~ item, and ~~product~~ item design capabilities. Acceleration of various stresses is a well established technique published in the literature, books and articles. They are based on the assumption that the test demonstrates the strength of ~~a product~~ an item regarding the applied environmental and operational stresses, and shows whether the ~~tested product/item~~ UUT did have a related failure (success ~~/~~ or life test). When using such tests, the design can be improved to withstand these stresses (reliability growth test). This methodology is briefly discussed in Clause B.2 ~~while the detailed explanation of the resultant data analysis methodology is explained in Clause B.8.~~

B.2 Determination of stresses and stress duration

The ~~product~~ item is expected to be reliable regarding each of the applied environmental and operational stresses, thus its overall reliability is the product of individual respective reliabilities. For a predetermined life t_0 , ~~product~~ item reliability is then written as:

$$R_{\text{Item}}(t_0) = \prod_{i=1}^S R_{\text{Stress}_i}(t_i) \quad (\text{B.1})$$

In the above equation R_{Stress_i} denotes reliability of the ~~product~~ item regarding individual stresses (operational or environmental). Environmental stresses here are those climatic (thermal exposure, thermal cycling, humidity, the ramp rate of the use temperature, etc.) and dynamic (vibration – random or sinusoidal or both, shock – such as potholes for vehicles, transportation, door slam, etc.). Their application and levels depend on ~~product~~ item use ~~environments~~ environmental stresses, average and extreme. Other stresses related to ~~product~~ item operation which vary with the use profile, are included in the group operational stresses. Examples of such operational stresses are: ON/OFF cycling, power stresses, ~~and~~ voltage variations, ~~etc.~~

For the test, a reliability value is allocated to each of the multiples in the expression for the ~~product~~ item reliability. The allocated values to reliability regarding individual stresses differ depending on the ~~product~~ item intended use and usage profile and its sensitivity to a particular ~~environment~~ environmental parameter. Reliability value also ~~must~~ should be allocated to the interaction factor. The nominal duration of the test for the actual stresses is calculated based on the cumulative damage model and the stress-strength criteria. Here the equivalent test damage occurs by increasing the magnitude of each of the individual stresses, all within the maximum design limits of the ~~product~~ item.

In this accelerated reliability test to simulate real life exposure, all of the test units (n) are subject to each of the stresses in the entire test sequence.

~~Duration necessary for reliability demonstration of an applied stress in test, is denoted as the mean duration of the stress application, μ_{s-i} , which ultimately is to be a factor in the measure of the product demonstrated strength. The load and stress here are of the same level as their levels in use, but duration of their application is different to produce equivalent cumulative damage.~~

Since the assumption still is that the stresses applied are of the same level as in actual use, the cumulative damage depends on their duration, Reliability regarding a specific stress, S_i , can be expressed as:

$$R_i = \Phi \left[\frac{S_i \times \mu_{S_i} - S_{\times i} \times \mu_{L_i}}{\sqrt{(S_i \times \mu_{S_i})^2 + (S_i \times \mu_{L_i})^2}} \right] \quad (\text{B.2})$$

Reduced Equation (B.2) becomes:

$$R_i = \Phi \left[\frac{\mu_{S_i} - \mu_{L_i}}{\sqrt{(\mu_{S_i})^2 + (\mu_{L_i})^2}} \right] \quad (\text{B.3})$$

For easier determination of the needed applied stress, duration of the applied stress in test is determined as a multiple of the duration of the expected load. This multiplier is chosen as the variable k . The standard deviations can be assumed to be a multiple of their respective mean values if no better information is available. **12**

$$R_i(t_0) = \Phi \left[\frac{\mu_{S_i} - \mu_{L_i}}{\sqrt{(a \times \mu_{S_i})^2 + (b \times \mu_{L_i})^2}} \right] \quad (\text{B.4})$$

Simplified, Equation (B.4) then becomes:

$$R_i(t_0, k, \mu_{L_i}) = \Phi \left[\frac{k - 1}{\sqrt{(a \times k)^2 + (b)^2}} \right] \quad (\text{B.5})$$

To investigate how reliability depends on the factor k , the stress duration multiplier, three different assumption cases in Equation (B.5) were plotted in Figure B.1.

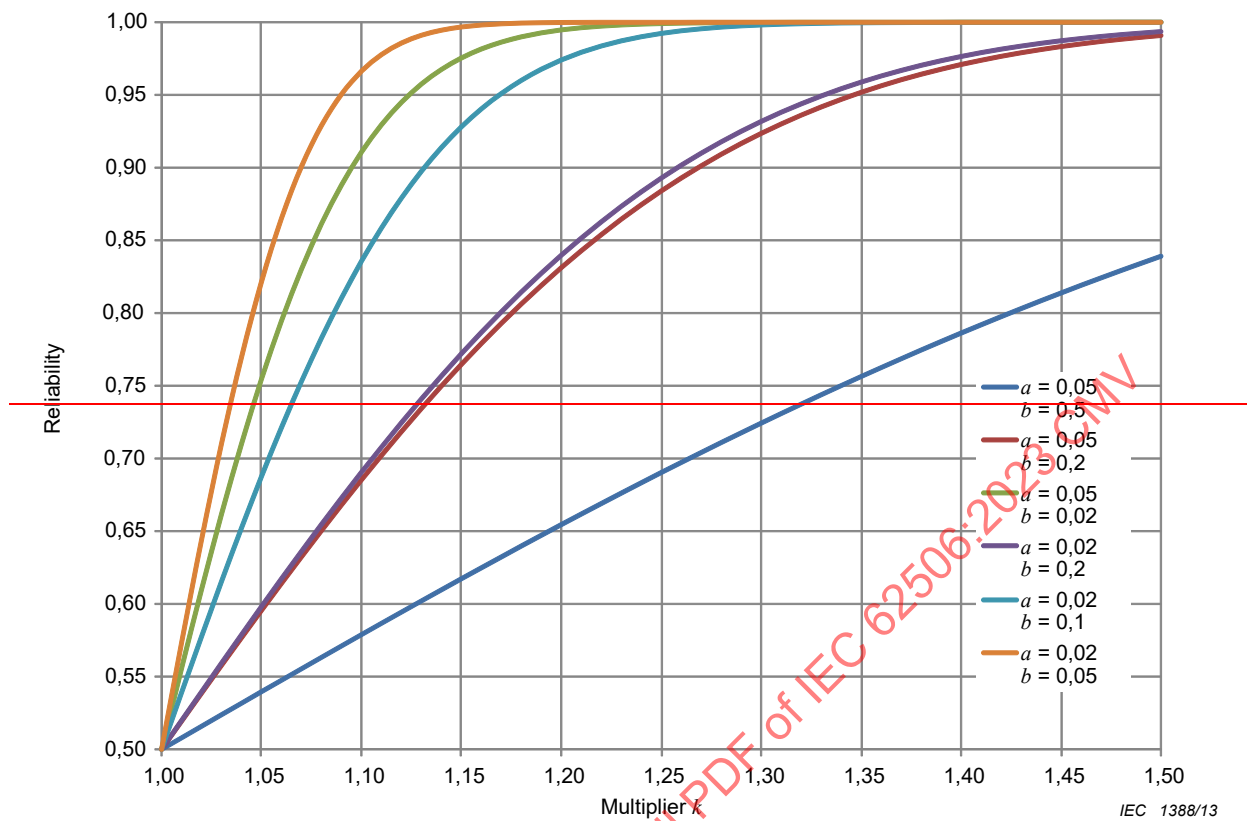


Figure B.1 – Reliability as a function of multiplier k and for combinations of parameters a and b

Figure B.1 shows a plot of the demonstrated reliability ($R_i(t_0)$) for one specific stress. To demonstrate the overall product reliability, this product needs to demonstrate the allocated reliability regarding each of the stresses. Multiplier k defines the increase in test exposure durations to achieve the allocated reliability.

Figure B.2 is plotted for the specific example, where $a = 0,05$, and $b = 0,3$.

The reliability test is designed based on the product usage profile. With that profile the parameters shown in Table B.1 are usually listed. Table B.1 is just an example of some basic stress parameters where the values are given as numerical examples, and not an exhaustive list of all the parameters given as the usage profile.

B.3 Overall acceleration of a reliability test

Regardless of the reliability demonstration test type, the main principle is the failure rate acceleration:

$$\lambda_A = A_{Test} \cdot \lambda_0 = \sum_{i=1}^{N_S} \left(A_i \prod_k A_k \cdot \lambda_i \right) \quad (B.6)$$

$$\lambda_A = AF_{Test} \times \lambda_0 = \sum_{i=1}^{N_S} \left(AF_i \prod_k AF_k \times \lambda_i \right) \quad (B.2)$$

where

λ_0 is the failure rate that the item has in its use conditions;

λ_A is the accelerated test failure rate;

A_i is the acceleration factor for each of the increased stresses in test;

λ_i is the failure rate of the item corresponding to the specific stress;

N_S is the number of stresses;

$\prod_k A_k$ is the product of the acceleration factors of stresses affecting the failure mode i .

The total equivalent test acceleration is:

$$A_{Test} = \frac{\sum_{i=1}^{N_S} \left(A_i \cdot \prod_k A_k \cdot \lambda_i \right)}{\lambda_0} \quad (B.7)$$

$$A_{Test} = \frac{\sum_{i=1}^{N_S} \left(A_i \cdot \prod_k A_k \cdot \left[-\frac{\ln(R_i(t_0))}{t_0} \right] \right)}{\lambda_0} \quad (B.8)$$

$$AF_{Test} = \frac{\sum_{i=1}^{N_S} \left(AF_i \times \prod_k AF_k \times \lambda_i \right)}{\lambda_0} \quad (B.3)$$

$$AF_{Test} = \frac{\sum_{i=1}^{N_S} \left[AF_i \times \prod_k AF_k \times \left[-\frac{\ln(R_i(t_0))}{t_0} \right] \right]}{\lambda_0} \quad (B.4)$$

Simplified by assumption that equal reliability can be allocated to each of the stresses:

$$\begin{aligned} R_i(t_i) &= R_S(t_0) = \sqrt[N_S]{R_0(t_0)} \\ \lambda_i &= \lambda_s = \text{const.} \\ \lambda_0 &= N_S \times \lambda_s \end{aligned} \quad (B.5)$$

$$A_{test} = \frac{\sum_{i=1}^{N_S} \left(A_i \times \prod_k A_k \times \left[\frac{1}{N_S} \times \frac{\lambda_0 \times t_0}{t_0} \right] \right)}{\lambda_0} \quad (B.10)$$

$$AF_{\text{Test}} = \frac{\sum_{i=1}^{N_S} \left(AF_i \times \prod_k AF_k \times \left[\frac{1}{N_S} \times \frac{\lambda_0 \times t_0}{t_0} \right] \right)}{\lambda_0} \quad (\text{B.6})$$

Then the overall acceleration factor becomes:

$$A_{\text{Test}} = \frac{1}{N_S} \sum_{i=1}^{N_S} \left(A_i \prod_k A_k \right) \quad (\text{B.11})$$

$$AF_{\text{Test}} = \frac{1}{N_S} \times \sum_{i=1}^{N_S} \left(AF_i \times \prod_k AF_k \right) \quad (\text{B.7})$$

B.4 Example of reliability compliance test design assuming constant failure rate or failure intensity

B.4.1 General

The reliability compliance tests in IEC 61124 are based on the assumption of the constant failure rate or failure intensity. The primary measure of reliability in these tests is mean time to failure, MTTF, or mean time between failures, MTBF; therefore, these tests are applicable for the tests without replacements or repair of the failed units as well as for the tests with replacement or repair of the tested units.

In this example constant failure rate or failure intensity is assumed and the life time-ratio L_v is 1, since no wear-out is assumed. But L_v is retained in the equations to enable computations of cases assuming non constant failure intensity. **13**

In each case, the tests are based on requirements or goals for reliability as well as for producer and customer risk or confidence in the test results. Table B.1 represents an example of the use environment for an automotive electronic device.

Table B.1 – Environmental stress conditions of an automotive electronic device

Parameter	Symbol	Value
Required life	t_0	10 years = 87 600 h
Required reliability	$R_0(t_0)$	0,8
Time ON	t_{ON}	2 h/day = 7 300 h
Temperature ON	T_{ON}	65 °C
Time OFF	t_{OFF}	22 h/day = 80 300 h
Temperature OFF	T_{OFF}	35 °C
Thermal cycling	ΔT_{Use}	45 °C, twice a day
Total cycles	N_{Use}	7 300
Temperature ramp rate	ξ	1,5 °C/min
Vibrations, random	W_{Use}	16,68 m/s ² RMS
Relative humidity	RH_{Use}	50 %
Activation energy	E_a	~~1,2 eV~~ 0,7 eV – for moisture 0,9 eV

NOTE The software program used to calculate this example uses Boltzmann's constant k_B as $8,63 \times 10^{-5}$ eV K⁻¹ in accordance with [22].

To ensure as much synergy among different stresses as possible, it usually is the practice to apply multiple stresses during the same test, as many as the test set-up equipment or facilities allow. Thus it is often the case that the thermal cycling is combined with the thermal exposure, operational cycling and the applied power. In those cases, the stresses are distributed so that they are spread throughout the duration of such a test. Those tests for which it is not possible or practical to perform simultaneously with others, such as humidity and often vibration, it is recommended that the tests are evenly distributed so that the cumulative damage of the stress on the units corresponds to that experienced in use.

For the example given in Table B.1, where the required 10 year reliability was 0,8, the corresponding MTBF is:

$$\theta_0 = -\frac{t_0}{\ln(R_0(t_0))} = 392\,000 \text{ h} \quad (\text{B.12})$$

$$\Theta_0 = -\frac{t_0}{\ln(R_0(t_0))} \approx 393\,000 \text{ h} \quad (\text{B.8})$$

~~A required test duration could be, depending of how many failures experienced in test, if it was the SPRT Method A8 from the IEC 61124, to about 5 times MTBF, meaning it could be required that the test duration be 2 000 000 h. If there were 50 test units, then the test would have to continue through about 50 000 h (a cost and schedule prohibitive endeavour).~~

Depending on how many failures are experienced in the test, if the SPRT test plan A.10 from IEC 61124 is used, the minimum test time is 3,23 times the MTBF, meaning it can be required that the test duration be 1 268 008 h. If there were 20 test units, then the test would have to continue through for about 63 400 h = 7,2 years (a cost and schedule prohibitive endeavour). Therefore accelerated testing is used.

The reliability of the item regarding each of the stresses is:

$$R_i(t_0) = [R_0(t_0)]^{1/4} = 0,946 \quad (\text{B.9})$$

This example uses the stress conditions shown in Table B.1.

~~For the assumed value of constants a and b , 0,05 and 0,2 respectively, the multiplier k is determined from the graph in Figure B.2 to be $k = 1,5$.~~

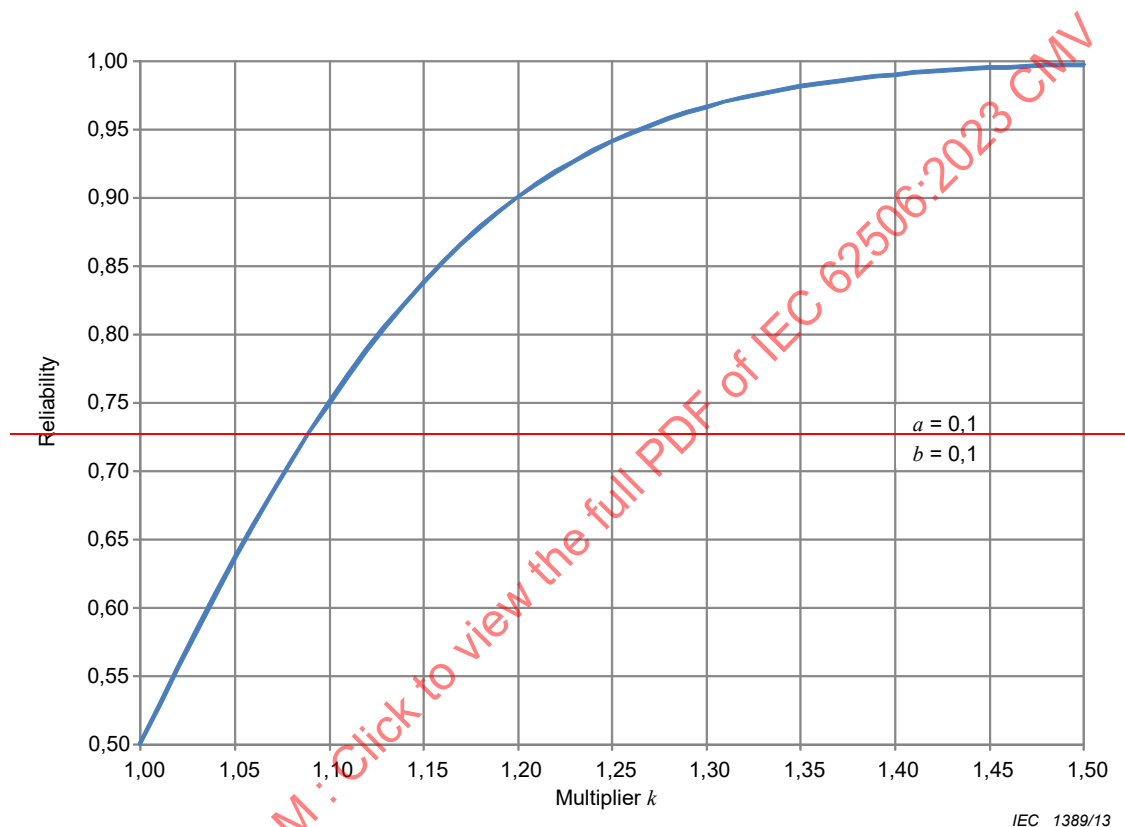


Figure B.2 — Determination of the multiplier k

B.4.2 Thermal cycling

$$\Delta T_{Use} = 45^{\circ}\text{C}$$

$$T_{Test} = 105^{\circ}\text{C}$$

$$\Delta T_{Test} = 105 - (-20) = 125^{\circ}\text{C}$$

$$\xi_{Use} = 1,5^{\circ}\text{C/min}$$

$$\xi_{Test} = 10^{\circ}\text{C/min}$$

$$m = 2,5$$

$$\underline{N_{Test} = N_{Use} \cdot k \cdot \left(\frac{\Delta T_{Use}}{\Delta T_{Test}} \right)^m \cdot \left(\frac{\xi_{Use}}{\xi_{Test}} \right)^{1/3}} \quad (B.14)$$

$$\underline{N_{Test} = 452 \text{ cycles}}$$

$$\Delta T_{Use} = 45 \text{ °C};$$

$$T_{Test} = 105 \text{ °C to } -20 \text{ °C (the 105 degrees consists of a chamber temperature of 85 °C and a 20 degree temperature rise in the UUT when ON);}$$

$$\Delta T_{Test} = 105 + (20) = 125 \text{ °C};$$

$$\xi_{Use} = 1,5 \text{ °C/min};$$

$$\xi_{Test} = 10 \text{ °C/min};$$

$$m = 1,9;$$

$$N_{Test} = N_{Use} \times L_v \times \left(\frac{\Delta T_{Use}}{\Delta T_{Test}} \right)^m \times \left(\frac{\xi_{Use}}{\xi_{Test}} \right)^{1/3} \quad (B.10)$$

$$N_{Test} = 557 \text{ cycles.}$$

B.4.3 Thermal exposure, thermal dwell

Normalize the duration at the OFF temperature to the ON conditions:

$$\underline{t_{ON_N} = t_{ON} + t_{OFF} \cdot \exp \left[\frac{E_a}{k_B} \cdot \left(\frac{1}{T_{OFF} + 273} - \frac{1}{T_{ON} + 273} \right) \right]} \quad (B.15)$$

$$\underline{t_{ON_N} = 8\,754 \text{ hours}}$$

$$t_{ON_N} = t_{ON} + t_{OFF} \times \exp \left[- \frac{E_a}{k_B} \left(\frac{1}{T_{OFF} + 273} - \frac{1}{T_{ON} + 273} \right) \right] \quad (B.11)$$

$$t_{ON_N} = 15\,055 \text{ h.}$$

Calculate the necessary accelerated test duration:

$$\underline{t_{T_Test} = t_{ON_N} \cdot k \cdot \exp \left[\frac{E_a}{k_B} \left(\frac{1}{T_{ON} + 273} - \frac{1}{T_{Test} + 273} \right) \right]} \quad (B.16)$$

$$\underline{t_{T_Test} = 168,1 \text{ h}}$$

$$t_{T_{Test}} = t_{ON_N} \times L_v \times \exp \left[-\frac{E_a}{k_B} \times \left(\frac{1}{T_{ON} + 273} - \frac{1}{T_{Test} + 273} \right) \right] \quad (B.12)$$

$$t_{T_{Test}} = 1\,188 \text{ h.}$$

For stress synergism, combine the thermal exposure with the thermal cycling, distributing the thermal exposure over the high temperature of the thermal cycling to determine thermal dwell at the high temperature.

$$t_{TD} = \frac{t_{T_{Test}}}{N_{Test}} = 0,37 \text{ h} = 22,3 \text{ min} \quad (B.17)$$

$$t_{TD} = \frac{t_{T_{Test}}}{N_{Test}}$$

$$t_{TD} = 2,13 \text{ h} = 128 \text{ min} \quad (B.13)$$

With the ramp rate measured on the device of 10 °C/min and the stabilization time at high and low temperature of 5 min the duration of the thermal cycle will be:

$$t_{TC} = 2 \times (\text{ramp time}) + (\text{stabilization time} + \text{thermal dwell}) + \text{dwell at cold} \quad (B.18)$$

$$t_{TC} = 2 \times \frac{125}{10} + 22,3 + 5 = 52,3 \text{ min} = 0,875 \text{ h}$$

$$t_{TC} = 2 \times (\text{ramp time}) + (\text{stabilization time} + \text{thermal dwell}) + \text{dwell at cold}$$

$$t_{TC} = 2 \times (125/10) + 128 + 5 = 158 \text{ min} = 2,63 \text{ h} \quad (B.14)$$

B.4.4 Humidity

Test performed at $RH_{Test} = 95 \%$, and temperature, $T_{RH} = 85 \text{ °C}$ (65 °C chamber + 20 °C internal temperature rise).

Duration of humidity exposure is equal to the normalized temperature exposure, t_{ON_N} .

$$t_{RH_{Test_{Test}}} = t_{ON_N} \times \left(\frac{RH_{Use}}{RH_{Test}} \right)^h \times \exp \left[\frac{E_a}{k_B} \times \left(\frac{1}{T_{ON} + 273} - \frac{1}{T_{RH} + 273} \right) \right] \quad (B.19)$$

$$h = 2,3$$

$$t_{RH_{Test}} = 300 \text{ h}$$

where parameter h is exponent for power law humidity acceleration factor.

This test is performed at $RH_{Test} = 95 \%$, and temperature, $T_{RH} = 85 \text{ °C}$.

The duration of humidity exposure is equal to the normalized temperature exposure, t_{ON_N} .

$$t_{RH_Test} = L_V \times t_{ON_N} \times \left(\frac{RH_{Use}}{RH_{Test}} \right)^h \times \exp \left[\frac{E_a}{k_B} \times \left(\frac{1}{T_{ON} + 273} - \frac{1}{T_{RH} + 273} \right) \right] \quad (B.15)$$

with

$$h = 3;$$

$$E_a = 0,9;$$

$$t_{RH_Test} = 392 \text{ h.}$$

where parameter h is the exponent for the power law humidity acceleration factor.

Since the humidity test also contributes to the thermal dwell damage there is a need to compensate for this. Equation (17) can be used to estimate the equivalent of 392 h at 85 °C at a temperature of 105 °C. This is 118 h that need to be subtracted from the 1 188 h. Distributed on 557 cycles this means that the 105 °C dwell in each cycle has to be reduced by 13 min out of the 128 min. **14**

B.4.5 Vibration test

The required kilometre age for ten years was 240 000 km, which translates into 150 h per axis vibration at 1,7 g RMS:

$$W_{Use} = 1,7 \text{ g r.m.s.}$$

$$W_{Test} = 3,2 \text{ g r.m.s.}$$

$$k = 1,5$$

$$t_{Vib_Test} = k \cdot t_{Vib_Use} \cdot \left(\frac{W_{Use}}{W_{Test}} \right)^w \quad (B.20)$$

With : $w = 4$

$$t_{Vib_Test} = 18 \text{ hours per axis}$$

$$W_{Use} = 1,7 \text{ g RMS;}$$

$$W_{Test} = 3,2 \text{ g RMS;}$$

$$L_V = 1,0.$$

$$t_{Vib_Test} = L_V \times t_{Vib_Use} \times \left(\frac{W_{Use}}{W_{Test}} \right)^w \quad (B.16)$$

with

$$w = 4;$$

$$t_{Vib_Test} = 12 \text{ h per axis.}$$

Vibration, when accelerated, shall have the same profile (same frequency content) as when not accelerated. A different vibration profile would not allow a meaningful acceleration.

B.4.6 Accelerations summary and overall acceleration

For the four tests accelerated in B.4.2, B.4.3, B.4.4 and B.4.5 (the number of stresses $N_S = 4$), the acceleration factors are as follows:

$$\begin{aligned}
 A_{TC} &= \left(\frac{\Delta T_{Use}}{\Delta T_{Test}} \right)^m \cdot \left(\frac{\zeta_{Use}}{\zeta_{Test}} \right)^{\frac{1}{3}} = \frac{k \cdot N_{Use}}{N_{Test}} = 24,2 \\
 A_{TD} &= \exp \left[-\frac{E_a}{k_B} \cdot \left(\frac{1}{T_{OFF} + 273} - \frac{1}{T_{ON} + 273} \right) \right] = \frac{k \cdot t_{ON-N}}{t_{T-Test}} = 52,1 \\
 A_{RH} &= \left(\frac{RH_{Use}}{RH_{Test}} \right) \exp \left[-\frac{E_a}{k_B} \cdot \left(\frac{1}{T_{ON} + 273} - \frac{1}{T_{RH} + 273} \right) \right] = \frac{k \cdot t_{ON-N}}{t_{RH-Test}} = 43,7 \\
 A_{Vib} &= \left(\frac{W_{Use}}{W_{Test}} \right)^w = \frac{k \cdot t_{Vib-Use}}{t_{Vib-Test}} = 12,6
 \end{aligned} \tag{B.21}$$

$$AF_{TC} = \frac{N_{Use}}{N_{Test}} = \frac{7300}{557} = 13,1 \tag{B.17}$$

$$AF_{TD} = \frac{t_{ON-N}}{t_{T-Test}} = \frac{15055}{1188} = 12,7 \tag{B.18}$$

$$AF_{RH} = \frac{t_{ON-N}}{t_{RH-Test}} = \frac{15055}{392} = 38,4 \tag{B.19}$$

$$AF_{Vib} = \frac{t_{Vib-Use}}{t_{Vib-Test}} = \frac{150}{12} = 12,5 \tag{B.20}$$

To determine the overall acceleration factor, it will be assumed that vibration and thermal cycling are stresses that would accelerate the same failure modes, while thermal exposure and humidity would accelerate another failure mode.

The overall acceleration factor would then be:

$$A = \frac{A_{TC} \times A_{Vib} + A_{RH} \times A_{TD}}{S} = 645 \tag{B.22}$$

$$AF = \frac{((AF_{TC} \times AF_{Vib}) + (AF_{RH} \times AF_{TD}))}{N_S} \quad (B.21)$$

$$AF = 162,86 \quad (B.22)$$

It is important to notice the difference between the standard practice of multiplying all of the acceleration factors, which would provide an overly estimated overall test acceleration of:

$$A_{SP} = A_{TC} \times A_{Vib} \times A_{RH} \times A_{TD} = 6,92 \times 10^5 \quad (B.23)$$

$$AF_{SP} = AF_{TC} \times AF_{Vib} \times AF_{RH} \times AF_{TD} = 8,05 \times 10^4 \quad (B.23)$$

It is intuitively apparent that this standard practice acceleration is extremely unrealistic and ~~may~~ **can** lead to grossly erroneous reliability conclusions.

The acceleration of test then produces the following result:

$$\lambda_0 = -\frac{\ln[R_0(t_0)]}{t_0} = 2,22 \cdot 10^{-6}$$

$$\lambda_{Test} = -\frac{\ln[R_0(t_0)]}{t_0} \cdot A = 1,64 \cdot 10^{-3} \quad (B.24)$$

Or using MTBF :

$$\theta_0 = 3,93 \cdot 10^5 \text{ hours}$$

$$\theta_{Test} = 608,7 \text{ hours}$$

~~The compliance test is then to be designed for the above MTBF as a requirement. However, the test will not have to demonstrate the very high required MTBF, $\theta_0 = 3,93 \times 10^5$ h, but the MTBF about 600 times lower MTBF, $\theta_{Test} = 508,7$ h. The accelerated test would have a duration of approximately 3 000 h compared to the non-accelerated test that would need a duration of 2 000 000 h.~~

$$\lambda_0 = -\frac{\ln[R_0(t_0)]}{t_0} = 2,55 \times 10^{-6} \quad (B.24)$$

$$\lambda_{Test} = -\frac{\ln[R_0(t_0)]}{t_0} \times AF = 4,16 \times 10^{-4} \quad (B.25)$$

Or using MTBF:

$$\theta_0 = 3,93 \times 10^5 \text{ h}$$

$$\theta_{\text{Test}} = 2\,416 \text{ h}$$

The compliance test shall then be designed for the above MTBF as a requirement. However, the test will not have to demonstrate the very high required MTBF, $\theta_0 = 3,93 \times 10^5 \text{ h}$, but owing to the test acceleration, the MTBF about 163 times lower, i.e. $\theta_{\text{Test}} = 2\,416 \text{ h}$ or 100 days. But the calendar duration of the test is determined by the number of thermal cycles (557 times $2,63 \text{ h} = 1464 \text{ h}$ or 24 days. To this, the humidity test of 392 h or approximately 17 days and the vibration test lasting $3 \times 12 \text{ h}$ have to be added. In total approximately 43 calendar days.

According to IEC 61124 Test plan A.10, the minimum test time (0 failures) is 3,23 times the MTBF to be verified, assuming a discrimination ratio $D = 1,5$ and the supplier and customer risk $\alpha = \beta = 20 \%$. If 20 items are tested in the accelerated testing the required minimum accumulated test hours is $T = 3,23 \times 2\,416 = 7\,804 \text{ h}$. With 20 items in the test the calendar duration of the compliance test is 390 h (16 days). For comparison with Clause B.5 the test time with three items to test would be 807 h (34 days). 15

B.5 Example of accelerated reliability growth test data analysis

B.5.1 General

In this example, the use parameters for an item are given in Table B.2.

Table B.2 – Product use parameters

Stress/Requirement/Property	Symbol/Value	Units
Product life	t_0	h
Time ON	t_a	h/day
Internal temperature when ON	T_{ON}	°C
Internal temperature when OFF	T_{OFF}	°C
Temperature change	ΔT_{use}	°C
Rate of temperature change	$\dot{T}_{\text{Use}}$	°C/min
Number of thermal cycles	e_T	Cycles/day
Temperature rise over the ambient	ΔT	°C
Relative humidity	RH_{Use}	%
Distance travelled in product life	D	Kilometres
Vibration level in use	W_{Use}	g
Operational (ON/OFF) cycling	e	Cycles/day

To ensure as much synergism among different stresses as possible, it is usually the practice to apply multiple stresses during the same test. Thus it is often the case that the thermal cycling is combined with the thermal exposure, operational cycling and the applied power. In these cases, the stresses are distributed so that they are spread throughout the duration of such test. For those tests that are not possible or practical to perform simultaneously with others, such as humidity and often vibration, it is recommended that the tests are evenly distributed so that the cumulative damage on the stress units corresponds to that experienced in use.

B.5.2 — Test acceleration and data analysis

The test is then accelerated using standard acceleration methods.

For data plotting in reliability growth analysis, the necessary information is time to a failure. In a test that is designed such that duration of each stress in the test represents duration of that stress type in life, the units of test performance (cycle, h) need to be translated in the corresponding time in the product life for respective stresses. This is done by test “deceleration” and by conversion of applied test cycles into the real time duration. For the basic stress tests it is done as shown below.

B.5.3 — Thermal cycling

In Table B.2, it is shown that the number of thermal cycles was given as n cycles per day. As an example this number could be number of cold starts of a vehicle (usually assumed to be $c_T = 2$). When the product life is given in h and the number of thermal cycles is given in cycles per day, then each thermal cycle in use corresponds to $24/c_T$.

The thermal cycling test is accelerated by increasing the thermal amplitudes of the test, ΔT_{Test} , over the thermal amplitudes expected in use, ΔT_{Use} .

The thermal cycling test acceleration is:

$$A_{TC} = \left(\frac{\Delta T_{Test}}{\Delta T_{Use}} \right)^m \quad (B.25)$$

The test is then further accelerated by faster rate of temperature change in test, ζ_{Test} , over the rate of change in use, ζ_{Use} .

$$A_{Ramp_Rate} = \left(\frac{\zeta_{Test}}{\zeta_{Use}} \right)^{1/3} \quad (B.26)$$

The total number of accelerated thermal cycles in test is then:

$$N_{TC_Test} = \frac{N_{TC_Use} \cdot k}{A_{TC} \cdot A_{Ramp_Rate}} \quad (B.27)$$

This means that equivalency of x accelerated thermal cycles in test to the time duration, h , in life (having in mind that one thermal cycle in life is $24/n$) is:

$$t_{TC_x} = x \cdot A_{TC} \cdot A_{Ramp_Rate} \cdot \frac{24}{c_T} \quad (B.28)$$

B.5.4 — Thermal exposure, thermal dwell

The product in its use can be exposed to several temperatures, dependent on its location, operation, etc. For simplicity, it will be assumed that the product is exposed to only the temperatures, as shown in Table B.1. One is the internal temperature when the product is ON

(t_a h/day of a total of $t_a \times \frac{t_0}{24}$ h), and the other when the product is turned OFF ($24 - t_a$) h/day or for a total of $(24 - t_a) \times \frac{t_0}{24}$ h.

To determine thermal acceleration, the time when the product is at the second temperature (OFF) will be normalized to the equivalent time at a higher temperature (ON) as follows:

$$t_{TD_Use} = t_a \cdot \frac{t_0}{24} + (24 - t_a) \cdot \frac{t_0}{24} \cdot e^{\left[\frac{E_a}{k_B} \left(\frac{1}{T_{OFF} + 273} - \frac{1}{T_{ON} + 273} \right) \right]} \quad (B.29)$$

Thermal acceleration for the test T_{Test} temperature is:

$$A_{TD} = e^{\left[\frac{E_a}{k_B} \left(\frac{1}{T_{ON} + 273} - \frac{1}{T_{Test} + 273} \right) \right]} \quad (B.30)$$

The total duration of a thermal exposure (thermal dwell) test is then:

$$t_{TD_Test} = \frac{t_{TD_Use} \cdot k}{A_{TD}} \quad (B.31)$$

If a failure occurs at y h in thermal dwell, then the corresponding time to failure in life will be:

$$t_{TD} = A_{TD} \cdot \frac{t_0}{t_{TD_Use}} \cdot y \quad (B.32)$$

It is usually the case that the thermal dwell is distributed over thermal cycling (N_{TC_Test}) and the duration at the high temperature extreme in each thermal cycle is:

$$t_{St} = \frac{t_{TD_Test}}{N_{TC_Test}} \quad (B.33)$$

In the above equation, t_{St} is the time at the thermal extremes in test.

The total duration of a thermal cycle is then:

$$t_{TC_Test} (\text{hours}) = \frac{(T_{Test} - T_{Amb})}{\xi_{Test} \cdot 60} + t_{St} + \frac{t_{TD_Test}}{N_{TC_Test}} + \frac{(T_{Test} - T_{Low})}{\xi_{Test} \cdot 60} + t_{Test_Low} + \xi \frac{(T_{Amb} - T_{Low})}{\xi_{Test} \cdot 60} \quad (B.34)$$

To make sure that the test cycling will produce cumulative damage resultant from temperature changes, some time exposure at the cold temperature, cold dwell, t_{test_low} is needed. This time should be equal or greater than the temperature stabilization time for that test item.

When the test data show time to a failure, related to thermal exposure, z , in the accelerated thermal test (as it usually happens in practice) this means that the total hours in thermal dwell are those that need to be correlated to the exposure in use, t_z :

$$t_{TD-z} = \frac{z(h)}{t_{TC_Test}(h)} \cdot \frac{t_{TD_Test}}{N_{TC_Test}} \cdot A_{TD} \cdot \frac{t_0}{t_{TD_Use}} \quad (B.35)$$

B.5.5 Humidity test

During the humidity test, the acceleration is achieved by raising relative humidity in test as well as the test temperature over those expected in use. The thermal acceleration, like in the thermal exposure test, will be determined over the equivalent use time calculated for ON temperature, t_{TD_Use} . Test acceleration for humidity test is:

$$A_H = \left(\frac{RH_{Test}}{RH_{Use}} \right)^h \cdot e^{\left[\frac{E_a}{k_p} \left(\frac{1}{T_{on}+273} - \frac{1}{T_{H_Test}+273} \right) \right]} \quad (B.36)$$

The total duration of humidity test is then:

$$t_{H_Test} = \frac{t_{TD_Use}}{A_H} \quad (B.37)$$

If a humidity failure occurs at w h in humidity test, the equivalent time to a failure in use is:

$$t_{H-w} = A_H \cdot \frac{t_0}{t_{TD_Use}} \cdot w \quad (B.38)$$

B.5.6 Vibration test

For vibration exposure, D kilometres represent t_0 h of product life.

Usually, non-accelerated, one hour of vibration represents approximately 1 600 km on a vehicle.

Duration of accelerated vibration test (h of test per axis) will be:

$$t_{Vib_Test} = \frac{D}{1\,600} \cdot \left(\frac{W_{Use}}{W_{Test}} \right)^M$$

$$A_{Vib} = \left(\frac{W_{Test}}{W_{Use}} \right)^M \quad (B.39)$$

In Equation (B.46) the parameter M is the the constant for the vibration acceleration power law. In absence of a constant specific for the test item, it is usually assumed to be: $M = 4$.

A vibration related failure that would occur at v h of vibration (in any of the axes) in the real life represents a failure at t_v h of life:

$$t_{\text{vib}_v} = v \times A_{\text{vib}} \times \frac{t_0 \times 1600}{D} \text{ (h)} \quad (\text{B.40})$$

B.5.7 Operational cycling

When the number of operational cycles is given as c per day, then one operational cycle regarding duration in use is $24/c$ h.

Operational cycling is accelerated by time compression as the stress level cannot be increased. Therefore, if a failure occurs at c operational cycles, then the actual time to a failure in use is:

$$t_{\text{OC}_o} = \frac{24}{c} \times c \text{ (h)} \quad (\text{B.41})$$

B.6 Test data analysis

B.6.1 General

For data plotting in reliability growth analysis, the necessary information is time to a failure. In a test that is designed such that duration of each stress in the test represents duration of that stress type in life, the units of test performance (cycle, hour) need to be translated in the corresponding time in the product life for respective stresses. This is done by test “deceleration” and by conversion of applied test cycles into the real time duration. For the basic stress tests it is done as shown below.

When corresponding times to failure in use are calculated for each of the failures that occurred in the reliability growth/life test, they are then ordered per increasing value, and analyzed using one of the reliability growth models. The preferred model would be the analytical AMSAA/Crow model, but, in case of a small number of test failures, Duane model can successfully be applied.

In the example shown below, for simplicity, the calculation model is Duane graphical model.

B.6.2 Test data analysis example

Data can be easier analysed if a worksheet is prepared with embedded acceleration equations.

Table B.3 shows the given use profile for the example automotive electronic device.

Table B.4 shows an example of a worksheet prepared for calculations for use times to failures (as would correspond to the product life) when the times to failures are expressed in accelerated test time. This example assumes occurrence of failures in each of the test stresses, except the ON/OFF cycling.

Table B.3 — Assumed product use profile

Parameter/requirement/use	Value
Design life	10 years
Operational time (ON)	2 h per day
Total distance driven	240 000 km
Average daily thermal excursion	45 °C
Random vibration at the location where product is installed	9,81 m/s ²
Rate of temperature change	1,5 °C/min
Number of thermal changes per day (number of vehicle cold starts)	2
Internal temperature when ON	55 °C

~~Internal temperature when device OFF~~	~~25 °C~~
~~Average relative humidity in use~~	~~50 %~~

~~Table B.4 — Worksheet for determination of use times to failures~~

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32												
33	Example: failure occurs within 212 h of thermal cycling											
34	τ (h)		t_{TD-Z}									
35			$= (A36/C31)^2 \cdot (A22/G7) \cdot G19 \cdot (A3/A19)$									
36	212		28 713,96	-	-	-	-	-	-			
37	Humidity											
38	RH_{use}	RH_{test}	t_{TD-use}	T_{H-test}			A_H					
39			$= (B3/24) \cdot A3 + ((24 - B3)/24) \cdot A3 \cdot \exp(-(E3/F3) \cdot ((1/(D3 + 273)) - (1/(C3 + 273))))$					$= ((B40/A40)^{K3}) \cdot \exp((E3/F3) \cdot ((1/(C3 + 273)) - (1/(D40 + 273))))$				
40	50	95	44 951,94	70			32,59					
41												
42	Example											
43	Failure in humidity at $\tau = 16$ h											
44	τ (h)		$t_{H-W,h}$									
45			$= A46 \cdot G40 \cdot (A3/A19)$									
46	16		3 821,33	Life	-	-	-	-	-			
47	Vibration											
48	D											
49	150 000											
50	W_{use}	W_{test}	M	A_{vib}	$f_{vib-test}$							
51				$= (B54/A54)^{G54}$	$= A51/D54$							
52	14,715	29,43	4,00	46	9 375							
53												
54	Example											
55	Failure in vibration at $\tau = 3$ h											
56	τ (h)		$t_{H-V,h}$									
57			$= A58 \cdot D52 \cdot (A3 \cdot 1000) / A49$									
58	4,6		44 016,00	Hours of life	-	-	-	-	-			
59	N_{oc-use}	e		1 cycle								
60		Cycles/day		$= 24/B61$								
61	-	8		3,00	-	-	-	-	-			

The times to failures are then ordered per their increasing value. Note that only one value for the thermal dwell has been taken for the reliability calculations (the time in the thermal dwell) as the second number of given time in thermal cycling is shown as an example of different reporting. **16**

Table B.5 shows data as recorded from Table B.5 prepared for Duane graphical analysis.

Table B.5 — Data for reliability growth plotting

Failure	Time to failure t_i	Cumulative time to failure $\theta_i = 24$	$\theta(t)$	$\log(t)$	$\log[\theta(t)]$
1	3 821,33	91 711,92	91 711,92	4,96	4,96
2	5 781,33	138 751,92	69 375,96	5,14	4,84
3	14 016	336 384,00	112 128	5,53	5,05
4	18 563,44	445 522,56	111 380,64	5,65	5,05
t_0^{*k}	131,400	3 153 600	788 400	6,50	5,90

Figure B.3 shows the plot of the last two columns to determine growth rate, α .

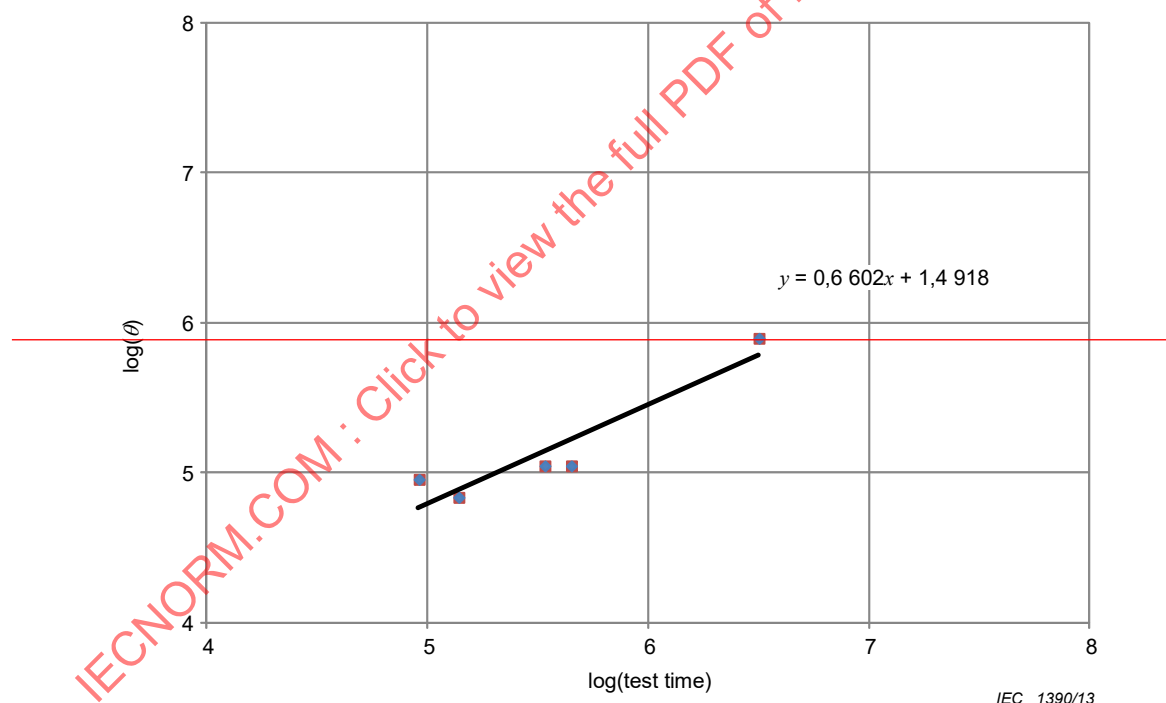


Figure B.3 — Determination of the growth rate

From the data in Table B.5, and the plot in Figure B.3, the results are as follows:

- growth rate, $\alpha = 0,66$;
- final test MTBF: $\theta_{Final} = 1 431 964$ h;
- reliability at $t_0 = 87 600$ h: $R(t_0) = 0,999 97$.

B.5 Example of reliability compliance test design assuming non-constant failure rate or failure intensity (wear-out)

In this example the same data as in Clause B.4 are used. But since possible wear-out should be taken into account in the test, the life time ratio is different from 1. Assuming three items for test ($n = 3$), and $\beta = 2,0$ Figure 11 gives a life time ratio $L_v = 1,5$ for a probability of acceptance $C = 80\%$ (20 % risk) and a minimum reliability $R = 80\%$ (20 % failures at the end of life). The factor L_v shall be included in all the equations ((B.10) to (B.16)). This has been chosen in order to facilitate the use of the example for different L_v values ($L_v = 1$ as well as L_v different from 1). But in this case it is easier to multiply the accelerated test time with the L_v factor.

Assuming 0 failures during the test, the required test time is 1,5 times the specified life time for the item (87 600 h). Note that all three items in the test shall be tested for 131 400 h since the accumulated test time cannot be used in this case. With the acceleration factor $AF = 162,86$ the calendar test time would be 538 h – 22 days to verify an item life of 10 years. 17

NOTE 1 The life time ratio $L_v = 1,5$ has been selected so that it is not necessary to recalculate all equations in Clause B.4. But it does not mean that the method in IEC 62506:2013, Clause B.2 was correct.

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Annex G **(informative)**

Comparison between HALT and conventional accelerated testing

Table C.1 – Comparison between HALT and conventional accelerated testing

Test type	Sample size	Test time	Number of failures	Analysis
Classical test	Large (typical 30 to 60)	Very long (months)	Zero or few failures (typical less than 5)	The test is planned so all observed failures should be relevant for field conditions
HALT test	Small (typically 10)	Very short (days)	Several failures (typically 10 or more)	Each failure has to be analysed to evaluate whether it is relevant for field conditions

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Annex C (informative)

Estimating the activation energy, E_a

The following example illustrates how the activation energy can be estimated based on a test.

To estimate the activation energy for a typical component like a power amplifier (size 5 mm × 5 mm × 2 mm), and a typical failure rate of 90 FIT in operating condition, the supplier should, for example, test:

- 500 components for one year at 100 °C and observe one failure. The failure rate can be calculated as 228 FIT;
- another 300 components for one year at 125 °C and observe three failures. The failure rate can be calculated as 1 146 FIT;
- another 300 components for one year at 140 °C and observe nine failures. The failure rate can be calculated as 3 465 FIT.

If all failures are caused by the same failure mode the three failure rates can be plotted in a linear-log plot. If the three data points, with an engineering approximation can be modelled with a straight line, the Arrhenius equation applies, and the activation energy E_a is the slope of the straight line as shown in Figure C.1 below:

$$E_a = k_B \times \frac{\ln[\lambda(T)] - \ln[\lambda(T_0)]}{\frac{1}{T_0} - \frac{1}{T}} \quad (\text{C.1})$$

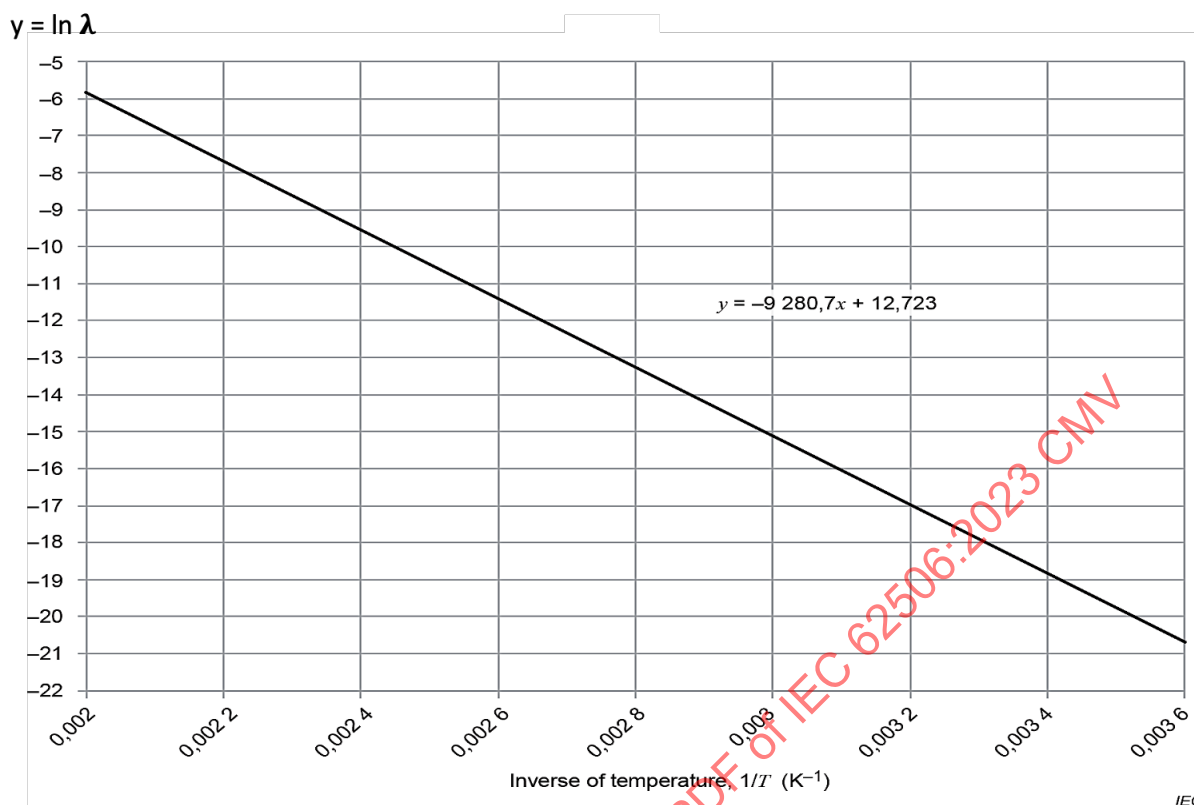


Figure C.1 – Plotting failures to estimate the activation energy E_a

From this example it can be clearly seen that estimating the activation energy is very time- and resource consuming. The activation energy should be estimated for each of the significant failure modes active in the component. Therefore the activation energies for the different failure modes are usually only estimated for a new component technology. Often these tests are made on test structures and not on functional components. The estimated activation energies are then used for all components manufactured using that component technology; therefore the user of components should get information on the activation energy of the dominating failure mode(s) from the component manufacturer.

Annex D (informative)

Calibrated accelerated life testing (CALT)

D.1 Purpose of test

The purpose of a calibrated accelerated life test (CALT) is to estimate the reliability or life time of ~~a product~~ an item based on three accelerated tests of a few samples. The procedure is adapted from GMW8758 [23]. There exists commercial software that supports the method.

D.2 Test execution

- Step 1 Based on an engineering evaluation determine the maximum stress level that can be applied in the test without the item failing immediately or after a very short time, or fail with a failure mode not expected in the field. This stress level will be higher than the normal stress level and outside the specifications for the item.
- Step 2 Select a stress level of for example 90 % of the level identified in Step 1. This is the high stress level.
- Step 3 Test at least two ~~products~~ items at the stress level determined in Step 2 and record the number of cycles to failure or time to failure for each item.
- Step 4 Make a failure analysis of the failures observed in Step 3. If all items fail with the same failure mode then continue with Step 5. If more than one failure mode is observed the test should continue with Step 5 hoping that Step 5 will identify the dominant failure mode so the non dominating failure mode(s) can be treated as suspended items (see IEC 61649).
- Step 5 Reduce the stress level of Step 2 with for example 10 %. This is the medium stress level.
- Step 6 Test at least two ~~products~~ items at the stress level determined in Step 5 and record the number of cycles to failure or time to failure of each item.
- Step 7 Identify the dominating failure mode and check that it is relevant for the failures expected in the field.
- Step 8 Plot the failures observed in Step 3 and Step 6 in ~~a two~~ Weibull plots and determine the characteristic life for the two test samples (see IEC 61649). Plot only the dominant failure mode and treat any deviating failure modes as suspended items. If there is more than one significant failure mode the test ~~has to~~ shall be performed and analysed for each failure mode separately.
- Step 9 Plot the two characteristic lives against the stress levels on a log-linear scale if the Arrhenius model is expected to be relevant or on a log-log scale if the inverse power law model is expected to be relevant.
- Step 10 Extrapolate the line through the two points in the plot down to the expected stress level in the field.
- Step 11 Select a stress level that is as close as possible to the expected stress in the field taking into consideration the trade-off between the following two factors: The stress level should be as close to the expected worst case operating conditions ("the severe user") in the field as possible in order to reduce the risk of the extrapolation. On the other hand the stress level should be as high as possible in order to reduce the test time. The chosen stress level is called the low stress level.
- Step 12 Test at least two ~~products~~ items at the stress level determined in Step 11 and record the number of cycles to failure or time to failure of each item. If more samples are available it is recommended to test them at this stress level.
- Step 13 Ensure that the same failure mode is dominating the tests at all three stress levels. Other failure modes are regarded as suspensions in this analysis (see IEC 61649). If more than one failure mode is significant they should be analysed separately.

- Step 14 Plot the failures observed in Step 12 in a Weibull plot and determine the characteristic life for the test samples (see IEC 61649). Plot only the dominant failure mode and treat any deviating failure modes as suspended items. If there is more than one significant failure mode the test ~~have~~ need to be ~~performed and~~ analysed for each failure mode separately.
- Step 15 Plot all three characteristic lives on the plot made in Step 9 and superimpose the best fit linear regression line through these three points. Extrapolate the line to the expected stress level in the field.
- Step 16 Read the expected characteristic life at the expected stress level in the field.
- Step 17 Estimate the empirical factors of the acceleration model based on the regression line identified in Step ~~14~~ 15.
- Step 18 Transpose the cycles ~~/~~ or time to failure for the data points from Step 8 and Step 14 to the expected stress level in the field, using the relevant acceleration model equations. There will be a different accelerating factor for each data point.
- Step 19 In the remaining analysis the data points estimated in Step 18 are plotted in a Weibull plot (see IEC 61649) as if all the items were tested at the expected stress level in the field. That means that the cycles ~~/~~ or time to failure are the times ~~/~~ or number of cycles estimated in Step 18 and the sample size is the total number of items tested including those that were suspended.
- Step 20 Add the confidence limit to the Weibull curve plotted in Step 19 and read the relevant reliability ~~/~~ or time to failure at the expected stress level in the field for the tested items.

Annex E (informative)

Example of how to estimate empirical factors

A certain component type has been tested with temperature shock. A group A of 22 samples was tested between -40 °C and $+85\text{ °C}$. One in this group failed after 700 cycles and ~~10~~ 2 after 1 000 cycles. A second test has been performed on 21 samples between -40 °C and $+150\text{ °C}$. In this second test group B, 4 failed after 300 cycles, 10 after 400 cycles, and an additional ~~5~~ 3 after 500 cycles. The failure mode in all cases was delamination in one of the layers. The ~~identical~~ failure mode indicates that Weibull distribution should be applied for data analysis.

Data was analysed using the graphical method with a goal that the test data could be fitted with straight lines where the slope would provide the values of shape parameter, and the value of intercept would yield the value of the scale parameter. The derivation of this graphical method starts from the probability of failure:

$$F(c) = 1 - e^{-\left(\frac{c}{\eta}\right)^\beta} \quad (\text{E.1})$$

where

c is the number of thermal cycles (the variable);

β is the shape parameter;

η is the scale parameter.

The number of cycles to failure is plotted in a Weibull diagram according to IEC 61649 (see Figure E.1). Two Weibull curves are parallel with a shape parameter β value of approximately ~~4~~ 6. This also indicates that it is the same failure mode in the two tests.

The equation for the probability of failure is rearranged to ultimately derive a straight line as follows:

$$\begin{aligned} 1 - F(c) &= e^{-\left(\frac{c}{\eta}\right)^\beta} \\ \frac{1}{1 - F(c)} &= e^{\left(\frac{c}{\eta}\right)^\beta} \\ \ln\left[\frac{1}{1 - F(c)}\right] &= \left(\frac{c}{\eta}\right)^\beta \\ \ln\left\{\ln\left[\frac{1}{1 - F(c)}\right]\right\} &= \beta \times \ln(c) - \beta \times \ln(\eta) \end{aligned} \quad (\text{E.2) to (E.5})$$

$F(c)$ is determined as the median rank of numbers of failures:

$$F(c) = \frac{i - 0,3}{n + 0,4} \quad (\text{E.6})$$

where

i is the cumulative number of failures at the observed number of cycles;

n is the total number of items in test.

The data is shown in Table E.1.

Table E.1 – Probability of failure of test samples A and B

c	$F_A(c)$	$F_B(c)$
300		~~0,200935~~ 0,172 9
400		~~0,668224~~ 0,640 19
500		~~0,808411~~ 0,780 47
700	0,031 25	
1 000	0,120 536	

Data transformation for plotting is shown in Table F.2.

Table F.2 – Data transformation for Weibull plotting

$\ln(c)$	$\ln\{\ln[1/(1-F_A(c))]\}$	$\ln\{\ln[1/(1-F_B(c))]\}$
5,703782		~~4,494715295~~
5,991465		~~0,098302188~~
6,214608		~~0,502231166~~
~~6,55108~~	~~3,449903552~~	
~~6,907755~~	~~2,952275323~~	

For data plotting see IEC 61649. The Weibull plot is shown in Figure E.1.

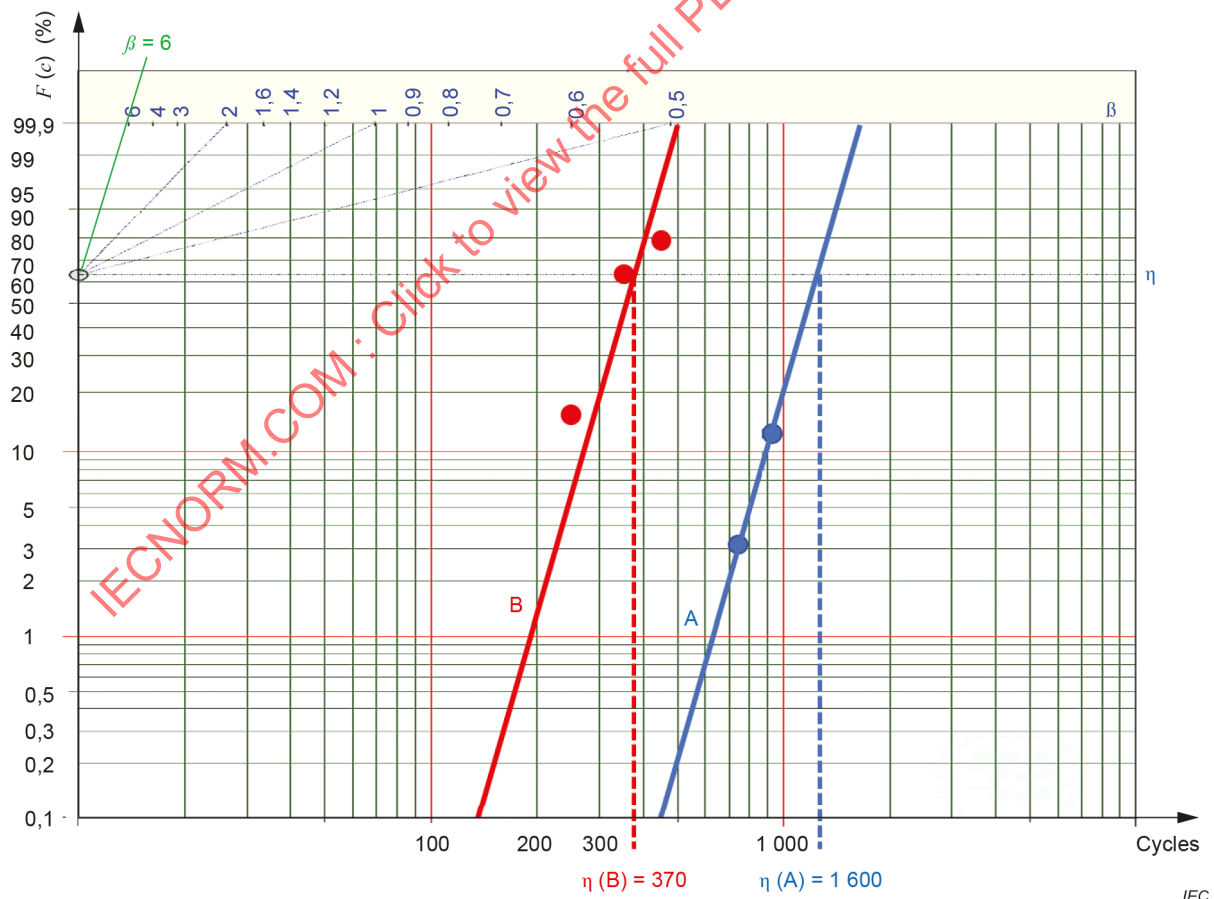
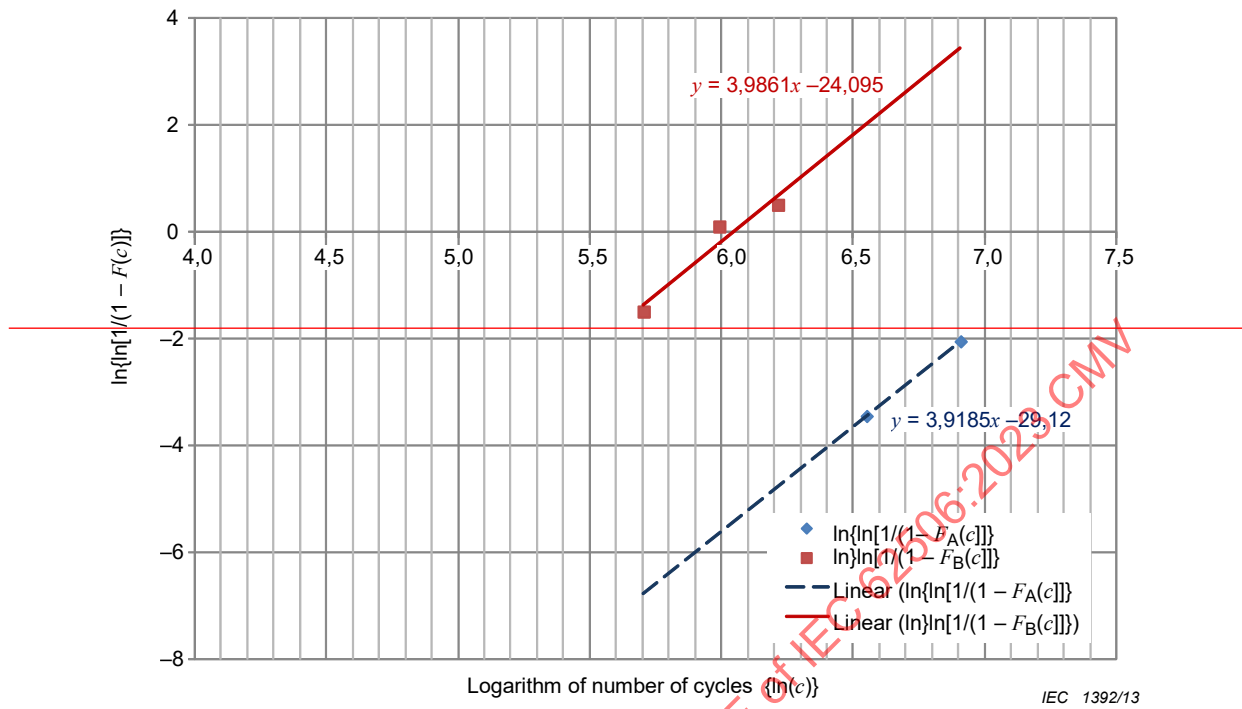


Figure E.1 – Weibull graphical data analysis

Equations of the linear data fit show values of the shape parameters ~~as~~ based on the slope, and the intercept is the negative ~~product~~ item of the shape parameter and the logarithm of the scale parameter.

~~Slopes of the two lines fitting test data have very similar values, confirming that the failure modes were indeed identical. The common value of the shape parameter is assumed to be:~~

$$\beta = 0,95$$

~~Scale parameter is then determined as:~~

$$\beta \cdot \ln(\eta) = -\text{intercept}$$

$$\eta = e^{\frac{\text{intercept}}{\beta}} \quad (\text{F.3})$$

~~From Equation (F.3), the scale parameters determined for the two tests are as follows:~~

$$\eta_A = 8\,231 \text{ cycles}$$

$$\eta_B = 446 \text{ cycles}$$

~~Thermal cycling acceleration, $A_{\Delta T_B - \Delta T_A}$ between $\Delta T_B = 190^\circ\text{C}$ and $\Delta T_A = 125^\circ\text{C}$ is:~~

$$A_{\Delta T_B - \Delta T_A} = \left(\frac{\Delta T_B}{\Delta T_A} \right)^m = \frac{\eta_A}{\eta_B} \quad (\text{F.4})$$

~~Solving for the exponent m , which is a characteristic of the test items:~~

$$A_{\Delta T_B - \Delta T_A} = \left(\frac{\Delta T_B}{\Delta T_A} \right)^m = \frac{\eta_A}{\eta_B}$$

$$m = \frac{\ln\left(\frac{\eta_A}{\eta_B}\right)}{\ln\left(\frac{\Delta T_B}{\Delta T_A}\right)} \quad (\text{F.5})$$

~~In this example, the value of parameter m is calculated to be~~

$$m = 6,96$$

~~To determine a scale parameter for any temperature range of thermal cycling, ΔT :~~

$$\eta(\Delta T) = \eta_B \times \left(\frac{\Delta T_B}{\Delta T} \right)^m \quad (\text{F.6})$$

~~Scale parameter as a function of thermal cycling temperature range is shown in Figure F.2.~~

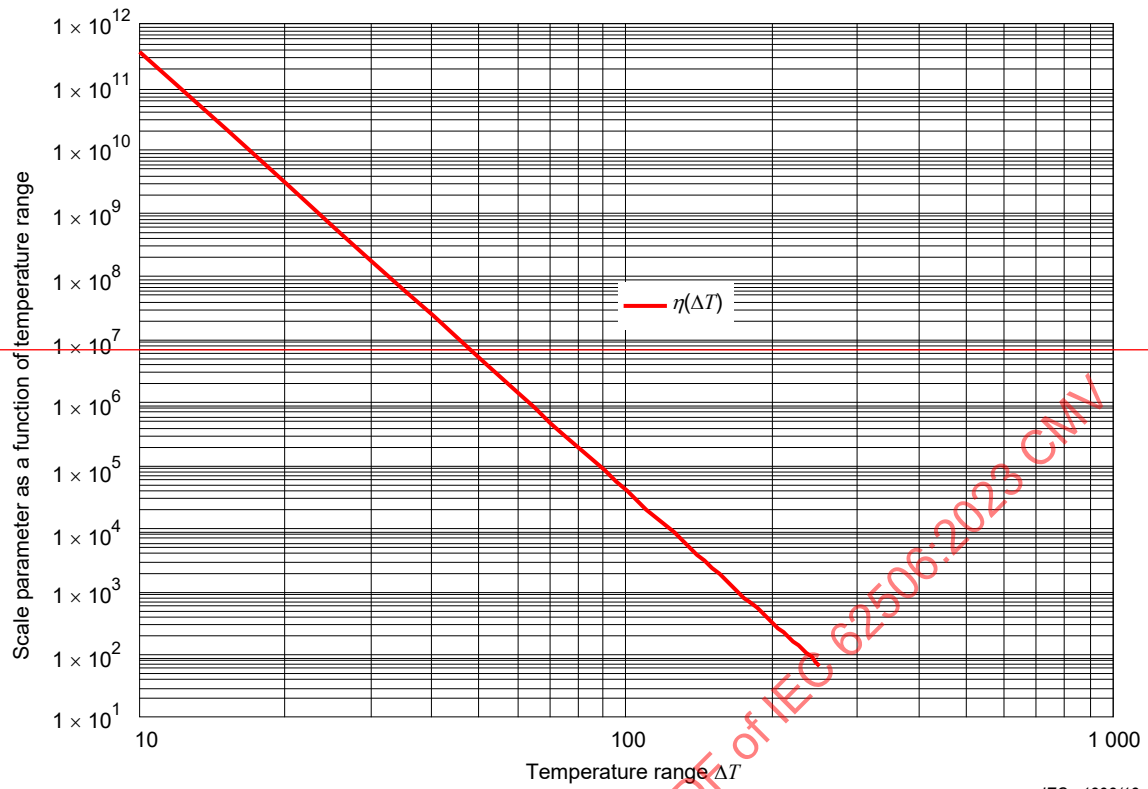


Figure F.2 — Scale parameter as a function of the temperature range

To calculate the scale parameter corresponding to the thermal cycling in use of $\Delta T = 50\text{ }^{\circ}\text{C}$:

$$\eta(50) = 446 \times \left(\frac{190}{50} \right)^{6,96} = 4,838 \times 10^6 \quad (\text{F.7})$$

For the temperature cycling range of $50\text{ }^{\circ}\text{C}$ (in use) probability of failure as a function of the number of cycles is shown in Figure F.3.

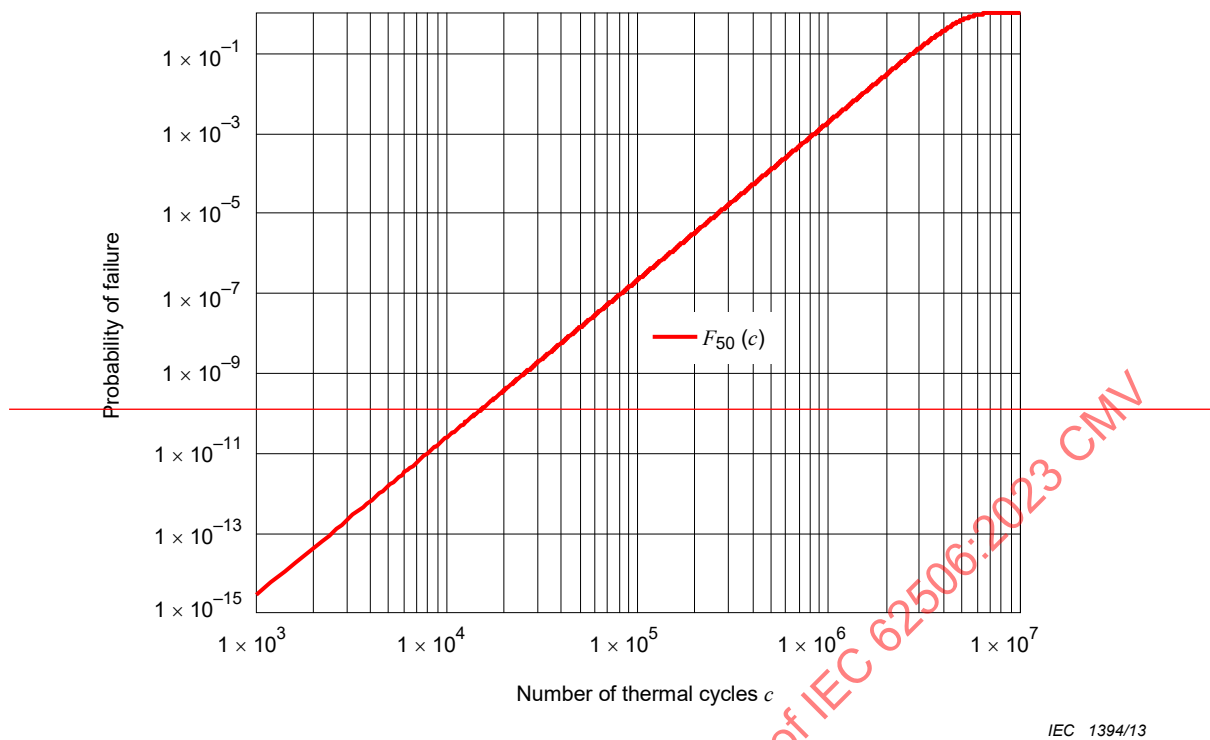


Figure F.3 — Probability of failure as a function of number of cycles $\Delta T = 50\text{ °C}$ 18

As an example, if an item (product) is exposed to a temperature range of 50 °C , probability of failure after a million cycles would be approximately 10^{-3} , meaning that one in a thousand items might fail after one million cycles.

Slopes of the two lines fitting test data have very similar values, confirming that the failure modes were indeed identical. The common value of the shape parameter is found to be:

$$\beta = 6,0$$

From the plot, the scale parameters determined for the two tests are as follows:

$$\eta_A = 1\,600 \text{ cycles}$$

$$\eta_B = 420 \text{ cycles}$$

The thermal cycling acceleration, AF_{190_125} between $\Delta T_B = 190\text{ °C}$ and $\Delta T_A = 125\text{ °C}$ is:

$$AF_{\Delta T_B \Delta T_A} = \left(\frac{\Delta T_B}{\Delta T_A} \right)^m = \frac{\eta_A}{\eta_B} \quad (\text{E.7})$$

Solving for the exponent m , which is a characteristic of the test items:

$$m = \frac{\ln\left(\frac{\eta_A}{\eta_B}\right)}{\ln\left(\frac{\Delta T_B}{\Delta T_A}\right)} \quad (\text{E.8})$$

In this example, the value of parameter m is calculated to be

$$m = 3,19$$

To determine a scale parameter for any temperature range of thermal cycling, ΔT , use Equation (E.9):

$$\eta(\Delta T) = \eta_B \times \left(\frac{\Delta T_B}{\Delta T}\right)^m \quad (\text{E.9})$$

To calculate the scale parameter corresponding to the thermal cycling in use of $\Delta T = 50$ °C and for the temperature cycling range of 50 °C (in use), the probability of failure as a function of the number of cycles is given by the following Equation (E.10):

$$\eta(50) = 420 \times \left(\frac{190}{50}\right)^{3,19} \quad (\text{E.10})$$

$$\eta(50) = 29\,700$$

Annex F (informative)

Determination of acceleration factors by testing to failure

F.1 Failure modes and acceleration factors

Single acceleration factors are most meaningful when expressing the process acceleration of a single failure mode. The overall acceleration factor from one set of combined stresses to another is determined in the same manner as described in 5.5.

A single stress type is applied at several (a minimum of three) levels, each on a single group of components. The test duration is determined by components' failures, i.e. the test continues until all or the majority of components fail. Times to failure are recorded for each of the components at each of the stress levels, and the appropriate failure distributions are constructed. The scale parameters of those distributions are plotted for each of the stress levels, and the values are then fitted with a function which is best fitted for the values as a function of the applied stress levels. The ratio of the scale parameter versus the ratio of the stress levels determines the acceleration factor.

F.2 Example of determination of acceleration factor

A voltage acceleration factor was determined for a semiconductor (power transistor) by test at three voltages as shown in Table F.1.

Table F.1 – Voltage test failure data for Weibull distribution

Failure no. and voltage	Time to failure h	$F(t)$	$\ln(t)$	$\ln(\ln(1/(1-F(t))))$
1 27 V	100	0,07	4,61	-2,66
2 27 V	180	0,16	5,19	-1,72
3 27 V	240	0,26	5,48	-1,20
4 27 V	290	0,36	5,67	-0,82
5 27 V	335	0,45	5,81	-0,51
6 27 V	377	0,55	5,93	-0,23
7 27 V	420	0,64	6,04	0,03
8 27 V	450	0,74	6,11	0,30
9 27 V	470	0,84	6,15	0,59
10 27 V	485	0,93	6,18	0,99
1 26 V	600	0,07	6,40	-2,66
2 26 V	1 100	0,16	7,00	-1,72
3 26 V	1 580	0,26	7,37	-1,20
4 26 V	2 030	0,36	7,62	-0,82
5 26 V	2 430	0,45	7,80	-0,51
6 26 V	2 810	0,55	7,94	-0,23
7 26 V	3 160	0,64	8,06	0,03
8 26 V	3 460	0,74	8,15	0,30
9 26 V	3 710	0,84	8,22	0,59
10 26 V	3 910	0,93	8,27	0,99
1 25 V	1 800	0,07	7,50	-2,66

Failure no. and voltage	Time to failure t_h	$F(t)$	$\ln(t)$	$\ln(\ln(1/(1-F(t))))$
2 25 V	3 500	0,16	8,16	-1,72
3 25 V	5 000	0,26	8,52	-1,20
4 25 V	6300	0,36	8,75	-0,82
5 25 V	7 450	0,45	8,92	-0,51
6 25 V	8 450	0,55	9,04	-0,23
7 25 V	9 300	0,64	9,14	0,03
8 25 V	10 080	0,74	9,22	0,30
9 25 V	10 730	0,84	9,28	0,59
10 25 V	11 330	0,93	9,34	0,99

The data was plotted as a Weibull distribution, as shown in Figure F.1, and the trend lines were drawn. A good linear fit indicated that the times to failure were Weibull distributed, and the process was the same (very similar shape parameters), meaning that the failure mechanism was the same.

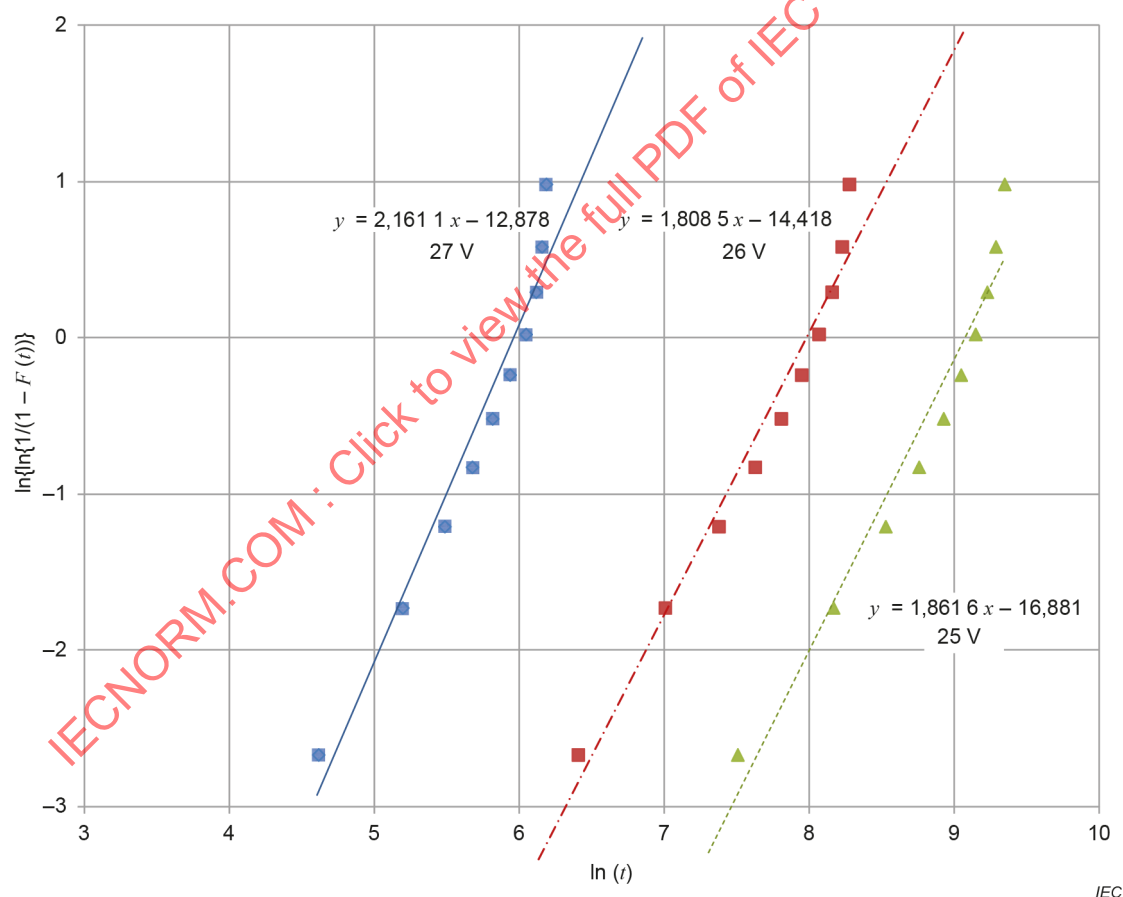
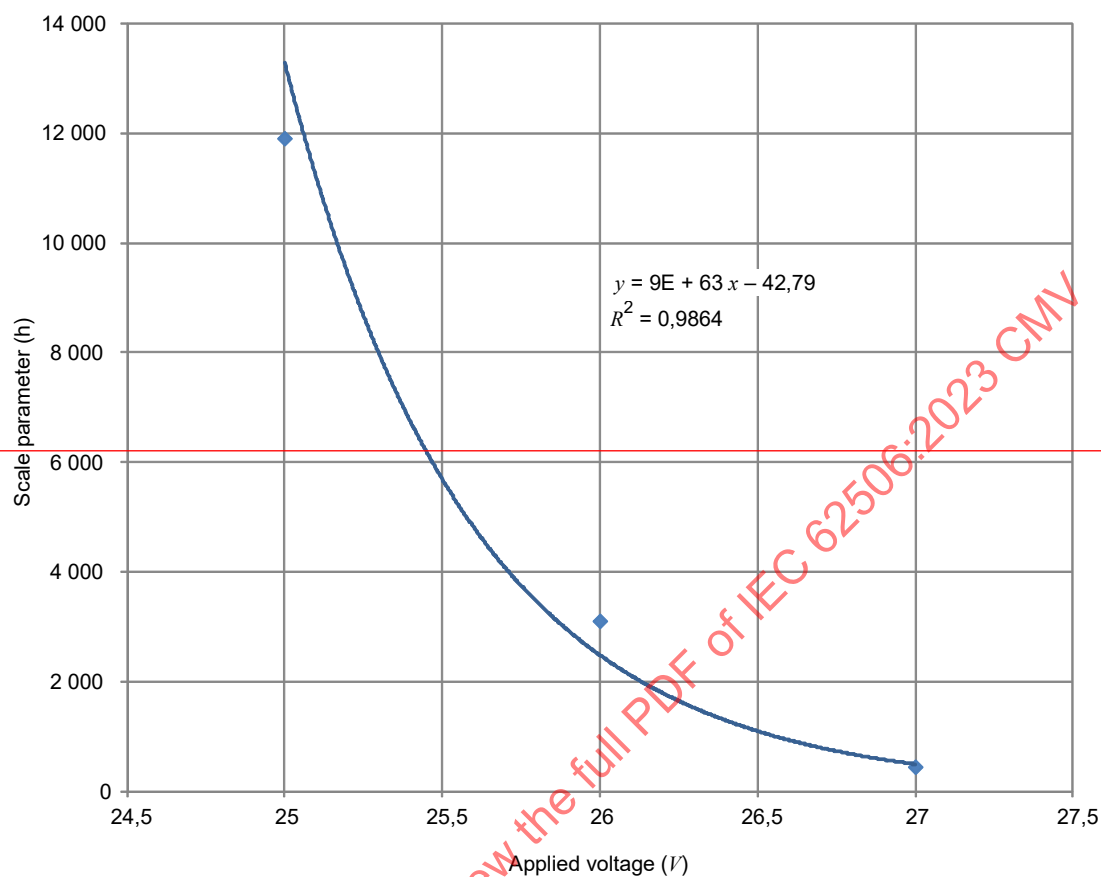


Figure F.1 – Weibull plot of the three data sets

From the equations shown in Figure G.1, the three values of scale parameter were determined, and the plot is shown in Figure G.2.



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Figure G.2 — Scale parameters' values fitted with a power line 19

The equation of the power line provides then values of the scale parameter as a function of voltage as:

$$\eta(V) = A \times 10^{B \times V^{-m}} \quad (\text{G.1})$$

The acceleration factor here is:

$$A(V) = \frac{10^{B \times \ddot{V}_2^{-m}}}{10^{B \times \ddot{V}_1^{-m}}} \quad (\text{G.2})$$

From the equations shown in Figure F.1, the three values of the scale parameter were determined using Equation (F.1):

$$\eta = \exp\left(-\frac{b}{a}\right) \quad (\text{F.1})$$

where a and b are the parameters of the linear equation $y = ax + b$

From Equation (F.1) and Figure F.1 we get:

$$\eta(25 \text{ V}) = 8\,673,3$$

$$\eta(26 \text{ V}) = 2\,899,7$$

$$\eta(27 \text{ V}) = 387,2$$

The acceleration factor therefore is:

$$AF(25 \text{ V to } 26 \text{ V}) = 8\,673 / 2\,899,8 = 2,99$$

$$AF(26 \text{ V to } 27 \text{ V}) = 2\,899,8 / 387,6 = 7,48$$

$$AF(25 \text{ V to } 27 \text{ V}) = 8\,673 / 387,6 = 22,37$$

Note that $AF(26 \text{ V to } 27 \text{ V}) = AF(25 \text{ V to } 26 \text{ V}) \times AF(26 \text{ V to } 27 \text{ V}) = 2,99 \times 7,48 = 22,37$

The values of the scale parameter η as a function of voltage is determined as a power function:

$$\log \eta(V) = B \times V^{-m} \quad (\text{F.2})$$

Taking logarithm two times gives the linear function:

$$\log(\log \eta(V)) = -m \log V + \log B \quad (\text{F.3})$$

Using regression on this function, the values of the regression parameters can be found:

$$m = 5,5182$$

$$B = 2,1537 \times 10^8$$

$$\log B = 8,333\,2$$

Inserting the values in Equation (F.3) gives:

$$\log(\log \eta(V)) = -5,5182 \log V + \log 8,3332 \quad (\text{F.4})$$

With Equation (F.5) the η values for different voltages can be predicted.

$$\eta(V) = AF \times 10^{B \times V^{-m}} \quad (\text{F.5})$$

Annex G (informative)

Median rank tables 95 % rank

Table G.1 – Median rank tables 95 % rank

[illegible][illegible]

[illegible]

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List of comments

- 1 This text is changed to make the figure easier to understand.
- 2 A number of equations are retyped due to change of symbols and correction of errors.
- 3 This text is deleted since it refers to the incorrect method in Subclause 5.7.2.2.
- 4 This introduction is added to time and event compression tests.
- 5 The symbol k is used for both the design margin and for the lifetime ratio – this is not correct.
- 6 This assumes that the damage accumulation is linear (stress times time). But for temperature and vibration loads the accumulation is highly unlinear, see for example the Arrhenius equation. For example 40 hours at 100 °C accumulates more damage than 100 hours at 40 °C.
- 7 Equations 43 and 44 are only applicable to one load. There is no time dimension (t) in the equation. The equation can therefore not be used to determine the duration of a test. The paper of Milena Krasich listed in the bibliography uses the equation to determine the reliability once the strength curve has been determined by test. This is correct. But the equation can not be used to determine the duration of the test based on the design margin (load versus strength). See A.D.S. Carter: Mechanical reliability.
- 8 This text is added to explain the difference between tests assuming constant failure rate and tests assuming wear-out (limited life).
- 9 This text was added to include “physics of failure” tests.
- 10 This is the correct method that replaces the incorrect method described in the old Subclause 5.7.2.2. The method is based on the work of Professor Bertsche.
- 11 This text is added to explain the lifetime ratio.
- 12 Equations B.3 and B.4 use the design strength and design stress (the design margin). But this has nothing to do with the test stresses. Here it is clear that the equation is only valid for one load (there is no time dimension (t)). Accumulated damage will result in the strength curve moving to the left, or being truncated because the weakest items fail. In both cases Equations B.2 and B.3 are not valid anymore.
- 13 A number of calculating errors are corrected in this example. It is calculated with a lifetime ratio of 1 to allow comparison between tests assuming constant failure rate and tests assuming wear-out (lifetime ratio different from 1).
- 14 This text is added to make the computations more correct. In practice the difference is not significant given the other uncertainties.
- 15 This text is added to explain the difference between a test assuming constant failure rate and a test assuming wear-out.
- 16 This example is deleted since it is based on the incorrect method.
- 17 This text is added to show the difference between a test assuming constant failure rate and a test assuming wear-out.
- 18 Figures are removed to make the example shorter and easier to understand.
- 19 Figures are removed to make the example shorter and easier to understand.

INTERNATIONAL STANDARD

NORME INTERNATIONALE



Methods for product accelerated testing

Méthodes d'essais accélérés de produits

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

METHODS FOR PRODUCT ACCELERATED TESTING

FOREWORD

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IEC 62506 has been prepared by IEC technical committee 56: Dependability. It is an International Standard.

This second edition cancels and replaces the first edition published in 2013. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) references have been updated;
- b) symbols have been revised;
- c) errors in 5.7.2.3 and Annex B, mainly, have been corrected;
- d) calculation errors in the examples of Annex B and Annex F have been corrected.

The text of this International Standard is based on the following documents:

Draft	Report on voting
56/2000/FDIS	56/2016/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

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INTRODUCTION

Many reliability or failure investigation test methods have been developed and most of them are currently in use. These methods are used to either determine product reliability or to identify potential product failure modes, and have been considered effective as demonstrations of reliability:

- fixed duration,
- sequential probability ratio,
- reliability growth tests,
- tests to failure, etc.

Such tests, although very useful, are usually lengthy, especially when the product reliability that has to be demonstrated is high. The reduction in time-to-market periods as well as competitive product cost, increase the need for efficient and effective accelerated testing. Here, the tests are shortened through the application of increased stress levels or by increasing the speed of application of repetitive stresses, thus facilitating a quicker assessment and growth of product reliability through failure mode discovery and mitigation.

There are two distinctly different approaches to reliability activities:

- the first approach verifies, through analysis and testing, that there are no potential failure modes in the product that are likely to be activated during the expected life time of the product under the expected operating conditions and usage profile;
- the second approach estimates how many failures can be expected after a given time under the expected operating conditions and usage profile.

Accelerated testing is a method appropriate for both cases, but used quite differently. The first approach is associated with qualitative accelerated testing, where the goal is identification of potential faults that eventually can result in product field failures. The second approach is associated with quantitative accelerated testing where the product reliability may be estimated based on the results of accelerated simulation testing that can be related back to the use of the environment and usage profile.

Accelerated testing can be applied to multiple levels of items containing hardware and software. Different types of reliability testing, such as fixed duration, sequential test-to-failure, success test, reliability demonstration, or reliability growth or improvement tests can be candidates for accelerated methods. This document provides guidance on selected, commonly used accelerated test types. This document should be used in conjunction with statistical test plan standards such as IEC 61123, IEC 61124, IEC 61649 and IEC 61710.

The relative merits of various methods and their individual or combined applicability in evaluating a given system or item, should be reviewed by the product design team (including reliability engineering) prior to selection of a specific test method or a combination of methods. For each method, consideration should also be given to the test time, results produced, credibility of the results, data required to perform meaningful analysis, life cycle cost impact, complexity of analysis and other identified factors.

In this document the term "item" is used as defined in IEC 60050-192 covering physical products as well as software. Services and people are however not covered by this document.

METHODS FOR PRODUCT ACCELERATED TESTING

1 Scope

This document provides guidance on the application of various accelerated test techniques for measurement or improvement of item reliability. Identification of potential failure modes that can be experienced in the use of an item and their mitigation is instrumental to ensure dependability of an item.

The object of the methods is to either identify potential design weakness or provide information on item reliability, or to achieve necessary reliability and availability improvement, all within a compressed or accelerated period of time. This document addresses accelerated testing of non-repairable and repairable systems. It can be used for probability ratio sequential tests, fixed duration tests and reliability improvement/growth tests, where the measure of reliability can differ from the standard probability of failure occurrence.

This document also extends to present accelerated testing or production screening methods that would identify weakness introduced into the item by manufacturing error, which can compromise item reliability. Services and people are however not covered by this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-192 – *International Electrotechnical Vocabulary (IEV) – Part 192: Dependability*, available at <http://www.electropedia.org>

IEC 60300-3-5, *Dependability management – Part 3-5: Application guide – Reliability test conditions and statistical test principles*

IEC 60605-2, *Equipment reliability testing – Part 2: Design of test cycles*

IEC 60721 (all parts), *Classification of environmental conditions*

IEC 61123:2019, *Reliability testing – Compliance test plans for success ratio*

IEC 61124:2023, *Reliability testing – Compliance tests for constant failure rate and constant failure intensity*

IEC 61649:2008, *Weibull analysis*

IEC 61709, *Electric components – Reliability – Reference conditions for failure rates and stress models for conversion*

IEC 61710, *Power law model – Goodness-of-fit tests and estimation methods*

IEC 62429, *Reliability growth – Stress testing for early failures in unique complex systems*

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-192 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>

NOTE Symbols for reliability, availability and maintainability measures follow those of IEC 60050-192, where available.

3.1.1

activation energy

E_a

empirical factor for estimating the acceleration caused by a change in absolute temperature

Note 1 to entry: Activation energy is usually measured in electron volts per degree Kelvin.

3.1.2

detection screen

low stress level exposure to detect intermittent faults

3.1.3

event compression

increasing stress repetition frequency to be at considerably higher levels than it is in the field

3.1.4

highly accelerated limit test

HALT

test or sequence of tests intended to identify the most likely failure modes of the product in a defined stress environment

Note 1 to entry: HALT is sometimes spelt out as the highly accelerated life test (as it was originally named in error). However, as a non-measurable accelerated test, it does not provide information on life duration, but on the magnitude of stress which represents the limit of the design.

3.1.5

highly accelerated stress audit

HASA

process monitoring tool where a sample from a production lot is tested to detect potential weaknesses in a product caused by manufacturing

3.1.6

highly accelerated stress screening

HASS

screening intended to identify latent defects in a product caused by manufacturing process or control errors

3.1.7

item

subject being considered

Note 1 to entry: The item may be an individual part, component, device, functional unit, equipment, subsystem, or system.

Note 2 to entry: The item may consist of hardware, software, people or any combination thereof.

Note 3 to entry: The item is often comprised of elements that may each be individually considered. See "sub-item" (IEV 192-01-02) and "indenture level" (IEV 192-01-05).

Note 4 to entry: IEC 60050-191:1990 (now withdrawn; replaced by IEC 60050-192:2015) identified the term "entity" as an English synonym, which is not true for all applications.

Note 5 to entry: The definition for "item" in IEC 60050-191:1990 (now withdrawn; replaced by IEC 60050-192:2015) is a description rather than a definition. This new definition provides meaningful substitution throughout this document. The words of the former definition form the new Note 1 to entry.

Note 6 to entry: In this document people and services are excluded.

[SOURCE: IEC 60050-192:2015, 192-01-01, modified – Note 6 to entry has been added.]

3.1.8

life time

<of a non-repairable item> time interval from first use until user requirements are no longer met

Note 1 to entry: The end of life time is usually called failure of the component.

Note 2 to entry: The end of life is often defined as the time where a specified percentage of the components have failed, for example stated as a B_{10} or L_{10} value for 10 % accumulated failures.

3.1.9

precipitation screen

screening profile to precipitate, through failure, conversion of latent faults into revealed faults

3.1.10

step-stress test

test in which the applied stress is increased, after each specified interval, until failure occurs or a predetermined stress level is reached

Note 1 to entry: The 'interval' could be specified in terms of number of stress applications, durations, or test sequences.

Note 2 to entry: The test should not alter the basic failure modes, failure mechanisms, or their relative prevalence.

[SOURCE: IEC 60050-192:2015, 192-09-10]

3.1.11

test acceleration factor

ratio of the stress response rate of the test specimen under the accelerated conditions, to the stress response rate under specified operational conditions

Note 1 to entry: Both stress response rates refer to the same time interval in the life of the tested items.

Note 2 to entry: Measures of stress response rate are, for example, operating time to failure, failure intensity, and rate of wear.

[SOURCE: IEC 60050-192:2015, 192-09-09]

3.1.12

time compression

removal of exposure time at low or deemed non damaging stress levels from a test for the purpose of acceleration

3.2 Symbols and abbreviated terms

ADT	accelerated degradation test(ing)
AF	acceleration, acceleration factor
AF_{Test}	overall acceleration in a test
CALT	calibrated accelerated life testing
B_{10}	life time, the time where 10 % of the items have failed
C	confidence
CD	compact disc player in a HiFi equipment
DL	destruct limit
DSL	design specification limit
FIT	failure in time (failure per 10^9 hours)
HALT	highly accelerated limit test
HASA	highly accelerated stress audit
HASS	highly accelerated stress screening test
HAST	highly accelerated stress test
L	load
L_v	life time ratio
LDL	lower destruct limit
LDT	lower destruct temperature
LOL	lower operating limit
LOT	lower operating temperature
LRTL	lower reliability test limit
MTBF	mean operating time between failures
MTTF	mean operating time to failure
OL	operating limit
OVL	operation vibration limit
P_A	acceptance probability
PDF	probability density functions
PWB	printed wiring board
$R(t)$	reliability as a function of time; probability of survival to the time t
RTL	reliability test level
S	strength
SL	specification limit
SPRT	sequential probability ratio test
t_0	time denoted time 0
t_L	a specified time, e.g. life
THB	temperature humidity bias test
TTF	time to failure
UDL	upper destruct limit
UDT	upper destruct temperature
UOL	upper operating limit
UOT	upper operating temperature

URTL	upper reliability test limit
UUT	unit under test
VDL	vibration destruct limit
$\lambda(S)$	failure rate as a function of a stress
$\lambda(t)$	failure rate as a function of time

4 General description of the accelerated test methods

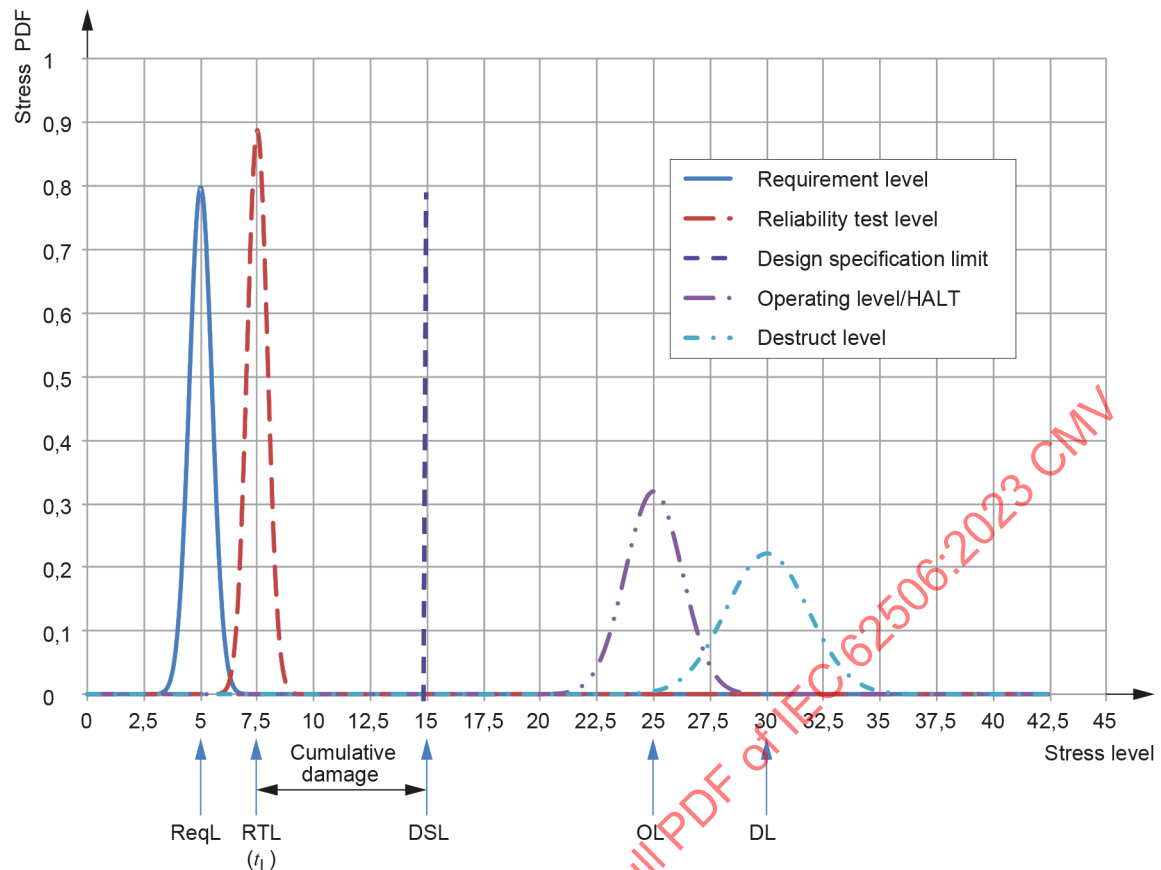
4.1 Cumulative damage model

Accelerated testing of any type is based on the cumulative damage principle. The stresses of the item in its life cause progressive damage that accumulates throughout the item life. This damage can, or not, result in an item's failure in the field.

The strategy of any type of accelerated testing is to produce, by increasing stress levels during testing, cumulative damage equivalent to that expected in the item's life for the type of expected stress. The determination of item destruct limits, without reliability estimation, provides information on whether there exists a sufficient margin between those destruct limits and item specification limits, thus providing assurance that the item will survive its predetermined life period without failure related to that specific stress type. This technique can, but not necessarily, quantify a probability of item survival for its life, and just provides assurance that the necessary adjustments in item strength would help eliminate such failure in item use. Where sufficient margins are determined unrelated to the probability of survival, the type of test is qualitative. In tests where this probability of survival is determined, the magnitude of the stress is correlated to the probability that the item would survive that stress type beyond the predetermined life, and this test type is quantitative.

Figure 1 depicts the principle of cumulative damage in both qualitative and quantitative accelerated tests.

In Figure 1, for simplicity, all stresses, operating limits, destruct limits, etc. are shown as absolute values. The specification values for an item are usually given in both extremes, upper and lower, thus the upper and lower (or low) specification limit, USL and LSL with the corresponding design limits (DSL), UDL and LDL, the upper and lower operating limits, UOL and LOL, and also the reliability test limits, URTL and LRTL. The rationale is that the opposite (negative stresses), can also cause cumulative damage probably with a different failure mechanism, thus the relationship between the expected and specified limits can be illustrated in the same manner as for the high or positive stress. As an example, cold temperature extremes can produce the same or different failure modes in an item. To avoid clutter, the positive and the negative thermal or any other stresses are not separately shown in Figure 1, thus the magnitudes of stresses are either positive or negative, and thus represented as absolute values only as upper or lower limits.



IEC

Figure 1 – Probability density functions (PDF) for cumulative damage, degradation, and test types

The graph in Figure 1 shows the required strength of an item regarding a stress for the duration of its life time, from beginning of life (e.g. time when the item is made), t_0 , through the end of life, t_L . The strength and stresses in tests are also assumed to have a Gaussian distribution.

The different types of accelerated tests can now be illustrated using Figure 1 as a conceptual model.

Functional testing is carried out within the range of the requirement specification and at the level of the specification. In this area no failures should occur during the test; design is validated to allow operation within the upper and lower specification limits. Accelerated testing of Types B and C (4.2.3 and 4.2.4), i.e. accelerated degradation testing (ADT) or cumulative damage testing can be illustrated as the distance between the design specification limit (DSL) and the level where the reliability demonstration test should be performed (RTL). When the degradation reduces the performance below the requirement specifications, the item can be declared as failed, if this behaviour is defined as a failure. When testing the item at time t_0 no failures should be expected for stress levels up to and including the design specification limit (DSL).

The item design specification should take into consideration certain degradation during the item's life which is resultant from the cumulative damage of the stresses expected in life, thus its limit is the design specification limit (DSL) which is higher than the requirement limit (RL) in order to provide the necessary margin. After item degradation resultant from the cumulative damage caused by expected stresses, the reliability test provides information on the existing margin between the test level (the remaining strength) and the requirement. This margin is a measure of reliability at the end of required period, t_L .

The ultimate strength of the design is considerably higher than the design specifications and this is the level determined in the qualitative accelerated test where the goal is to identify design weaknesses which can compromise item reliability, i.e. the weaknesses that can occur in the item's life span, as the item degrades. Thus, the strength in the qualitative test is demonstrated at operating limit (OL).

The destruct limit is above (beyond) the operating limit, and is denoted as DL. This is where a permanent failure is observed. If the OL or DL are close to the DSL or the standard deviation of the OL or DL distributions are high, then the test will indicate a potential weakness in the design as indicated in Figure 1.

Item reliability is a function of time, usually predetermined life time, t_L .

The cumulative normal distribution of the margin (difference of stress means divided by their common standard deviation) between the specified strength (use conditions) which is represented by the requirement and the reliability test level (RTL) determines item reliability. The test level and its duration are chosen so as to cause cumulative damage during testing corresponding to the degradation due to cumulative damage in the item's life span. The calculated value produces the item required reliability, which is then a quantitative measure.

A summary of listed tests and the mapping of their applications to the item life cycle is presented in Table 1.

Table 1 – Test types mapped to the item development cycle

Type	Design	Integration	Validation	Acceptance	Manufacturing	Services
A Qualitative	FMECA	HALT			HASS/HASA	
	Maturity Building		Maturity Confirmation			
B & C Quantitative			Reliability Growth Test	Reliability Qualification Test	Reliability Production Acceptance Test	
	Maturity Assessment					
Product Breakdown structure Opportunity	Type B/C : Component					
	Type A : Component	Type A : Assembly an/or Subsystem				
		Type B/C : Assembly	Type B/C : System			

Table 1 provides the users of this document a synthesis in order to get a better understanding of the different methods as and when required during the whole life cycle of the item.

4.2 Classification, methods and types of test acceleration

4.2.1 General

Based on the cumulative damage model, the information expected from the test and the item use assumptions, the accelerated test methods may be divided into three groups:

- Type A: qualitative accelerated tests: for detection of failure mode or phenomenon;
- Type B quantitative accelerated tests: for prediction of failure distribution in normal use;
- Type C: quantitative time and event compression tests: for prediction of failure distribution in normal use.

4.2.2 Type A: qualitative accelerated tests

Type A accelerated tests are designed to identify potential design weaknesses and also weaknesses caused by the manufacturing process. They can therefore be induced at levels considerably higher than OL, as shown in Figure 1. The goal of this type of test is not to quantify item reliability, but to induce or precipitate, during the test, the item's overall performance issues which are likely to take place in the field some time during the item's life time and result in an item failure. Improvement of the item design or manufacturing processes is executed to preclude those failures, producing a stronger or more robust item, expected to be more reliable in the field even under extreme or repetitive stresses as outlined in the design specifications.

Type A tests may be applied also to detect other weaknesses or latent failures not only for reliability but also for other dependability attributes.

Item development processes using this type of test increase item reliability through the mitigation of failure modes and by increasing item robustness without demonstrating a reliability target or measuring reliability improvement. These tests are often made with such high stress levels that, ideally, failures should be observed (DL in Figure 1) well beyond design specification limits. The purpose is to identify the failure modes, the weak links in the design and the margin between the functional limits, operating limit (OL) and the destruct limit (DL), as shown in Figure 1. The margin between the specification limit and the operating limit ensures that the weaknesses are identified in HALT (see 5.1.1) and are not expected to occur as failures during the expected item life, t_L .

NOTE Other tests of type A are marginal tests and overstress tests.

4.2.3 Type B: quantitative accelerated tests

Type B tests use cumulative damage methods to determine item reliability projected to the end of the expected item life. The necessary margin between the expected cumulative damage and the requirement produces a reliability measure. These tests are then accelerated to achieve the required cumulative damage in considerably shorter time than the item's expected life. Type B accelerated tests use quantifiable acceleration factors which are based on the physics of specific failures (or failure modes) and provide a relationship between the exposure time to the specific stresses during testing and in use environment. The failure, or failure mode distribution, is determined from information gathered through separate accelerated tests. Such test information provides the basis for a functional life model and can be used to quantify test acceleration for various reliability calculations, as necessary and applicable. In this way, item reliability can be estimated through estimation of the reliability or probability of occurrence of individual failure modes for any level of expected stresses. If necessary for data analysis using other test types (e.g. reliability growth or reliability demonstration tests), the determined test acceleration factor can be used to recalculate times to failure data from accelerated tests so as to represent times to failure occurrences in the use environment, and use the results for reliability calculations. In Figure 1, these tests are shown as reliability test levels (RTLs).

Another way of getting information from this type of test is to test to failure samples of items for the specific failure modes and the specific environments. This permits determination of applicable failure distributions and appropriate acceleration factors which can then be used for calculation of the probability of occurrence of the particular failure mode. This information can be useful for future tests as well as WeiBayes tests (1 parameter Weibull; see IEC 61649). The stress level of the Type B tests can be illustrated in Figure 1 as being higher than the requirement, but below the stress level that would be applied in HALT. The stress level can be between the design specification limit and the stress level of DL. The duration of the stress application shall be sufficient to cause cumulative damage with a margin over the cumulative damage produced by the expected life stresses during the item life.

Test time reduction is often achieved through an increase in operational or environmental stress beyond those specified for use. The increased level of these stresses produces a cumulative damage effect equivalent to that expected in the item life, but in a considerably reduced time period.

The accelerated degradation test (ADT) is a method where the degradation of an item is measured as a function of time or stress cycles. The degradation is plotted and extrapolated until the parameter reaches an unacceptable level (failure). This method is very useful for failures that are not sudden failures, but develop gradually. The stress levels applied in the test may be the nominal or worst case operating limits expected in the field use or the test may be accelerated by increasing test stresses as described in [1]¹.

4.2.4 Type C: quantitative time and event compressed tests

4.2.4.1 Use of Type C tests

Type C tests are mostly used for estimation of the life time of components where wear-out in active use is the dominating failure mode, for example switches, keyboards, relays, connectors or bearings. The data from these tests are often analysed using the Weibull distribution, and often in the form of the so-called "sudden death test" (see IEC 61649).

Type C time compression tests are also often used to identify:

- system integration issues (such as software and hardware integration or interaction);
- failure modes that are specific to the operating state, for example operating cycles for any mechanical and electrical cycling event;
- failure modes specific for environments where the range of stress is broad, but there is a threshold defined such that stress exposures below the threshold will not contribute significant damage to the item.

With the time compressions or event compression, the stress is accelerated by the duration or frequency of its application but not by the increase of its level.

Each of the above accelerated test methods is further described in Clause 5.

4.2.4.2 Time compression

Time compression is a test acceleration that can be applied in some circumstances, where the tests take into consideration only the time that an item is actually operational or operating in a state that produces significant damage (also known as removal of "non-damaging exposures"). The circumstances in which this type of acceleration may be applied are those where the operational stresses and their cumulative damage are significantly higher than those in other operational modes, for example non-operational or standby. To apply this rationale, the accumulated damage during the lower stress periods should be insignificant compared with the damage accumulated during the high stress periods, which physically will possibly not be easily justified (see IEC 60605-2).

4.2.4.3 Event compression

When a stress is repetitious, such as ON/OFF cycling, then the test can be accelerated by speeding up the repetition of stress (event compression). This is especially useful in cases where the test cannot be accelerated by increasing the stress level itself. In this manner, the number of operations remains the same as does the effect of the cumulative damage. Care should be taken that the higher repetition rate of the stress does not cause failure modes that would not occur in normal operation. Examples are self-heating in a plastic part, vibrations that do not dampen out before the next load and software sequences that do not finish before the next signal.

1 Numbers in square brackets refer to the Bibliography.

5 Accelerated test models

5.1 Type A, qualitative accelerated tests

5.1.1 Highly accelerated limit tests (HALT)

5.1.1.1 General

Each type of commonly applied accelerated test method is presented in this document with its advantages, disadvantages and necessary application cautions.

Type A tests are not only the classical HALT but there are also other highly accelerated test types such as the autoclave, thermal shock, marginal tests, over-stress tests and other quantitative accelerated tests (see JESD47B [2] and [3]).

NOTE 1 A classical HALT uses only thermal and vibrational stresses.

The model shown in Figure 1 illustrates the relationship between the specifications, the design limits and the test strategies of the HALT.

NOTE 2 The acronym HALT was inadvertently spelt out in the past as highly accelerated *life* test. By its nature of being a qualitative accelerated test, however, HALT does not measure the life of an item, even though the term "life" is implied by ensuring that the failures in HALT would not be experienced in the life of the tested item. The test effectively tests the strength limits of an item, thus the word "limit" is appropriately used in the spelt-out acronym.

When reliability demonstration or reliability growth tests are accelerated, there is a need to demonstrate a margin between the cumulative damage induced by the applied stresses during testing and the cumulative damages caused by stresses expected to take place during the life, or any other predetermined time for which reliability is to be demonstrated. The favourable test results for the applied margins provide information on item reliability in that predetermined time as expressed by strength versus stress criteria. Demonstrated strength is shown through the test results, while reliability is the complement of the area common to both, load and strength curves, shown in Figure 2 (the area common to both stress and strength distributions are associated with the probability of failure of the item; the larger this area, the greater the probability of failure will be).

In Figure 1 the requirement specifications are translated into design specifications. The figure further illustrates how the design margin is verified by the HALT.

In order to estimate the margin between the design specifications and the unit under test (UUT) it is necessary to increase the stress levels until failure occurs during Type A tests. The margins verified in these tests are illustrated by a HALT operating stress limit (OL), as well as a destruct limit (DL). This also indicates the margins for the variations in the materials and manufacturing processes during manufacturing.

5.1.1.2 Main principles of HALT

The methodology of HALT is to quickly precipitate failures to identify and mitigate design weaknesses in an item in order to increase robustness during the item field use. This type of accelerated test is not intended to measure, but to increase item reliability through the elimination of failure modes with the lowest margin between the field stress (load) and item strength (Figure 2 and Figure 3). This type of accelerated test only identifies potential failure modes and guides the development and improvement processes for the chosen stressors. It is from the experience of HALT that most products are very robust for the applied stresses, but that a few components or design details are significantly weaker than the rest. The idea of a HALT is to find those few components or design details and make them as strong as the rest of the item.

Figure 2 illustrates the interference between the strength and stress distribution. It is assumed that the stresses in the field from different applications, climatic conditions, etc. can be modelled by a load distribution. It is shown here as a normal distribution. The strength of the items will vary due to variations in raw materials and manufacturing processes. This can be modelled by a strength distribution which in Figure 2 is also shown as a normal distribution.

The area common to both load and strength distribution is associated with the probability of item failure. The larger this area, the greater the probability of failure will be. The graph in Figure 2 shows the classical design margin, stress versus strength criteria, but in the context shown in 5.1.1.2, it does not account for the cumulative damage model; therefore, it is applicable to the initial short duration test that would measure the ultimate strength of the item design. Also, if the extensive item quality control maintains a very narrow strength distribution (which can be a very expensive and time consuming measure), then the distributions would not overlap, meaning that the field failures for the specific failure mode would be unlikely.

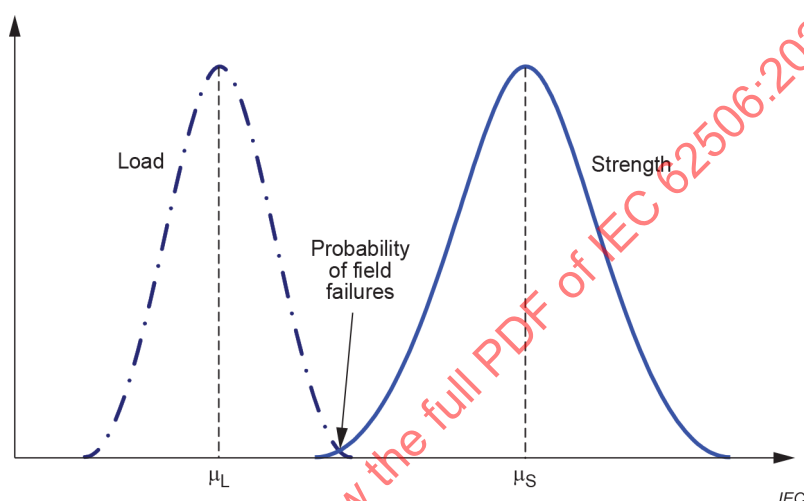


Figure 2 – Relationship of PDFs of the item strength versus load in use

Figure 3 illustrates the importance of design margins. The design margin not only have to cover the reduction in strength due to ageing, wear and fatigue, it also has to cover the variations in strength caused by the raw materials, components and manufacturing and assembly processes. Figure 3 a) illustrates a case of insufficient design margin, Figure 3 b) a case with sufficient design margin. The load curve illustrates the loads used during testing, representing the loads in the field. The strength curve is a PDF curve that covers all produced items from early test samples to mass produced items. The test samples are often manufactured in a special prototype test laboratory with optimum manufacturing conditions and maximum management attention. They are therefore typical of average strength or better (light blue circles). Later when the items are mass produced variations in strength from raw materials, components and manufacturing processes often cause the produced items to be of lower strength (the left "tail" of the strength distribution – the dark blue circles). When looking at the acceptance test of the design in Figure 3 a) the test level is H1 – the maximum stress expected in the field. The test samples (light blue circles) pass this test and the design is approved. However, once the mass production starts, some items in the left tail of the strength distribution (dark blue circles) are produced, and some of these cause failures in the field. In Figure 3 b) a HALT test is made on the design. Once the design survives the stress level H1 the stress is increased to H2, H3 and H4. In Figure 3 a) failure would be seen already at H2, had a HALT test been made, but in Figure 3 b) no failures are seen even at stress level H4. The conclusion is therefore that the design in Figure 3 b) has a sufficient margin, while the design in Figure 3 a) has an insufficient margin. This would not have been detected if a HALT test had not been made.

This is the rationale behind the application of tests such as step-stress tests and HALT, to ensure an appropriate margin over the expected stresses in life. In this way, these tests can be performed on a considerably smaller number of test samples than needed for conventional testing.

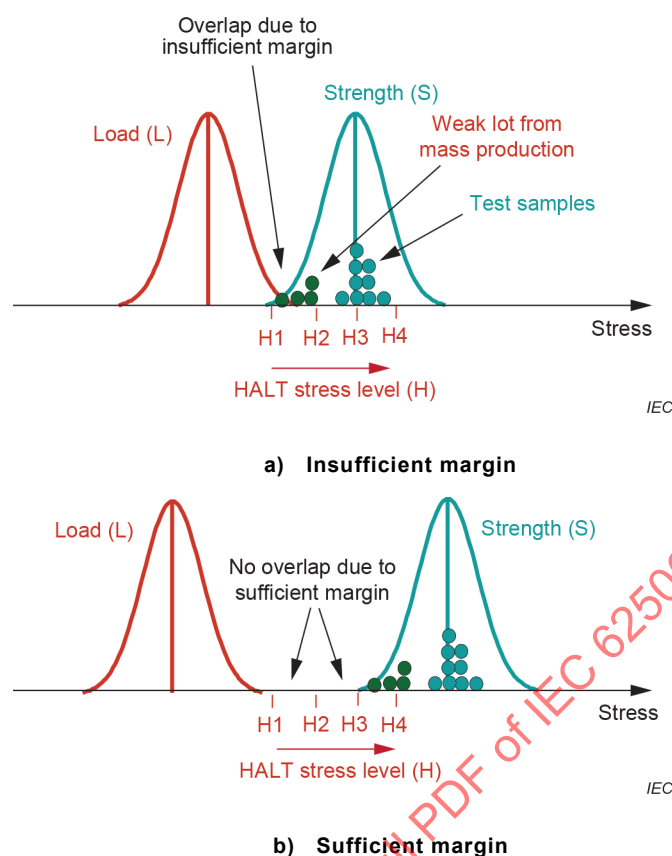


Figure 3 – How HALT tests detect the design margin

HALT is an explorative, qualitative design improvement test and should be accepted as such. It identifies the weakest link failure mode in the design for the related stress type(s). If this failure mode is related to the stress in the item use environment, the stress levels can only be estimated by an engineering judgement, considering the margin between the load and strength curves and including the additional margin for the expected variations in both the manufacturing process and the expected use environment. The comparison between HALT and a conventional accelerated test is illustrated in Table A.1. A step by step procedure can be found in Clause A.2 and examples in Table A.2, Table A.3 and Table A.4.

With the weakest link failing first, HALT is applied further to detect the second, third, and other consecutive weak links. This takes place until no more relevant failure modes are observed or until the technological limits of the tested system are reached.

HALT is designed to far exceed the item use environment as well as the design specifications. The stresses are applied in short durations, and the goal is to precipitate transition of faults into failures, and strengthen the item as much as it is economically and technically feasible. HALT identifies failure modes, but not their time dependency.

The UUT shall be functionally monitored during the test in order to detect the loss of its functions. If continuous monitoring is not possible, the item functions have to be tested while the stress level is kept constant. A typical procedure for a HALT is shown in Annex A.

The stress magnitude is not the focus of HALT; the real focus of an effective HALT programme is on item improvement activities and organizational response to failures. The item improvement should be continued to the point of a cost-effective rugged item where no part of the design is significantly weaker than the rest of the item. The goal is to keep improving the item to the level justified by the business case and utilization of cost-effective technology.

The operating and destruct limits for the item can be pictured as distributions on a stress axis, as illustrated in Figure 4, for both stress extremes, high and low (LOL, UOL, LDL, and UDL).

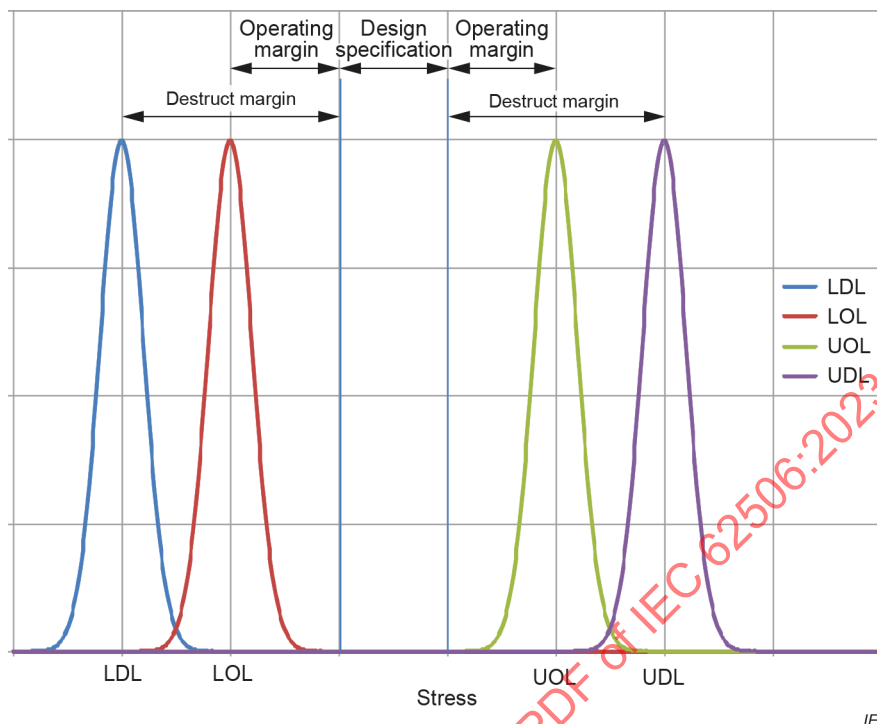


Figure 4 – PDFs of operating and destruct limits as a function of applied stress

Figure 4 is an example where both limits of the stress affect an item. This example can be the thermal stress where both, high and low temperatures, affect the performance of the item. It is possible that these effects will not be symmetrical, as the limits for high and low temperatures can be at a different distance from the nominal design stress. Even though these tests are performed on early prototypes they can provide information on design related failure modes. As shown in Figure 4, all of these limits can vary as indicated by the distributions. These distributions may have different standard deviations, and to determine HALT is to give an indication of the margins that allows the final item to accommodate these variations without failures in the field.

Even though Figure 4 depicts the temperature stress, other stresses may also be successfully applied in a HALT. In the case of other stress types, it is possible that lower limits will not exist as for example is the case for mechanical stresses, but they can exist with other stresses such as electrical stress and humidity.

5.1.1.3 Stress types and application

The primary or typically applied stresses in HALT are as follows:

- temperature;
- thermal cycling;
- vibration or shock;
- voltage;
- combination of vibration or shock and thermal cycling.

Other item-specific stresses can also be applied such as clock frequency for the microprocessor, voltage or power variations, contaminants or solvents, or a combination of these [3].

Verification of margins and item improvements made in response to HALT serve to increase the likelihood that the item will be robust and reliable in the field.

An example of typical stress levels is shown in Annex A. Ideally, the HALT stresses are applied as described in 5.1.1.2 until the predetermined maximum stresses are achieved. These maximum stresses are determined as follows:

- by the material limits and technological limits of the used materials and components;
- by the maximum stress achievable with the available methods and equipment.

It should be noted that the applied stress levels should not exceed the ultimate material limits where the physical or chemical characteristics can change.

It is normal to expect that there are some fragile elements in the UUT that are not designed for the stress levels normally applied in HALT. Those fragile elements should if possible be protected during HALT or disregarded in the test data evaluation. Fragile elements may be protected for example by applying cooling air to them, by isolating them against cold air, by suspending them outside the UUT in order to isolate them from vibration and shock or even by moving them outside the HALT test chamber and extending their connections to the rest of the UUT. Fragile elements that have been protected during the HALT test then have to be tested by a separate test for example a component test or a survival test.

Each failure observed during the HALT should be investigated and root cause failure analysis should be performed (see IEC 62740 [4]). If the identified failure mode is likely to occur in the field where the stress level is expected to be considerably lower than in a HALT, a corrective action should be proposed and implemented in accordance with engineering as well as management decisions.

5.1.2 Highly accelerated stress test (HAST)

This type of testing may be considered to be a cross between the qualitative, Type A, and quantitative, Type B, tests. This test type is very popular in the electronic components industry where it is widely used as a more efficient (shorter) alternative to the much longer temperature humidity bias test (THB), i.e. a pressure cooker test, which has a duration of 1 000 h. The stresses in these tests consist usually of temperature and humidity where corrosion of vias (metal conductors) in dies and thin film resistors can occur. The components are normally voltage biased during the test. Even though these tests do not yield numerical reliability estimates, they are used as effective re-qualification tests to provide certainty that reliability of the components is not compromised by any changes introduced in the components, see JESD22-A110 [5]. The duration of a HAST in the electronic component industry is usually about 100 h, and the stress levels for temperature and humidity are usually 130 °C and 85 % RH, respectively.

5.1.3 Highly accelerated stress screening or audit (HASS or HASA)

5.1.3.1 Applicability and principle of HASS or HASA

HASS and HASA are not classified as tests. Yet, both are included in this document because they apply accelerated stress for defect detection or screening. HASS is used for screening of production units using stresses considerably higher than those expected in normal use or in shipping, but with lower levels than those that can significantly reduce item life in the field. These levels are determined based on the finding from the HALT programme. The screening may be performed on all (100 %) production units or on a sample. The purpose of screening is to detect any latent manufacturing defects that would eventually appear in the normal use of the item. Detection of latent defects, followed by failure analysis and necessary corrective action (verified through a test designed to detect the specific failure mode), reduces the number of faults. The resulting field reliability improvement is due to the reduction in the number of field components with latent manufacturing defects and not due to a change in the inherent design reliability. HASS is ideally suited to pilot production or production ramp-up, i.e. when production rate is slow and 100 % screening can easily be accomplished. HASS may continue during normal production for very critical items that are manufactured in small volumes.

The stress levels in HASS or HASA are used for defect precipitation screening. The precipitation screen consists of combined stresses with their levels barely inside the operational limits. The purpose of this screen is to precipitate manufacturing defects into intermittent or permanent failures. To detect the failures, it is recommended to monitor the functions of the UUTs during screening as it is possible that some operational abnormalities will not be discovered in the post test operational checks. Further, it is not known when, during the precipitation screening, the possibly intermittent functional failure can be detected. The precipitation screen may combine several different stress types and stress levels. As with HALT, intermittent failures can be verified by using a detection screen (see Clause A.2, Step 4). Constant monitoring should provide functional coverage that is as complete as possible. Coverage and effectiveness of the monitoring should be optimized prior to beginning of the screen development process. The monitoring process should facilitate root cause analysis.

A typical precipitation screen itself will require a relatively short stress application time such as from 3 min to 1 h of stress. Additional time will be required for the test and monitoring equipment set-up.

HASA is a process monitoring tool where a sample from a production lot is exposed to the precipitation screen to detect possible defects. HASA is often performed before the production lot is released. HASA often supplants HASS when the manufacturing process reaches its maturity. HASA is further reduced and even eliminated when the effectiveness of production controls is established.

5.1.3.2 Selection of stresses and their magnitudes

Stresses should be selected so as not to compromise functionality, material properties, or the life of non defective hardware. The initial levels are determined from information gained in HALT.

The precipitation screen is performed with stress levels a little lower than the operating limits since the UUT have to be monitored for function during screening. Typically, the temperature stress is reduced by 5 °C and the vibration level by 2 g RMS (19,62 m/s²). Before the precipitation screen is used for HASS or HASA it should be verified that the precipitation screen does not significantly reduce the item life in the field. This can be tested, for example, by exposing one sample to the precipitation screen 10 times.

5.1.4 Engineering aspects of HALT and HASS

5.1.4.1 Advantages of HALT and HASS

The advantages of HALT and HASS are as follows:

- verified and selectively increased design margins for reliability improvement;
- sample size for determination of a specific failure mode is small;
- quick determination of dominant failure modes for specific stressors and easily combined stresses (the duration of the test is typically three days);
- efficient trade-off analysis information and determination of necessary corrective actions;
- quick verification of corrective actions;
- efficient short-term production screening;
- elimination of weak or defective components (HASS) from the main population (quality and reliability improvement).

5.1.4.2 Disadvantages of HALT and HASS

The disadvantages of HALT and HASS are as follows:

- a) possibility of stimulating failure modes that would not normally be observed in item use;
- b) potential for over-improvement of design margin (over-design);
- c) resultant reliability not known;
- d) no statistical confidence in the test result (over- or under-estimation of the design margins);
- e) testing does not address all interactive effects of multiple failure modes;
- f) impractical for very large items, very small items and items with diverse fragility;
- g) limited number of stress types (primarily temperature, vibration, shock and thermal cycling);
- h) inability to evaluate the design limits for a stress influenced by synergy with other stress types not provided by the HALT types.

5.2 Types B and C – Quantitative accelerated test methods

5.2.1 Purpose of quantitative accelerated testing

The purpose of quantitative accelerated tests is to estimate one or more measures of reliability, for example failure rate, probability of failure or survival, or time to failure (TTF). Often the purpose of quantitative accelerated testing is to determine the life time of components with a limited life (wear-out), or to determine (quantify) and improve the reliability of systems and components. For this, Weibull analysis is very useful (see IEC 61649).

5.2.2 Physical basis for the quantitative accelerated Type B test methods

5.2.2.1 General

The goal of Type B accelerated testing is to measure the reliability and verify acceptable reliability performance of the item within a short period of time. Thus, the goal in accelerated testing is to accelerate the damage accumulation rate for relevant repetitive stress and wear-out failure mechanisms (a relevant failure mechanism is one that is expected to occur under life-cycle conditions).

In order to accelerate tests, it is necessary to have a thorough understanding of the potential failure mechanisms and the operational and environmental stresses of the item or system. This can also be achieved through failure mode analysis of the designed item associated with the intended item usage profile, for example using an FMEA (see IEC 60812 [6]). Effective measures can then be taken not only to prevent their manifestation under predetermined life or usage stresses, but also to precipitate them effectively during accelerated testing for item improvement. Accelerated wear-out or reliability testing has been recognized to be a valuable activity to assess the reliability of high reliability electronics, electro-mechanical and mechanical systems. The application of elevated stresses is usually for the purpose of:

- a) making the design more robust and improving the manufacturing process through systematic step-stress testing and increasing the stress margins through corrective actions (reliability growth testing);
- b) conducting accelerated life tests in the laboratory to measure and verify in-service reliability.

The extent of acceleration, usually termed the acceleration factor (AF), is defined as the ratio of the life under use conditions to that under the accelerated test conditions. This acceleration factor is needed to quantitatively extrapolate reliability measures (such as time-to-failure and failure rates) from the accelerated test environment to the usage environment, with some reasonable degree of confidence. The acceleration factor depends on hardware parameters (e.g. material properties, item architecture) of the UUT, usage stress conditions, accelerated stress test conditions and the relevant failure mechanism. Thus, each relevant failure mode (assuming it is a result of one failure mechanism) in the UUT has its own acceleration factor and the test conditions (e.g. duty cycle, stress level, stress history, test duration) shall be tailored based on these acceleration factors.

The physics of failure approach means that each failure mode is addressed separately and the margin to the life time or to the required reliability is verified for each of them. With this approach, each of the failure modes has its own failure distribution and failure rate. In other cases, the result is combined to an estimated reliability for the whole item.

When planning a test the potential failure modes in the item should be listed. The test is then planned with stress levels and durations so that the failure modes should be observed in the test if they are present in the item. For this planning, empirical factors from previous items, from the component suppliers or from literature, can be used to estimate the acceleration factor of the test. After the test is performed the actual failure modes are known, and the test can be analysed for each failure mode separately. It is recommended to use a test set-up where the empirical factors can be estimated from the test itself. See Annex E and Annex F.

Type B tests can be run by increasing the level of a variety of loads such as thermal loads (e.g. temperature, temperature cycling, and rates of temperature change), chemical loads (e.g. humidity, corrosive chemicals like acids and salt), electrical loads (e.g. steady-state or transient voltage, current, power), and mechanical loads (e.g. quasi-static cyclic mechanical deformations, vibration, and shock impulse or impact). The accelerated test environment may include a combination of these loads. Interpretation of results for combined loads and extrapolation of the results to the life-cycle conditions requires a quantitative understanding of the relative interactions of the different test stresses and the contribution of each stress type to the overall damage.

5.2.2.2 Advantages of the Type B test

The acceleration stress test provides quantitative information on the reliability of the tested item:

- this test type can be designed
 - for selected failure modes (e.g. from FMEA) to assess, with reasonable confidence, overall reliability;
 - for combined stresses also to simulate the interactive effects of those stresses and a realistic assessment of the item reliability;

- an acceleration test can be effectively carried out to enable the test to represent cumulative damage in use.

5.2.2.3 Disadvantages of the Type B test

- A risk that the stress acceleration can exceed the physical properties of item materials and cause unforeseen damage.
- A risk that the acceleration of combined stresses can cause additional unforeseen damage to the item that would not have happened in actual use.
- The base line for accelerated testing is not a single stress but is generally a multiple stress that varies with user and location. It is necessary to take this into consideration when quantifying the results.

5.2.3 Type C tests, time (C₁) and event (C₂) compression

5.2.3.1 Type C₁ tests

5.2.3.1.1 General

Time compression is achieved by eliminating "OFF-time" (e.g. non-operating time or time with low stress levels) by compressing the duty cycle through addressing just the ON time. Furthermore, when items are exposed to a wide range of stresses, it is typical that the highest stresses (the primary stresses) will induce the most damage, and that there are some levels of usage stress that, compared to the primary stresses, are assumed to produce negligible damage. Any exposure below a chosen damage threshold stress can be assumed to produce negligible damage and can be eliminated from the test programme. This is particularly true for mechanical fatigue and is often applied in accelerated structural fatigue testing (see IEC 60605-2).

An example of duty cycle compression is when the test duration is 24 h per day, whereas the item in its actual use environment operates for only 8 h per day. This results in a time compression factor of 3. Each day of test time is equal to three days of actual use time.

5.2.3.1.2 Advantages of time compressed tests

Items with a minimal or short operating use time compared with calendar time can be tested within a very reasonable test time relative to its required life (e.g. office equipment, cars, harvesting machinery). For example, a snow plough is used only in one season, once a year, and only when there is a reasonable accumulation of snow to justify its use. Even when used, it is expected to be on for 2 h to 3 h on average. There are several primary damaging stresses such as vibration, stress in the motor, wear-out of blades. For the rest of the year, it is stored in a shed, and protected from extreme weather conditions. Thus a snow plough that has a required life of ten years, but effectively is used four times a month for three months, for durations of 2 h, can be tested for a required usage duration of 240 h. Therefore, a test of approximately 300 h would provide a good margin to prove the snow plough's reliability.

With a relatively short test duration at nominal stresses, there is no reason to increase the stresses, and therefore, there is no need to determine stress acceleration factors; otherwise there is a risk of overstressing the UUT.

5.2.3.1.3 Disadvantages of time compressed tests

Concentration exclusively on operational time means considering the operational environment only with its associated failure modes, while the failure modes occurring in the "non-operational" environments may be neglected. Such failure modes can even be more damaging to the item, since they are a result of stresses that are perhaps considerably lower than those when the item is in use, but are applied for a considerably longer time to produce the same or greater cumulative damage than the stresses applied in use.

Considering the same example of the snow plough, there are 87 600 h in its ten-year lifespan when the snow plough is exposed to extreme cold temperature for approximately 20 000 h, leading to the failure mode of embrittlement of materials; very high temperatures for approximately 6 000 h, leading to ageing of plastic parts, paint, adhesives, thermal cycling; approximately 7 200 cycles causing multiple structural damage; and humidity, applied for a minimum of 30 000 h per year, causing corrosion. Testing only under operational conditions would disregard the influence of non-operating environments.

For items where active time is considerably shorter than the passive (OFF time), it is necessary to combine time accelerated testing for the operational periods with tests that accelerate the passive periods, for example corrosion tests, humidity tests. In some cases the item can be preconditioned before the time compressed tests by applying some stresses from the passive periods, for example moisture, cold storage, solar radiation or mechanical loads like vibrations and shocks simulating the non-operating conditions. The purpose of such preconditioning is to simulate the inter-relationship of the failure modes of active use with the failure modes expected in storage, which in turn highly affect the failure modes in use. As an example, corrosion of the snow plough would highly affect the influence of applied vibrations on the item structure.

5.2.3.2 Type C₂ tests

5.2.3.2.1 General

The event compression tests apply repetitions of events with considerably higher rates than those applied in actual item use. As an example, the ON/OFF cycling of the above-mentioned unit (the snow plough) can be compressed to a test of several hours, by applying the ON/OFF cycling repeatedly. Therefore, the 120 required ON/OFF cycles in the 10-year life with a sufficient margin to demonstrate reliability would be a very short test.

Type C₂ tests can be combined with the time compression tests for further test acceleration. This can result in a very short test with "high reliability" demonstration, however, several important precautions shall be taken when carrying out this combined acceleration. For example, the rapid application of repetitious stresses can influence test results by varying cumulative damage.

The event compression tests may also be combined with the stress acceleration tests to further shorten the test time. Caution should be exercised when preparing such tests, as the time compression can influence the stress acceleration. For example, fast ON/OFF cycling results in a very short time in the OFF condition, which does not then allow the UUT to properly cool down. This can then result in additional thermal acceleration of the UUT's degradation and precipitation of failures. Also, this type of acceleration can neglect the failures due to non-use, such as material deterioration.

5.2.3.2.2 Advantages of the Type C₂ test

The advantage of the Type C₂ test is that in a short time, by speeding up the stress repetition, the cumulative damage can be reproduced within a much shorter time than in regular use.

5.2.3.2.3 Disadvantages of the Type C₂ test

This type of testing can also produce some negative effects by applying continuous stress and in a manner that precipitates failures that normally would not occur. For example, in mechanical parts with a wear-out mechanism induced by friction during operation, continuous friction can produce heat that would further precipitate a failure that would normally be delayed by periods of cooling. Another example can be the metal fatigue caused by stress repetition, if applied without allowing time for the material relaxation.

5.3 Failure mechanisms and test design

The importance of correct failure analysis shall be strongly emphasized. Understanding the failure mechanisms is essential for designing and conducting successful accelerated life test or other test as advocated in physics-of-failure based reliability design and prediction methodologies (provided that the predictions are done using the physics of failure approach). To achieve this, a rational method shall be identified to relate the results of accelerated tests quantitatively to the reliability or failure rates in use conditions, using a scientific acceleration transform. The amount of test-time compression achieved in an accelerated test need to be determined quantitatively, based on the physics of the relevant failure modes. Accelerated life tests attempt to reduce the time it takes to observe failures. In some cases, it is possible to do this without actually changing the equation for the instantaneous failure rate. However, if the hazard function changes, it is termed a "proportional hazard model." Mathematically, the differences between these two can be seen in the following two equations for a Weibull distribution in which $H_{AL}(t)$ is the cumulative hazard function for accelerated life, $H_{PH}(t)$ is the cumulative hazard function for the proportional hazard model, AF is an acceleration factor due to some sort of stimulus and $(t/\eta)^\beta$ is the unmodified cumulative hazard for a Weibull distribution (t = time, η = characteristic life and β = shape parameter).

$$H_{AL}(t) = \left(\frac{AF \times t}{\eta} \right)^\beta \quad (1)$$

$$H_{PH}(t) = AF \times \left(\frac{t}{\eta} \right)^\beta \quad (2)$$

In $H_{AL}(t)$, there is a linear relationship between time and the acceleration factor. In $H_{PH}(t)$, the hazard function itself is being modified. By rearranging the equation for $H_{PH}(t)$, it can be seen that there is a non-linear relation between time and acceleration factor. The difference between these two types of accelerated tests is that $H_{AL}(t)$, requires knowledge only of the ratio of the actual test time to calendar time (non-accelerated time) caused by the applied environmental stimulus whereas $H_{PH}(t)$, requires knowledge of how the AF changes as a function of the parameter β . For the Weibull distribution, of which the exponential distribution is a special case, the resultant distribution for either of these two conditions is still a Weibull distribution.

Equation (1) is usually applied when the acceleration is made with the increased repetition rate of the applied repetitious stress such as operational cycling. Equation (2) is preferred when the acceleration is applied to the physical states of the unit under test such as thermal acceleration, where the acceleration factor itself depends on the distribution.

To summarize the above rationale, it can be said that the stress acceleration provides reduction in time to failure by increasing the stress levels beyond those expected in the normal use of the item.

5.4 Determination of stress levels, profiles and combinations in use and test – Stress modelling

5.4.1 General

It is equally important to understand the operational and environmental stresses that generate the failure mode based on physics of failure. This stress modelling serves as the base point from which acceleration occurs. How this baseline is handled is extremely important when the stresses will vary depending on item use.

5.4.2 Step-by-step procedure

The following procedure is applicable:

- a) identify the relevant stress factors from the field, including storage and transportation (see the IEC 60721 series);
- b) determine which stress types that will be accelerated, which will be nominal and which can be omitted, for example because they are covered by other tests;
- c) determine if the stresses can be applied simultaneously to include stress interactions or whether they will have to be applied sequentially, for example in a test cycle (see IEC 60605-2);
- d) determine if the acceleration factor (AF) can be estimated from the test or estimate the acceleration factors based on relevant acceleration equations and relevant empirical factors;
- e) determine the sample size (see IEC 61649, IEC 61123 and IEC 61124);
- f) perform the test (see IEC 60300-3-5);
- g) perform failure analysis;
- h) analyse the test – each failure mode separately (see IEC 61649, IEC 61710 and IEC 61124);
- i) report test result (see IEC 60300-3-5).

5.5 Multiple stress acceleration methodology – Type B tests

In cases where two or more stresses are the cause of reactions affecting the component or item life (reliability), the test acceleration is made by increasing each individual stress using models appropriate for those stresses. In these cases, failure rates representing each of the failure mechanisms are individually accelerated and the overall reliability (R) or failure probability (F) should be estimated separately. This can generally be expressed as follows:

$$R = \prod_{i=1}^{N_S} R_i \quad (3)$$

where

R_i represents the influence of a stress i on the reliability of the UUT when stresses are independent;

R represents the reliability of the UUT;

N_S is the total number of independent stresses.

The specific case of competing risks is described in IEC 61649:2008, Annex G.

If the time to failure of all the components or items can be modelled by the exponential distribution this can be simplified as follows:

$$AF \times \lambda_{\text{item}} = \sum_{i=1}^{N_S} AF_i \times \lambda_{\text{item}} (\text{Stress}) \quad (4)$$

In the case of Weibull distribution where all of the failure modes distributions have the same shape parameter, the scale parameter of an item under combined stresses is as follows:

$$\frac{1}{\eta_{\text{Item}}^{\beta}(\text{Stress})} = \frac{1}{\eta_U^{\beta}} + \sum_{i=1}^{N_S} \frac{1}{\eta_i^{\beta}(\text{Stress})} \quad (5)$$

where

- β is the shape parameter of the Weibull distribution;
- η_{Item} is the item scale parameter for the combined individual stress;
- η_U is the base scale parameter;
- η_i are the individual stress scale parameters.

For different shape parameters, the resultant distribution can be different to Weibull and the complexity of the relationships increases beyond the scope of this document.

It is to be noted that the Weibull rationale may be used only when accelerating single failure modes because it expresses dependency of times to failure, as Weibull modelling is not applicable to the mix of different failure modes. Times to failure are not related in the case of different failure modes, not even if applied to a single component.

Equation (4) presents a rather accurate way of expressing the overall item failure rate with applied stresses. It assumes that the part or component failure rate is a sum of a basic failure rate, resultant from undetermined failure modes related to the part inherent defects, and of failure rates attributed to the failure modes sensitive to particular stresses and accelerated by them. Then, failure rates representing individual stresses can be determined by separate stress tests. Individual stress accelerations then apply to each of these stress-relevant failure modes.

If each stress type accelerates one and only one failure mode, the acceleration factor will influence each failure mode separately. With the assumption that the exponential distribution is applicable, which is often the case when assemblies and systems are tested for multiple different failure modes, the item failure rate as accelerated is:

$$AF \times \lambda_{\text{Item}} = \sum_{i=1}^{N_S} AF_i \times \lambda_{\text{Item}}(\text{Stress}) \quad (6)$$

Having in mind that more than one stress can accelerate the same failure mode, the test acceleration from Equation (6) becomes Equation (7):

$$\lambda_A = AF_{\text{Test}} \times \lambda_0 = \sum_{i=1}^{N_S} \left(\left(\prod_k AF_k \right)_i \times \lambda_i \right) \quad (7)$$

where

- λ_0 is the failure rate that the item has in its use conditions;
- λ_A is the accelerated test failure rate;

$\left(\prod_k AF_k\right)_i$	is the product of acceleration factors of stress, i , affecting the failure mode k ;
λ_i	is the failure rate of the item corresponding to the specific stress;
N_S	is the number of stresses;
AF_{Test}	is the acceleration factor of the failure rate of the item in use conditions to produce the overall accelerated, test failure rate.

$$AF_{\text{Test}} = \frac{\sum_{i=1}^{N_S} \left(\left(\prod_k AF_k \right)_i \times \lambda_i \right)}{\lambda_0} \quad (8)$$

If the failure rate λ_i is defined in terms of reliability at a predefined time t_1 , $R_i(t_1)$ then the test acceleration is:

$$AF_{\text{Test}} = \frac{\sum_{i=1}^{N_S} \left(\left(\prod_k AF_k \right)_i \times \left[-\frac{\ln(R_i(t_1))}{t_1} \right] \right)}{\lambda_0} \quad (9)$$

If all stresses influence all failure modes, the resulting acceleration factors (AF_i) can be multiplied. Then the easier or simpler way of calculating the total part failure rate can be in a form of its base failure rate modified by multiple compounded environmental stresses:

$$\lambda_{\text{Item}}(\text{Stress}) = \lambda_0 \times \prod_{i=1}^{N_S} AF_i \quad (10)$$

Equation (10), although widely used in the industry, assumes that each applied stress accelerates the base failure rate, and the next applied stress accelerates the total failure rate accelerated by the previous stress, and so on. This simplistic approach can lead to overestimation of effects of multiple stresses, as the failure mechanisms are different, and some are not accelerated by all of the stresses.

The result of overestimation of acceleration is the overestimation of the probability of failure or leads to tests that are unreasonably short and inadequate.

The best way to calculate realistic test acceleration is to investigate what stresses do influence the same failure modes in which case they can be multiplied.

5.6 Single and multiple stress acceleration for Type B tests

5.6.1 Single stress acceleration methodology

5.6.1.1 General

With this methodology, test acceleration is accomplished with a single stress only. These models are life stress models, where the damage per unit time of test is appropriately accelerated by increasing the level of stress.

The three most frequently used relationships are:

- inverse power law model, used for test acceleration when stresses other than constant temperature are considered, such as electrical, mechanical, chemical (corrosion);
- Arrhenius reaction rate model, used for constant temperature stresses, based on the effect that the absolute temperature has on a failure mechanism;
- Eyring model which is used in cases where the acceleration is achieved with temperature and moisture stress levels.

With all acceleration models, test data can be analysed using established analytical models to determine characteristic accelerated life parameters. Using the acceleration factors, the parameters corresponding to use environments are determined and used for reliability projections as necessary. The acceleration models should, if possible, be verified by plotting the test data.

5.6.1.2 Inverse power law

5.6.1.2.1 General

The inverse power law is applicable to:

- dynamic stresses such as shock (any pulse type) and vibration (sinusoidal and random);
- climatic stresses such as thermal cycling, temperature changes (shock and thermal cycling), humidity, solar radiation, or any other climatic stresses with cumulative damage.

The inverse power law model [7] is very simple to understand and use, and is very easily adaptable to any failure distribution. Graphical solutions (best fit by eye) are possible, and the parameters can also be determined using maximum likelihood methodology.

With the inverse power law, the characteristic that represents item reliability related to time, such as characteristic life, mean life, mean time to a failure, is represented as:

$$L(S) = C^{-1} \times S^{-m} \quad (11)$$

where

S is the stress;

C is the constant (> 0) to be determined;

m is the parameter dependent on stress behaviour, also to be determined;

$L(S)$ is the life or other predetermined time duration as a function of stress.

The power law model is simple when expressed or plotted in logarithmic form, where it becomes a straight line with the slope representing the value of parameter m , and the value of the intercept with the y-axis is a function of the constant C :

$$\ln[L(S)] = -m \times \ln(S) - \ln(C) \quad (12)$$

The inverse power law is applicable to all distributions regularly used in reliability.

The test acceleration factor is then:

$$AL_{S_{IPL}} = \frac{L(S_{Use})}{L(S_{Test})} = \frac{C^{-1} \times S_{Use}^{-m}}{C^{-1} \times S_{Test}^{-m}} = \left(\frac{S_{Test}}{S_{Use}} \right)^m \quad (13)$$

where

- $AL_{S_{IPL}}$ is the acceleration of stress by inverse power law;
- $L(S_{Use})$ is the life as a function of stress in actual use;
- $L(S_{Test})$ is the life as a function of stress applied in test.

In the Equation (13) the subscripts "Test" and "Use" denote accelerated test condition and non-accelerated use condition, respectively.

Parameter C in the test acceleration cancels out, but the parameter m shall be determined for the item and the stress type.

If not readily known, the parameter m can be determined through tests performed on the same component or item at various stress levels to failure (Annex E and Annex F). The test data is analysed then to determine the distribution and the distribution parameters. The parameter of that distribution that corresponds to the life is then plotted as a function of stress in log-log coordinates, and the slope of the straight line determines the value of the parameter m while the negative intercept will produce the value of the constant C .

This process that appears easy when described can become a very tedious process for items that are more complex than a single component, as the test can involve long periods of time and a large number of samples. However, using test acceleration factors that are loosely estimated can lead to large errors in design of accelerated tests.

When extrapolating the stress-life curve well beyond the test points the predicted stress life curve can represent a more conservative estimate of life since the actual stress-life curve for the specific failure mode can exhibit a lower slope.

The inverse power law is usually applicable to thermal shock, electrical and mechanical stresses (static and dynamic) and to humidity.

When accelerating a component life test with a specific stress, failures should be understood and grouped together for the same failure modes to ensure that the applied stresses are generating the same failure mechanism. For example, an accelerated test of a chip ceramic capacitor with nickel electrodes by voltage increase can exhibit two different failure mechanisms: dielectric breakdown, and movement of oxygen vacancies, both resulting in shorting of the capacitor. The two can appear as the same failure mode as the two mechanisms would not be distinguished if the failures were not analysed. One of the indicators of presence of two different failure mechanisms can be a resultant bimodal Weibull distribution (see IEC 61649).

Confidence limits on parameters, life functions and reliability for each of the distributions can be determined with appropriate statistics, as described in for example IEC 61649. Care should be exercised when applying statistical limits for the stress-life curve as, due to small sample size, the resultant extrapolated stress-life curve can be incorrect.

5.6.1.2.2 Advantages of the inverse power law model

The primary advantage of this model is its simplicity and easy determination of the parameters from a test, provided that there is an easy separation between failure modes. Another advantage is that it is widely used so that the specific parameter values can be found in relevant literature.

5.6.1.2.3 Disadvantage of the inverse power law model

The model disadvantages are as follows:

- the simplicity of the model can lead to errors in fitting life-related parameters of different distributions;
- often, due to time and cost constraints, it is not possible to determine the inverse power law parameters, hence common average values that can be misleading are used;
- tests to failure, to be statistically defensible, require a large number of samples to be tested to failure at each of the chosen stresses. Components at lower stresses can require a long test time, and should those at the same time have a high level of reliability, the sample size may have to be large, and the test can be lengthy;
- caution should be exercised when accepting an assumed value for the parameter m , borrowed from a seemingly similar item.

5.6.1.3 Arrhenius model

5.6.1.3.1 General

The Arrhenius model [7] is based on expressing the reaction rate as a function of the component type and its failure mode and the absolute temperature, T . This model assumes that the reaction rate is exponentially dependent on the absolute temperature.

The reaction rate is expressed as follows:

$$\rho(T) = K \times e^{-\frac{E_a}{k_B \times T}} \quad (14)$$

where

K is the constant (not a function of temperature);

E_a is the activation energy (eV);

k_B is Boltzman's constant = $8,617\,385 \times 10^{-5}$ eV/K;

T is the absolute temperature (K);

$\rho(T)$ is the reaction rate as a function of the absolute temperature.

A function that represents reliable life is expressed as a function of temperature:

$$L(T) = C \times e^{\frac{D}{T}} \quad (15)$$

To represent the above equation as a straight line:

$$\ln[L(T)] = \frac{D}{T} + \ln(C) \quad (16)$$

where

T is the variable absolute temperature measured in degrees K (absolute temperature);

D is the slope of the straight line ($= E_a/k_B$);

$\ln(C)$ is the intercept of the straight line with the Y axis.

The acceleration factor is then found for the use with respect to test environment as the ratio of the two reaction rates:

$$AF = \frac{\rho(T)}{\rho(T_0)} = \frac{K \times e^{-\frac{E_a}{k_B \times T}}}{K \times e^{-\frac{E_a}{k_B \times T_0}}} = e^{-\left[\frac{E_a}{k_B} \left(\frac{1}{T_0} - \frac{1}{T}\right)\right]} \quad (17)$$

The failure rates as a function of absolute temperature, T , can be correlated to the failure rate at a specified absolute temperature, T_0 , as follows:

$$\lambda(T) = C \times e^{-\frac{E_a}{k_B \times T}} \quad (18)$$

The failure rate λ_0 at a specified temperature T_0 is:

$$\lambda(T_0) = C \times e^{-\frac{E_a}{k_B \times T_0}} \quad (19)$$

Division of Equations (18) and (19) will provide the following relationship:

$$\lambda(T) = \lambda_0(T_0) \times e^{-\left[\frac{E_a}{k_B} \left(\frac{1}{T_0} - \frac{1}{T}\right)\right]} \quad (20)$$

where

T_0 and T are the absolute temperatures in use and test environment, respectively.

An example of use of the Arrhenius model for the determination of the value of failure rate λ_0 which, at the temperature of 25 °C (298 K), was 1×10^{-8} failures/h, as a function of absolute temperature, T , is shown in Figure 5.

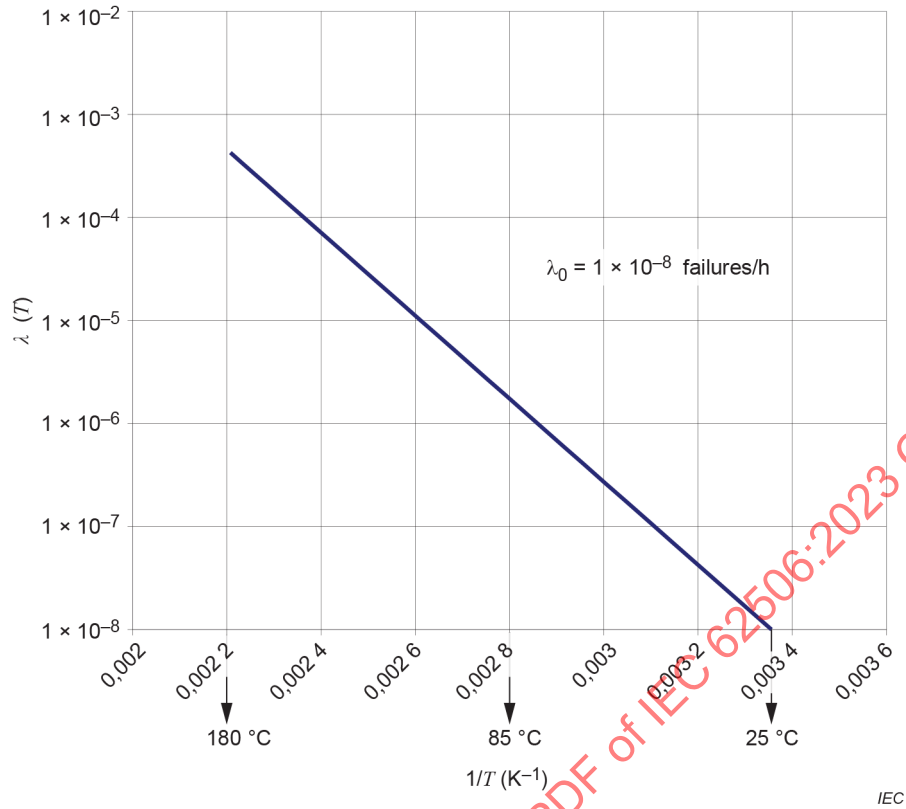


Figure 5 – Line plot for Arrhenius reaction model

The parameter E_a (activation energy) should be known for application of the Arrhenius model. The activation energy can be estimated as described in Annex C, but this is very time consuming. Component manufacturers estimate the activation energy for the relevant failure modes each time they qualify a new component technology. The estimate is often made on test structures and not on functioning components. The estimated activation energy is then applied to all components using the qualified technology. Therefore, the component supplier will usually be able to state the activation energy for the dominating failure modes of a given component.

Activation energy can be determined from the plot in Figure 5 by solving the equation used for the failure rate plot for E_a as follows:

$$E_a = k_B \times \frac{\{\ln[\lambda(T_F)] - \ln(\lambda_0)\}}{\frac{1}{T_0} - \frac{1}{T_F}} \quad (21)$$

$$E_a = k_B \times \text{SLOPE} \quad (22)$$

$$\text{SLOPE} = \frac{\{\ln[\lambda(T_F)] - \ln(\lambda_0)\}}{\frac{1}{T_0} - \frac{1}{T_F}} \quad (23)$$

where

$$\lambda_0 = 1 \times 10^{-8} \text{ failures/h;}$$

$$\ln(\lambda_0) = -18,421;$$

$$T_0 = 25 \text{ °C} = (25 + 273) \text{ K} = 298 \text{ K}$$

$$\ln(\lambda_F) = -7,764 5;$$

$$T_F = 180 \text{ °C} = (180 + 273) \text{ K} = 453 \text{ K;}$$

$$E_a = 0,8 \text{ eV.}$$

Figure 6 shows the determination of the activation energy.

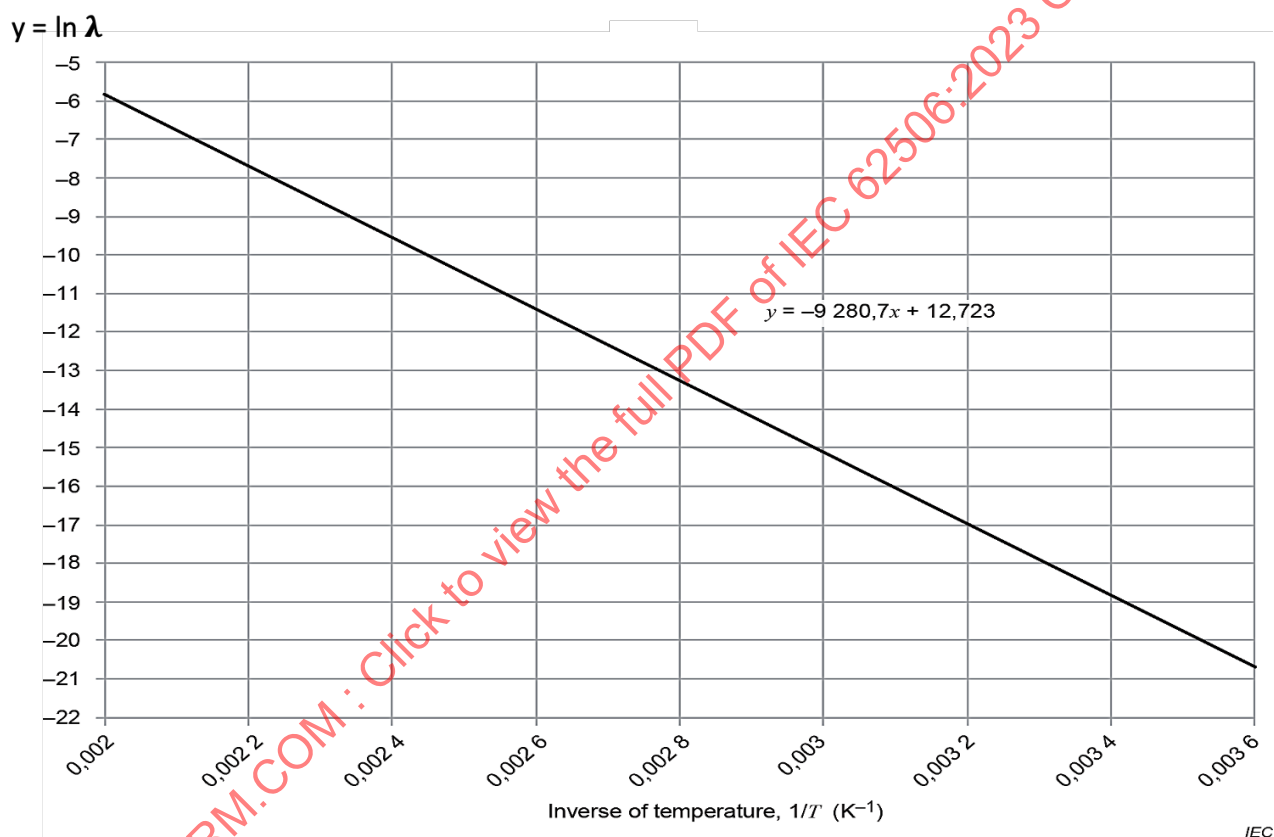


Figure 6 – Plot for determination of the activation energy

The Arrhenius method is applicable to a multitude of statistical distributions used in reliability analysis.

Confidence limits on parameters, life functions and reliability for each of the distributions can be determined with appropriate statistics.

5.6.1.3.2 Model applicability

This model is applicable to the circumstances where the thermal exposure in form of constant high temperature is expected to cause cumulative damage of materials thus changing their physical properties. Change of physical properties may then be demonstrated as a change in electrical and other specific properties.

The model is not applicable for damages caused by low temperatures. For these, it is advised that tests to failure be used to establish the specific model.

5.6.1.3.3 Advantages of the Arrhenius model

The Arrhenius model is simple to use and, when the failure mode is truly only dependent on the absolute temperature, can produce realistic test acceleration.

5.6.1.3.4 Disadvantages of the Arrhenius model

The model is easy to apply for single components provided that their failure rates are indeed dependent on and activated by temperature. For assemblies made of various electronic and mechanical parts, the model can be hard to apply, as the components will often have different thermal activation energies for different failure modes (see JESD85 [8] and IEC 61649:2008, Annex G). Acquiring relevant values of activation energy is not simple for various tested items. Sometimes it requires extra specific experiments to get it. For more details see Annex C.

5.6.1.4 Eyring model

5.6.1.4.1 General

As with the Arrhenius model, the Eyring model is primarily used when thermal stress is a factor in the acceleration process. Unlike the Arrhenius model, the Eyring model is also used for stresses other than temperature, such as humidity, or some chemical reactions [7].

The function related to expected life is shown as follows:

$$L(S_E) = \frac{1}{S_E} \times e^{-\left(A - \frac{B}{S_E}\right)} \quad (24)$$

where

A and B are the function parameters that need to be determined through test or approximated by values from literature. Parameter B may be a constant, but more often it is a function of some stress, normally temperature;

S_E is the stress as used in this model (usually absolute temperature measured in degrees Kelvin);

$L(S_E)$ is the measure of life such as MTTF, characteristic life, half life.

The acceleration factor AF with this model is:

$$AF_{S_E} = \frac{L(S_{E_{Use}})}{L(S_{E_{Test}})} = \frac{\frac{1}{S_{E_{Use}}} \times e^{-\left(A - \frac{B}{S_{E_{Use}}}\right)}}{\frac{1}{S_{E_{Test}}} \times e^{-\left(A - \frac{B}{S_{E_{Test}}}\right)}} = \frac{S_{E_{Test}}}{S_{E_{Use}}} \times e^{B \left(\frac{1}{S_{E_{Use}}} - \frac{1}{S_{E_{Test}}} \right)} \quad (25)$$

where

$S_{E_{Use}}$ and $S_{E_{Test}}$ are stresses in use and test, respectively;

B is a constant that has to be determined through test or approximated by values from the literature.

The Eyring model can be applied to all distributions used in the reliability analysis.

Confidence limits on parameters, life functions and reliability for each of the distributions can be determined with appropriate statistics.

5.6.1.4.2 Advantages of the Eyring model

The model is relatively simple, yet it is applicable for stresses other than thermal. For a known parameter B , rather accurate test acceleration can be achieved.

5.6.1.4.3 Disadvantages of the Eyring model

As with the Arrhenius model, knowledge of the parameter B is critical for correct test acceleration. For items with moderate complexity, accurate test acceleration can become questionable because of different components and materials having a different value for the constant B .

5.6.2 Stress models with stress varying as a function of time – Type B tests

5.6.2.1 General

The time varying stress models are used to account for precipitation of failure modes in order to shorten the test time. These models can be used as a presentation of item usage profile and those are the cumulative damage or cumulative exposure model.

5.6.2.2 Step-stress model

5.6.2.2.1 General

The model most frequently used is the step-stress model, where the units under test are subject to a succession of increasing stress levels that are applied for a predetermined time, and at the predetermined stress levels [9].

The stress levels are constant in each of the intervals.

The model can be presented mathematically using the life characteristic for an assumed distribution. As an example, the step-stress mathematical representation is as follows.

If reliability of a test unit for a test duration t and the stress S represented as a Weibull distribution is:

$$R(t, S) = e^{-\left(\frac{t}{\eta(S)}\right)^\beta} \quad (26)$$

where

$R(t, S)$ is the reliability as a function of time, t , and stress, S ;

β is the shape parameter of the Weibull distribution;

$\eta(S)$ is the scale parameter, a function of stress, S ;

then the probability of failure is:

$$F(t, S) = 1 - R(t, S) \quad (27)$$

In the Equations (26) and (27) with an example of the inverse power law model, the characteristic life is:

$$\eta(S) = C^{-1} \times S^{-m} \quad (28)$$

For successive stresses (stress levels) S_i , where $i = 1, 2, 3 \dots$

$$F_i(t, S_i) = 1 - e^{-\left(C \times S_i^m \times t\right)^\beta} \quad (29)$$

Data should be analysed using the appropriate distribution (in the case of the above example Weibull), using a cumulative exposure model, which makes a correlation between the failure distributions at the two successive levels. The failure distribution of the test units in each step will be specific to that step; however, the zero time of each particular step coincides with the total accumulated test time prior to that step.

Denoting an equivalent ageing time as τ_i , to account for ageing at the previous stress level: i

$$\tau_i = (t_i - t_{i-1}) \times \left(\frac{S_i}{S_{i-1}}\right)^m + \tau_{i-1} \quad (30)$$

Probability of failure in the segment, i , then is:

$$F_i(t, S_i) = 1 - e^{-\left(C \times S_i^m \times (t - t_{i-1}) + \tau_{i-1}\right)^\beta} \quad (31)$$

Distribution parameters may be then determined by maximum likelihood or other methods.

Confidence limits can also be set for the probability of failure, reliability, or any other item life measure as described in the related standards on confidence limits, depending on the established distribution.

5.6.2.2.2 Advantages of step-stress model

The method is effective to discover potential item weaknesses in the short time period. The associated mathematics is not too complicated, so that the life characteristic of an item as related to the particular stress can be calculated.

5.6.2.2.3 Disadvantages of step-stress model

The method does not account for ageing of the test units for the time that the previous stress steps are applied. Nor is the time involved enough typically to produce time dependent failure modes such as wear, or creep or high cycle fatigue. The primary driver is stress intensity. Further, this does not take into account potential fatigue or material changes resulting from the repetitive stress. This potential fatigue can precipitate appearance of the failure modes earlier than they would normally appear without the fatigue factor and thus erroneously predict an early time to failure. The effect of the stress is usually logarithmic, so care should be taken not to use a stress level that will cause immediate failure of the UUTs.

The method also does not suggest how to handle appearances of failure modes unrelated to the applied stress, and how to account for them.

Care should be taken to not exceed the short time destruct limit of the UUT.

5.6.3 Stress models that depend on repetition of stress applications – Fatigue models

5.6.3.1 General

Fatigue can be defined as a gradual deterioration of item materials or item structure when those are subjected to repeated loads. Those loads can be mechanical, dynamic, thermal cycling, voltage cycling, etc. With cycling loads (such as thermal cycling, bending) the fatigue is proportional to more than one parameter, usually to the load extremes (the difference between extremes) number of repetitions and to a rate of change.

To represent the relationship between the number of load repetitions and the level of the load, testing is done on a number of items at different stress levels in a series of tests. The endured stress is plotted against the number of applied stress cycles or applications for which the failures have not occurred. The stress levels are reduced and the number of stress applications is increased. This continues to a point where seemingly, the stress is low enough that the item can endure an "infinite" number of applications. The stress value at this point is often known as the fatigue limit. Not all materials have a fatigue limit; exceptions are, for example, some types of aluminium alloys and plastics.

5.6.3.2 Calculating life time according to Miner's rule

The Palmgren-Miner linear-cumulative-fatigue-damage-theory (Miner's rule) is used to calculate the resultant pitting or bending fatigue lives for gears that are subjected to loads which are not of constant magnitude but vary over a wide range. According to Miner's rule, failure occurs when:

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \dots + \frac{n_i}{N_i} + \dots + \frac{n_m}{N_m} = 1 \quad (32)$$

where

n_i is the number of cycles at the i -th stress level;

N_i is the number of cycles to failure corresponding to the i -th stress level;

n_i / N_i is the damage ratio (fraction of life) at the i -th stress level.

Replacing number of cycles by the life times:

$$\frac{l_1}{L_1} + \frac{l_2}{L_2} + \dots + \frac{l_i}{L_i} + \dots + \frac{l_m}{L_m} = 1 \quad (33)$$

where

l_i is the time at the i -th stress level;

L_i is the life at the i -th stress level;

$\frac{l_i}{L_i}$ is the damage ratio at the i -th stress level.

If the time at each of the stress level is expressed as a fraction of time of the total life, L :

$$\begin{aligned} l_1 &= \alpha_1 \times L \\ l_2 &= \alpha_2 \times L \\ l_i &= \alpha_i \times L \end{aligned} \quad (34)$$

where

α_i is the time at the i -th stress level;

L is the life to failure under the applied set of loads.

If the same ratio for lives applies as to the number of cycles, then:

$$\frac{\alpha_1 \times L}{L_1} + \frac{\alpha_2 \times L}{L_2} + \dots + \frac{\alpha_i \times L}{L_i} + \dots + \frac{\alpha_m \times L}{L_m} = 1 \quad (35)$$

$$L = \frac{1}{\frac{\alpha_1}{L_1} + \frac{\alpha_2}{L_2} + \dots + \frac{\alpha_i}{L_i} + \dots + \frac{\alpha_m}{L_m}} \quad (36)$$

The stress versus number of cycles diagram is plotted from the fatigue tests and is known as the S-N curve. From a series of S-N curves, and with the assumption of the inverse power law of stress levels the parameter m , described in 5.6.1.2 can be determined.

5.6.4 Other acceleration models

5.6.4.1 General

Other acceleration models can be found in IEC 61163-2 [10] and in [7].

5.6.4.2 Time and event compression tests

In event compressed tests events that determine the reliability of life of the item are repeated more often than in the field (in use). Examples can be the number of copies in a copy machine or the number of couplings for a circuit breaker. The repetition frequency should not be so large that it changes the operating conditions, for example the test item has to cool down and stabilize in normal "idle" conditions before the next event. For factors not determined by the number of events, see below.

In time compressed tests, the time periods where the load from use and environment are low are left out of the test, leaving only the time periods that influences most the reliability or life of the item. But it has to be checked if loads and environmental conditions that are omitted does not add up to a significant contribution to the deterioration of the item. Such environmental conditions can typically be "off" periods where moisture and corrosion are dominant (the heat during use will often reduce corrosion by reducing the relative humidity in the item). Such "off" periods are typically determined by calendar time and not operating time. Separate tests may be needed to take these loads into account, for example moisture tests or corrosion tests. These considerations also apply to event compressed tests.

5.6.4.3 Step-by-step procedure for event compression and time compression tests (Type C tests)

- Step 1: determine which factors can be event compressed and how much without changing failure modes;
- Step 2: determine if the test need be added to cover the failure mechanisms that are not determined by the number of events or are left out for time compression.
- Step 3: determine which periods in the mission profile can be time compressed or event compressed and how much (IEC 60605-2);
- Step 4: estimate the acceleration factor(s) for the potential failure modes (see 5.6);
- Step 5: determine the sample size (see IEC 61649);
- Step 6: perform the test (see IEC 60300-3-5);
- Step 7: perform failure analysis;
- Step 8: analyse test results for each failure mode separately (see IEC 61649);
- Step 9: report results (see IEC 60300-3-5).

5.7 Acceleration of quantitative reliability tests

5.7.1 Reliability requirements, goals, and use profile

5.7.1.1 General

This material is discussed at length and in detail in other dependability standards and literature, but, for completeness some brief explanations are included in this document.

5.7.1.2 Item and component use profile

Often the manufacturers choose to test an item in an accelerated test that simulates environmental stresses as they are experienced in the field. Some of the reasons for such tests can be to verify that the previous tests (e.g. HALT) did not miss a failure mode that could appear in life or to estimate field reliability of that item. There are instances where, due to space or performance constraints, one or more components in that item can be insufficiently derated which will possibly not provide adequate stress versus strength margin. In these instances, item reliability can be highly dependent on the manner of its use, operational and environmental stresses, their combination and sequence.

An item use profile consists of the following:

- operational and environmental stresses, their magnitude and sequence;
- the duration and number of sequence segments.

These use profiles can be chosen from one of the following evaluation conditions: average use profile, aggressive use profile, and a spectrum of use profile conditions.

These operational stresses and sequences should be known down to the assembly, critical components, and those components that may have to be subjected to accelerated reliability testing.

5.7.1.3 Reliability goals or requirements

The overall reliability goal should be expressed in terms that are acceptable and understandable to the organization or to the customer (see IEC 60300-3-4 [11]). This goal may be expressed as a percent failed items at the end of a specific time period (i.e. warranty) or multiple periods. The goal may also be expressed as a warranty or maintenance cost. At times it is found appropriate to express the goal reliability in terms of a mean time to failure (MTTF) or mean operating time between failures (MTBF).

Regardless of how the goal is specified, it has to be understood that the goal reliability is related to the manner the item is going to be used, and that the same "number" or "reliability measure" is different for different use profiles (operational stresses of location). Conversely, the MTTF or MTBF of that item is only an average value representing the specific stress combinations. For that reason, any claimed reliability values of an item should be accompanied with the explanation of the expected use and relative degree of severity.

In cases where two or more stresses are applied to an item consisting of several components, the test acceleration is done by increasing each individual stress using models appropriate for those stresses. In these cases, failure rates representing each of the failure mechanisms are individually accelerated and the overall component reliability (R) or failure probability (F) shall be estimated separately. This can be expressed in general form for a combination of n independent stresses as:

$$R_{\text{equipment}} = \prod_{i=1}^n R_i \quad (37)$$

For the failure probability:

$$R_{\text{equipment}} = 1 - \prod_{i=1}^n (1 - F_i) \quad (38)$$

The problem of competing risks is described in IEC 61649:2008, Annex G.

If an item consists of m components or piece parts which at any given time are subject to a set of n stresses that influences all the failure modes simultaneously, then its reliability R_p in a segment of time (part of a use profile where a specific stress combination exists) t_k is:

$$R_{\text{item}}(\text{Stress } t_k) = \prod_{j=1}^m \left[\prod_{i=1}^n R_p(\text{Stress}_i \times t_k) \right]_j \quad (39)$$

If there are w segments in total use profile with different stress combinations, then the total reliability of that item for a life or other predetermined time, t_0 is:

$$R_{\text{item}}(\text{Stress } t_0) = \prod_{k=1}^w \left\{ \prod_{j=1}^m \left[\prod_{i=1}^n R_p(\text{Stress}_i \times t_k) \right]_j \right\} \quad (40)$$

Where

$$t_0 = \sum_{k=1}^w t_k \quad (41)$$

These equations are conservative, i.e. they can seriously underestimate the reliability of the equipment.

The total average failure rate of such an item is also a function of applied stresses and uses profile, and can be written as:

$$\lambda_{\text{aitem}}(\text{Stress}, t_0) = - \frac{\ln[R_{\text{item}}(\text{Stress}, t_0)]}{t_0} \quad (42)$$

For any other stress conditions or use profile, the average failure rate of the item will be different.

Reliability requirements for repairable items shall be viewed in terms of expected preventive maintenance, that is, parts of the item should be viewed separately for reliability and the time duration for which the requirements are prepared should correspond to the expected maintenance time.

5.7.2 Accelerated testing for reliability demonstration or life tests

5.7.2.1 Applicable test types

Since many tests are calendar time consuming many tests need to be accelerated. Most tests can be accelerated to shorten the test time. Certain reliability tests that can be accelerated are reliability demonstration, improvement, or assurance tests which can be:

- success tests, fixed duration;
- tests with failures, fixed duration;
- tests to failure (usually for components or small assemblies and individual failure modes);

- reliability improvement or growth tests, which are usually prepared for a predetermined time period;
- sequential probability ratio tests (SPRT) (see IEC 61124).

Engineering evaluation tests which are usually performed in view of a suspect failure mode can also be accelerated provided there is some knowledge of acceleration factors for those test items and the expected or suspect failure modes.

5.7.2.2 Reliability testing of an item

When a reliability test programme is prepared in view of the reliability for the specific use profile then the results of the test programme are valid for that specified use profile only. If reliability estimates for other use profiles are required for the same item, this can be achieved by additional testing or adjusting the test results by mathematically modelling the test results to the new use profile. This modelling can be done in cases where there is a known relationship between the stresses and the use profile applied in the test and to the new adjusted use profile (see IEC 61709).

In case there are multiple differences between the two use profiles, there is more chance of model inaccuracy in adjusting the reliability estimate for the new profile. These differences rapidly increase with complexity of the system under evaluation.

Item and component reliability in regards to operational and environmental stresses as a function of predetermined time (life time) t_0 , can be expressed as follows:

$$R(t_0) = R_U(t_0) \times \prod_i R_{S_i}(t_0) \times \prod_i R_{E_i}(t_0) \quad (43)$$

In the above Equation (43), $R_E(t_0)$ denotes the reliability of the item regarding environmental stresses for the time duration t_0 , while $R_S(t_0)$ denotes the reliability regarding operational stresses. Factor $R_U(t_0)$ is used to represent the unknown interaction or synergism of individual environmental and operational stresses as determination of individual stress duration and magnitude assumes stress independency, which in most cases will possibly not be a valid assumption.

Equation (43) can be generalized to be written in the form:

$$R_{\text{Item}}(t_0) = \prod_{i=1}^{N_S} R_{\text{Stress}_i}(t_i) \quad (44)$$

If $R_{\text{Item}}(t_0)$ is the item reliability goal or the item reliability requirement that needs to be demonstrated in test, then a reliability value may be allocated to each of the multiples in the expression for the item reliability. Simplified for illustration the allocated individual reliabilities may be assumed to be the same.

$$R_{\text{Item}}(t_0) = \left(R_{\text{Stress}_i}(t_i) \right)^{N_S} \quad (45)$$

$$R_{\text{Stress}_i}(t_i) = \sqrt[N_S]{R_{\text{Item}}(t_0)} \quad (46)$$

The allocated values to reliability regarding individual stresses differ depending on the item intended use and usage profile and its sensitivity to a particular environment. Besides the magnitude of stresses expected in the actual use, it is their cumulative effect that affects item reliability. The test duration is then calculated based on the duration of each of the stresses applied in actual use, while the test acceleration is achieved by increasing the magnitude of each of the individual stresses or by their time acceleration.

When the purpose of the test is to estimate reliability in the field, an average user stress profile should be used. This profile can be estimated for given climatic conditions as for example Central Europe (see the IEC 60721 series). Different locations can have different prevalent or extreme stresses. As an example, in some countries such as Northern Scandinavia, Canada and Russia, low temperature can be one of the highest stresses, while New Mexico, Africa and India it can be high temperatures. In Singapore and Japan the most pronounced stress can be humidity and in New Delhi it can be air pollution. Regarding the manner of use, the test can simulate an average user or an extreme user (e.g. where less than 1 % of the customers load the item more severely). It is not advisable to transfer a test result from one environmental and user profile to another. Therefore many companies supplement the environmental test with survival tests where the purpose of the test is to determine if the item will survive a few extreme loads that are not expected to be repeated so often that they would influence the long term reliability of the item. Such environmental tests are described in the IEC 60068 series [12].

Often, items are tested with a stress cycle in order to expose the item to several stresses in combination or sequentially. Ideally, the stresses should be applied combined and intermittent in order to simulate the field conditions as well as possible. But in practice this is seldom possible. In order to use the test equipment in an optimum way and make it easier to locate the stress type and level that caused the failure the test is often made using a test cycle, for example of one week duration (see IEC 60605-2).

In the following it is assumed that the item is tested for each of the expected stresses, operational and environmental, having in mind their levels and cumulative duration in actual use and the corresponding total use period, t_0 .

To make testing possible, the stress levels are then accelerated by applying the appropriate acceleration factors. The stress acceleration type and the item specific acceleration factors for the various expected stresses need to be known. These can be obtained through tests-to-failure at different stress levels for the specific components (see Annex E and Annex F).

The above programme can be prepared in different forms:

- as a success test, test with no failures;
- as a test with an allowed number of failures;
- as a fixed duration test, but without reliability requirement, thus the reliability of the item will be estimated based on the number of failures in the test;
- as a reliability growth or improvement test based on an assumed growth rate (see IEC 61014 [13]).

In a success test, the result is a minimum reliability estimate. Without failures, the test demonstrates the reliability requirement with applied (minimum) confidence intervals.

If this test is to allow a certain number of failures, then the determination of its duration should account for the allowed number of failures. The test then becomes the "fixed number of failures" test.

If the test is a reliability growth test, then the total test duration (or sample size in view of accumulated test time) is prepared for the expected total numbers of test failures, having in mind the total duration of the applied stresses, required confidence and the required demonstrated reliability (see IEC 61014 [13]).

5.7.2.3 Accelerated tests assuming non-constant failure rate or failure intensity

It is assumed that the failure rate or failure intensity follow the so called bath-tub curve (see Figure 7). In the early failure period the failure rate or failure intensity is declining with time.

This is covered by IEC 61163-1 [14] and IEC 61163-2 [10]. In constant failure rate period the failure rate or failure intensity is assumed to be constant. In the wear-out period the failure rate or failure intensity is increasing. This often define the life time of the item. The end of life can be defined as the time when the failure probability has reached a specified value for example 10 % stated as the B_{10} value (see IEC 61649). An indication of whether the failure rate is decreasing, constant or increasing can be tested using IEC 61649 for non-repaired items. For repaired items IEC 61710 has to be used. In both cases a value of $\beta < 1$ indicates the decreasing failure rate or failure intensity.

$\beta = 1$ indicates constant failure rate or failure intensity, and $\beta > 1$ indicates increasing failure rate or failure intensity.

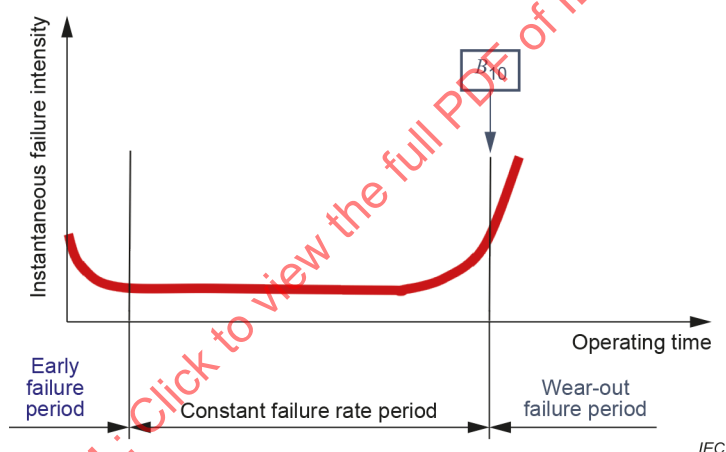


Figure 7 – Bathtub curve

NOTE 1 Some standards define the life time as the time where the instantaneous failure intensity has increased a number of times. This document uses the definition of B_{10} , the time when 10 % of the items have failed (accumulated probability of failure). The instantaneous failure intensity therefore increases before the life time point. See also Figure 10.

Often tests are aimed at estimating the life time of the item for example by estimating the B_{10} value. Here it is a special problem that the failure rate or failure intensity curve often has a tail to the left from the B_{10} value. This means that a small percentage of wear-out failures can occur before the B_{10} value. Because of the limited sample size for most accelerated tests the probability of observing the early wear-out failures are small. An important issue in planning accelerated tests is therefore to estimate the probability of wear-out failures before the B_{10} value. It is important to note that the definition of B_{10} only states that at the B_{10} time the accumulated probability of failure is 10 %. This makes no assumption if the 10 % was caused by early failures, the constant failure period or wear-out failures.

When the failure rate or failure intensity can be assumed constant the test can be analysed based on the accumulated test time as described in IEC 61124. For example 77 items tested each for 1 000 h would mean an accumulated test time of 77 000 h. To estimate the equivalent hours of operation at operating conditions (in the field) the accumulated test hours then shall be multiplied with the acceleration factor (AF).

NOTE 2 Other measures of operation like cycles, mileage or copies made can replace hours as a measure of the test duration.

When the failure rate or failure intensity cannot be assumed constant, accumulated test hours cannot be used to analyse the test. In that case 77 items tested for 1 000 h each would have to be analysed as 77 independent tests each truncated after 1 000 h. In this case the 1 000 h shall be multiplied with the acceleration factor (AF) to estimate the equivalent duration of the test under field conditions.

Commercial software programs often include test planning features. It is important before using such programs to check if the program assumes constant failure rate or failure intensity and whether it assumes repaired or non-repaired items or allows replacement of failed test items during the test. If the program assumes non-constant failure rate or failure intensity it is important to note which β value is used or specified when using the Weibull distribution. For including previous knowledge using the Bayes theorem see IEC 61710.

5.7.2.4 Success tests

A success test is planned to end with zero failures. Since no failures were observed, success tests demonstrate a minimum reliability for a defined confidence level. No knowledge about the real reliability (or shape parameter) can be determined using the success test.

If the failure rate or failure intensity is assumed to be constant, a lower 60 % confidence limit of an MTBF value can be estimated (see IEC 60605-4 [15]).

The physics of failure interpretation of a success test is that during the observed test time, there were, with a certain probability, no active failure modes.

The equations for a success test are the following:

$$P_A = 1 - R(t)^n \quad (47)$$

$$R(t) = (1 - P_A)^{1/n} \quad (48)$$

$$n = \ln(1 - P_A) / \ln(R(t)) \quad (49)$$

where

$R(t)$ is the reliability at time t ;

P_A is the confidence level;

n is the sample size.

NOTE Equation (47) is often referred to as "success run".

It should be noted that these equations do not use accumulated test time, but the test time for each individual item in the test (t). The reliability $R(t)$ is estimated without assumptions about the failure rate or failure intensity.

5.7.2.5 Physics of failure tests

This test is planned to evaluate or verify the reliability based on the physics of failure model i.e. focusing on determining which failure mechanisms (if any) are active during the planned life time of the item under the expected operating and environmental conditions.

Step 1: From an engineering evaluation determine the worst expected failure mode and find from previous tests, in handbooks or literature the relevant acceleration equation (see 5.6) and the relevant empirical factors (e.g. activation energy (E_A) or m factor for the inverse power law).

Step 2: Determine the acceleration factor (AF) between the accelerated test conditions and the operating conditions in the field (see Annex B). If possible tests should be performed at two or three different stress levels to verify the acceleration factor (see Annex E and Annex F).

Step 3: Determine the test time t required to simulate the operating time in the field at the time where the reliability needs to be estimated for example at life time.

Step 4: Determine the required sample size for a reliability $R(t)$ and a confidence level of P_A using Equations (47) to (49).

Step 5: Perform the test of n samples for the test time t at each stress level (one to three different stress levels).

Step 6:

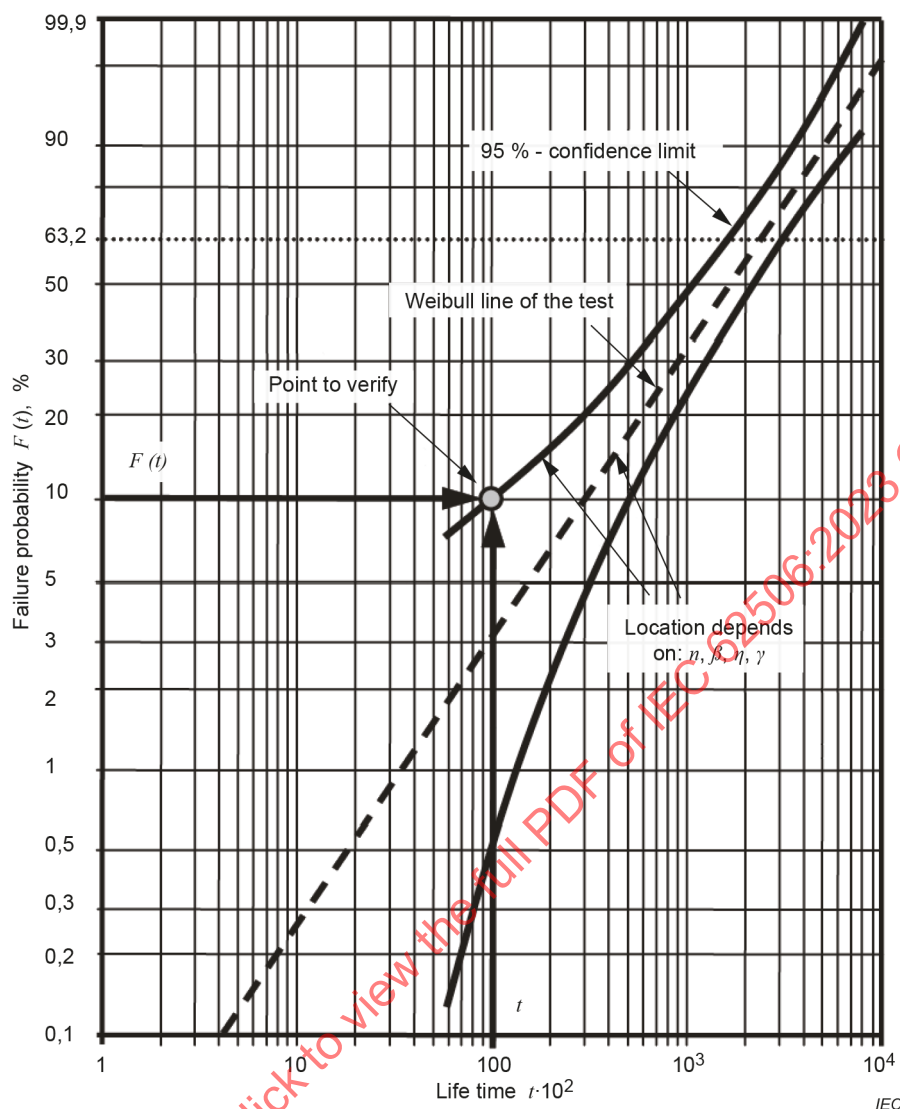
- a) If no failures were observed it can be stated with confidence P_A that the failure mode(s) assumed in step 1 are not active in the tested items up to time t . In this case the accelerating factor cannot be verified.
- b) If failures were observed during the test, perform a failure analysis. If the failure mode is the same as assumed in step 1, the probability of failure or reliability at time t may be estimated using IEC 61649 for non-repaired items and IEC 61710 for repaired items. If more than one stress level was used during the test, the empirical factors in the acceleration factor equation may be estimated (see Annex E and Annex F), and a better equivalent operating time in the field can be estimated. If the failure mode is different from the one assumed in step 1 the reliability for this failure mode can be estimated using IEC 61649 for non-repaired items and IEC 61710 for repaired items. If more than one stress level was used during the test, the empirical factors in the acceleration factor equation may be estimated (see Annex E and Annex F), and an equivalent operating time in the field can be estimated. If only one stress level was used, empirical factors from handbooks may be used to estimate the acceleration factor (AF) for that failure mode and estimate the operating time in the field equivalent to the test time t .

Step 7: Consider if, based on an engineering evaluation, the second worst failure mode should be tested in a similar way, returning to step 1. Depending on the acceleration factor the second largest failure mode may be covered by the initial test with an acceptable confidence.

A variant of this test method, the so called CALT test is described in Annex D.

5.7.2.6 Test planning based on the Weibull distribution

This test is also a success test, since it is planned to end with zero failures. The principle of the test is illustrated in Figure 8 below. For further information see [16] and IEC 61649. If a reliability of 90 % at 10 000 h has to be verified with 95 % confidence in a test, the procedure can be illustrated in a Weibull plot as shown in Figure 8 below.



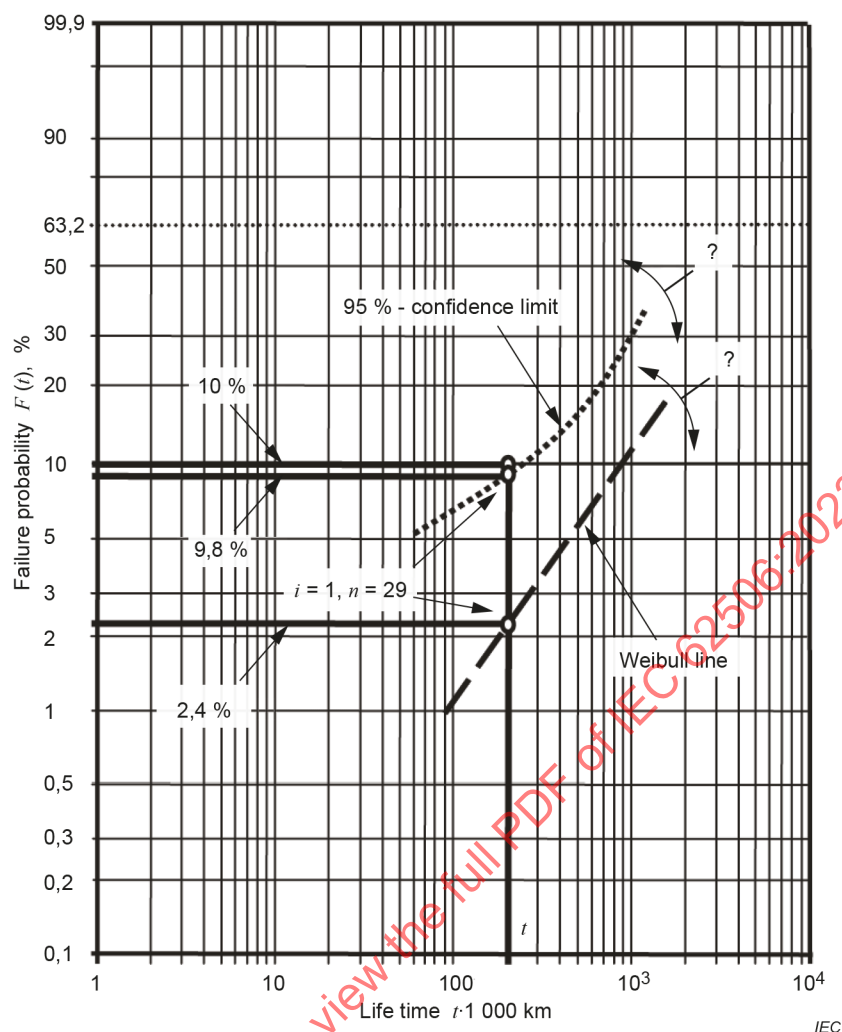
SOURCE: Reference [9], reproduced with the permission of the authors.

Figure 8 – Test planning with a Weibull distribution

The point to verify in a Weibull plot is 10 % failures at 10 000 h.

The Weibull curve is drawn with the assumed slope (β) and its 5 % and 95 % confidence limits are drawn so that the 95 % confidence line goes through this point (10 000 h, 10 %). This means that if the test of n items each for 10 000 h result in no failure, a reliability of 90 % (10 % failures) have been estimated with 95 % confidence. The rationale for this conclusion is that if a failure had occurred at exactly 10 000 h this failure had to be plotted in the point (10 000 h, 10 %).

The value of β can be obtained from previous tests of similar items, from literature or based on engineering judgement. An example is shown in Figure 9 below.



SOURCE: Reference [9], reproduced with the permission of the authors.

Figure 9 – Example of a test based on the Weibull distribution

The procedure for planning the test is described below, illustrated with a practical example.

A reliability of $R(20\,000\text{ km})$ of 90 % is required with a confidence level of $C = 95\%$.

Step 1:

In Table G.1 of Annex G, find the sample size n where the 95 % median rank for the first failure ($i = 1$) is close to 10 %. To find the 50 % median rank use the approximation median rank = $(i - 0,3)/(n + 0,4)$ (see IEC 61649), where i is the failure rank order and n is the sample size. The median rank for $n = 29$ for $i = 1$ is found to be 9,8 %.

Step 2:

Test 29 items, each for 20 000 km. If no failure is observed the reliability $R(20\,000\text{ km})$ has been estimated with 95 % confidence.

NOTE If the test estimate $R(20\,000\text{ km}) = 90\%$ with 95 % confidence it will estimate $R(20\,000\text{ km}) = 97,6\%$ with 50 % confidence (best estimate), since the point 20 000 km, 2,4 % is on the Weibull line, which is the best estimate.

5.7.2.7 Life time ratio

The life time is often defined as the time where a stated percentage of failures have occurred for example B_{10} value for 10 % failures (see IEC 61649). This means that the failure rate or failure intensity will start to increase before the wear-out period as illustrated on Figure 10. The small sample size reduces the probability of including items that fail before the life time in the test. In order to compensate for this the test can be continued beyond the required life time of the item.

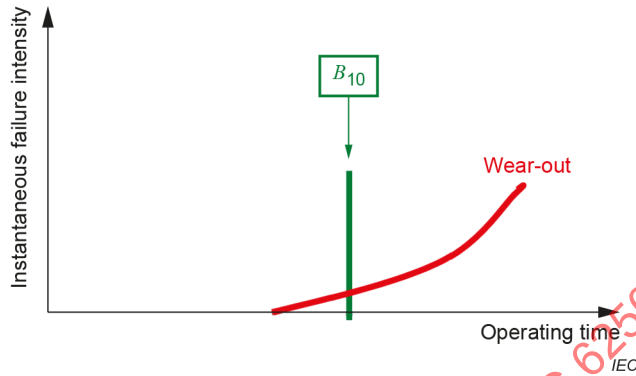


Figure 10 – Life time and "tail" of the failure rate or failure intensity

The extension of the test beyond the end of the specified life time are measured as the life time ratio L_V . The L_V value is defined as:

Life time ratio (L_V):

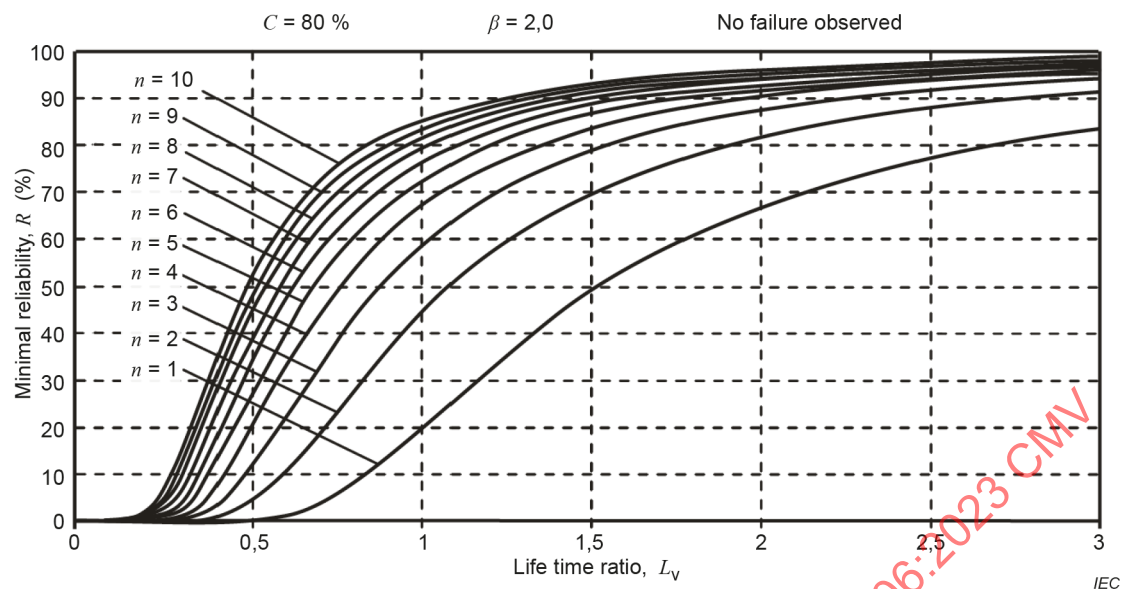
$$L_V = \frac{t_{\text{Test}}}{B_X} \quad (50)$$

where B_X is the specified life, for example B_{10} .

Success run formula with life time ratio:

$$R(t) = (1 - P_A) \frac{1}{L_V^{\beta} \times n} \quad (51)$$

The necessary input for the success test with life time ratio is the Weibull shape parameter β , which should be assumed conservatively i.e. with a value in the lower range. The assumption can be made for example based on predecessor items or tests. Using an L_V value in the test can increase or decrease the test time as shown in Figure 11 below.



SOURCE: Reference [9], reproduced with the permission of the authors.

Figure 11 – Reliability as a function of life time ratio L_v and number of test items

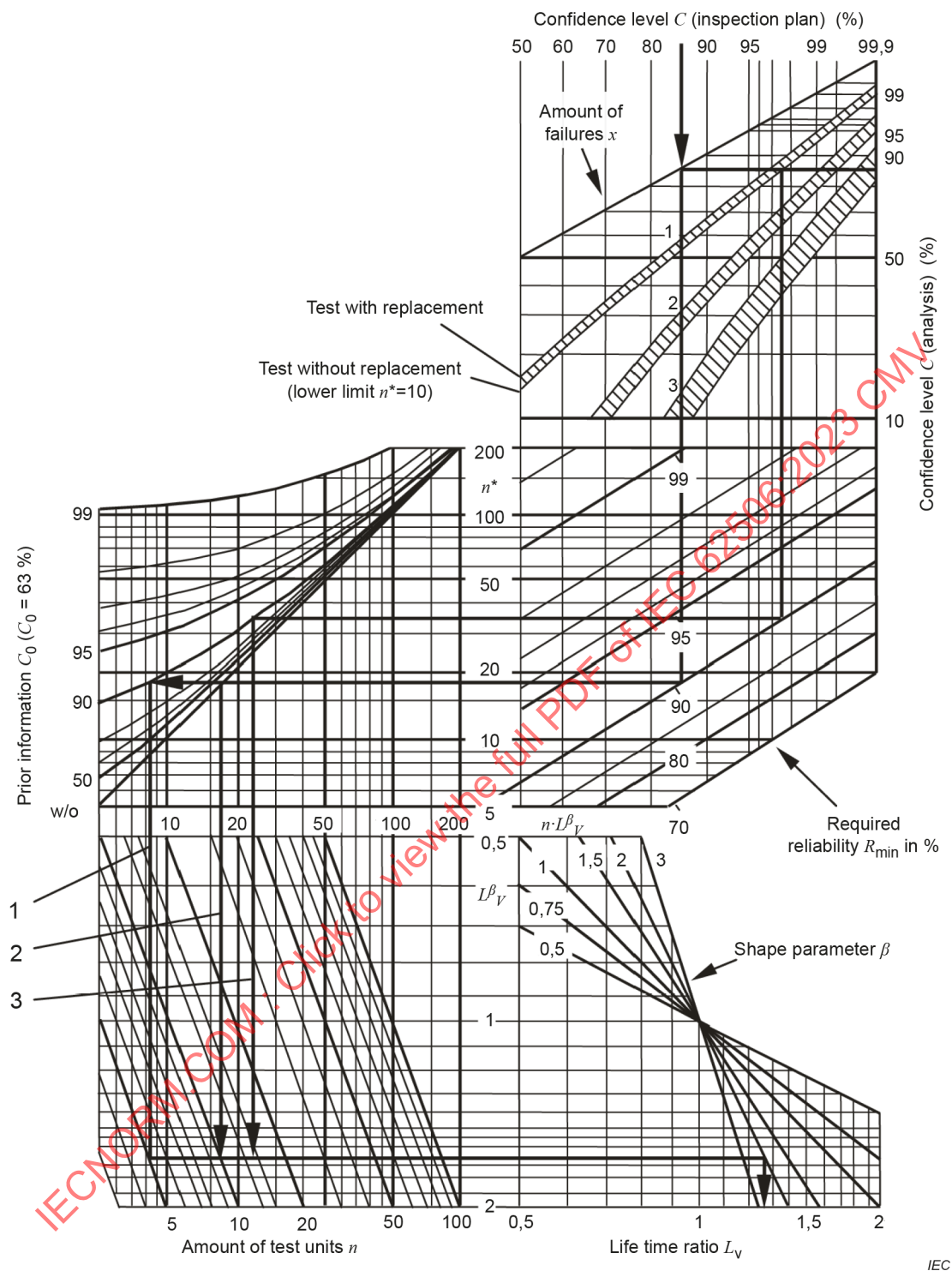
This test is also a success test, since it is planned to end with zero failures.

A practical example can be found in Clause B.4. More diagrams can be found in [16].

5.7.2.8 Consideration of failures and prior knowledge in success tests (Bayes)

This is also a special kind of a success run, where a small amount of failures is allowed and prior knowledge is used to reduce the sample size.

In case of more than one failure the following nomogram (from [16]) can be used. This nomogram gives the necessary life time ratio (L_v) as a function of β , the sample size n , the number of failures x and the prior information (see IEC 61710).



SOURCE: Reference [9], reproduced with the permission of the authors.

Figure 12 – Nomogram for test planning

A life test shall be made on an item. A life time of $B_{10} = 20\,000$ h is specified ($R(20\,000\text{h}) = 0,9$).

Knowledge about the items from previous items are: $R_0 = 0,9$ (with 63,2 % confidence) and the Weibull shape parameter $\beta = 2$.

The verification should be made with $P_A = 85\%$ and $n = 5$ test items.

According to Figure 12 the life time ratio is $L_v = 1,25$. Therefore the test time $t_{\text{test}} = 25\,000\text{ h}$ (line (1)).

If some of the assumptions are changed the following modification to the test can be made using Figure 12:

- if no prior information exists then $n = 10$ test items should be used (line (2));
- if one failure occurs during the test the number of test items increases to $n = 14$ (line (3)).

For more information see [16].

5.7.3 Testing of components for a reliability measure

Mass produced electronic components are subject to accelerated stress testing to determine their reliability measure (failure rate or other) under the use stress. To determine the appropriate acceleration factors, test structures for new component technologies are tested at several stress levels to failure, and the appropriate failure modes and empirical factors for the acceleration models are determined. The qualification method is described in JESD47B [2]. The selection of stresses and their levels is made dependent on the expected failure modes of the components.

Larger components manufactured in smaller volumes can often be reliability tested using accelerated test methods and statistical tools like IEC 61649 or IEC 61124. Based on the ratio of parameters of the specific distribution (i.e. characteristic lives in Weibull distribution), acceleration factors are established for the particular stresses which are then used to predict their reliability at other stress levels of the same stress types. If more than one distribution parameters are different for the different levels of the same stress, then it can be expected that the physical characteristics can change too. As an example, if the characteristic life as well as the shape parameter in Weibull distribution is different at different stress levels, it can be an indicator that perhaps the stress level was too high and has changed the physical characteristics of that component or that the manufacturing process was flawed. If that happened within the component rating it can mean that the component rating needs to be re-evaluated.

Usual environmental stresses for component testing are as follows:

- temperature;
- vibration;
- humidity;
- thermal cycling;
- salt exposure.

Some examples of operational stresses include

- voltage,
- current,
- force,
- friction.

An example of accelerated testing for a component is shown in Annex B.

The accelerated test time is relevant for the estimated life of the components. It is testing to failures that provides meaningful results while testing with no failures can provide information only if the test approximates a component life with a margin. The traditional total accumulated test time of multiple components (the total test time is a sum of all the times accumulated on single components) can lead to meaningless results in predicting the reliability beyond the actual test duration for a single component. As an example, 32 000 km on 100 tyres with zero failures can lead to an erroneous conclusion that 36,8 % of the tyres would last 3 490 000 km. The calculated failure rate is only valid to 32 000 km of the test. It is possible, however, to estimate failure rates beyond the duration of test through WeiBayes analysis, assuming a known Weibull slope (see IEC 61649).

While obvious for the tyre example, this fact is not too obvious for other components. Electronic components are normally tested by the manufacturers for 1 000 h, and usually on 77 components from each of three different lots. If that test is accelerated, it can provide information only for the equivalent life time (normalized to use level). The fact that the multiple components were tested does not improve the test results, only the degree of confidence (see JESD47B [2] and JESD85 [8]).

5.7.4 Reliability measures for components and systems

5.7.4.1 Electronic components

With electronic components, the preferred reliability measure is the instantaneous failure rate determined for standard profile conditions (see IEC 61709).

This allows the instantaneous failure rate to be re-calculated for the actual stresses of the operational use profile of the item. The re-calculations are done using appropriate acceleration models (see IEC 61709).

This information is provided at a given environment (such as temperature as well as other specified stresses).

The stated failure rate is often the average failure rate over the life time of the component, assuming exponential time to failure. However, some electronic and electro-mechanical components have a limited life (wear-out). For these components, it is necessary to estimate their life time. Components with limited life include, for example: power transistors, opto-couplers, LEDs and laser diodes, wet electrolytic capacitors, varistors, light bulbs, relays, switches, connectors and batteries (see IEC 61709).

5.7.4.2 Mechanical components

With mechanical components, the preferred reliability measure is the percent failures determined for standard profile conditions. Often this is stated as the operating time for a given percentage of failures as for example 10 % (often denoted as B_{10} or L_{10} life) or 1 % failures (often denoted as B_1 or L_1 life). For the estimation method, see IEC 61649.

This allows the reliability to be re-calculated for the actual stresses of the operational use profile of the item. The re-calculations are done using appropriate acceleration models.

If expressed in terms of failure rate, the failure rate is often calculated as the equivalent failure rate calculated from the estimated probability of survival and is valid for the specified stresses; however, this gives no information about the expected life time of the component.

5.7.4.3 Assemblies, systems (items)

The more complex items made of components (electrical and mechanical, including software) would be best represented by expressing probability of survival or probability of failure. These measures allow combinations of different failure distributions and are more appropriate when including software.

5.8 Accelerated reliability compliance or evaluation tests

Reliability compliance tests, sequential probability ratio test (SPRT) and fixed duration tests are designed with the assumption of a constant failure rate, as the complexity of items and their failure modes would not accommodate any other distribution unless the tests were used for the determination of item reliability with regard to individual failure modes, which is the case for components (piece parts).

Given the high reliability (or MTTF or MTBF) of the items, these tests traditionally have cost or schedule prohibitive duration and need to be accelerated. As the test designs are the same for repaired or replaced items as for those that are not repaired, in this Subclause 5.8 the term MTBF is used for both MTTF and MTBF.

There are many descriptions, mathematical derivations, plot fitting and explanations of this test type in the literature, however the actual tests, what they consist of and what stresses are to be applied, as well as the rationale behind them, are not readily available.

The average failure rate that shall be demonstrated through the test is determined from the appropriate reliability equation. In its simplest form, the failure rate, assuming exponential distributed time to failure, is as follows:

$$\lambda_0 = -\frac{\ln[R(t_0)]}{t_0} \quad (52)$$

where

t_0 is the expected operating time.

The failure rate is then accelerated using proper acceleration factors for each of the applied environmental stresses and becomes:

$$\lambda_A = AF_{\text{Test}} \times \lambda_0 = \sum_{i=1}^{N_S} \left(AF_i \left(\prod_k AF_k \right) \times \lambda_i \right) \quad (53)$$

where

λ_0 is the failure rate that the item has in its "in use" conditions;

λ_A is the accelerated test failure rate;

AF_i is the acceleration factor for each of the increased stresses in test;

λ_i is the failure rate of the item corresponding to the specific stress;

N_S is the number of stresses.

The total equivalent test acceleration factor is then the acceleration model for constant failure rate:

$$AF_{\text{Test}} = \frac{\sum_{i=1}^{N_S} \left(AF_i \left(\prod_k AF_k \right) \times \lambda_i \right)}{\lambda_0} \quad (54)$$

$$AF_{\text{Test}} = \frac{\sum_{i=1}^{N_S} \left(AF_i \times \left(\prod_k AF_k \right) \times \left[-\frac{\ln(R_i(t_0))}{t_0} \right] \right)}{\lambda_0} \quad (55)$$

The reciprocal of the accelerated failure rate from Equation (52) will yield the MTBF, m_0 , which can be determined from tests.

$$m_0 = \frac{1}{\lambda_0} = -\frac{t_0}{\ln(R_0(t_0))} \quad (56)$$

Other parameters of the SPRT and fixed duration tests are then applied in accordance with normal SPRT test design (discrimination ratio, producer's and customer's risk, etc.).

The main difference between the accelerated reliability compliance and the conventional test is the minimum test time. This minimum test time shall not be shorter than the required minimum test time, determined for the accelerated test which, in turn, is a function of required reliability, the applied stresses and the test acceleration. The sample size, therefore, shall be limited so that the minimum test time, corresponding to zero failures on the acceptance line, is equal to or longer than the minimum required accelerated test duration for the demonstration of required reliability.

The SPRT is designed in the same way as the non-accelerated test; the accept and reject criteria are established, the test plan is prepared in accordance with the accepted producer and consumer risk, discrimination ratio, except the lower test MTTF is the reciprocal of the accelerated failure rate. The other exception is that the environmental stresses are accelerated and applied in the same way as they are applied in the fixed duration tests.

An example of the accelerated SPRT is shown in Annex B.

5.9 Accelerated reliability growth testing

When reliability growth testing is accelerated, each of the stresses that are expected to be present in the item life is accelerated in accordance with the acceleration criteria. The stresses can be applied individually, in which case it is preferred that they are distributed for example in a test cycle, so that the cumulative effect is simulated. The preferred manner is to apply as many stresses as possible simultaneously so as to include their possible interaction.

The duration of each applied stress is such that it represents its life application with the margin necessary for reliability demonstration (as shown in fixed duration tests). Time to failure is then the test time multiplied by the appropriate acceleration factor. When the stresses are applied simultaneously, then it is important to determine the cause of failure so that the proper time to failure can be established. Recalculated for the use time, the failure times are then organized in increasing order and one of the analysis methods used for reliability growth test type is applied (see IEC 61164 [17]).

When analysis is carried out in this manner, the order of stress application does not skew the test results, as the failures are re-calculated per their "real time" of occurrence.

Annex B provides examples of reliability growth test acceleration and data analysis.

5.10 Guidelines for accelerated testing

5.10.1 Accelerated testing for multiple stresses and the known use profile

When the accelerated testing is prepared for the various combinations of multiple stresses, it is important to simulate the conditions of use to the best degree possible.

The stresses, both environmental and operational, are usually not applied as they occur in life, which is in different combinations in each of the specific sequences. The test stresses are combined where possible for the test, but are also performed as a single stress. The thermal cycling and thermal exposure can be easily combined into one test, with the addition of operational cycling, voltage changes, applied sound power, etc. Vibration tests can be done also combined with thermal cycling, but the short duration of vibration compared with the thermal cycling and exposure makes it technically difficult. Some tests, such as pothole shocks, acoustic noise, dust accumulation, hazardous or explosive chemicals and lubricants, are very difficult to combine with others. In such cases, the environmental exposures are distributed so that they can cause cumulative damage in sequence. This is done usually by splitting up the duration of certain tests into two or even three segments, or even changing the sequence between the exposures.

5.10.2 Level of accelerated stresses

A reasonable general rule is that accelerated stress levels should not exceed the levels at which the physical or chemical properties of the test item can change.

For some tests where the intention is to understand the stress limits of the item, this guideline does not apply. With these tests, however, it is not recommended to relate the results to any reliability demonstration value, due to the inaccuracies of any acceleration model beyond the inherent assumptions. Examples of such tests are step-stress or failure mode sensitivity investigations.

5.10.3 Accelerated reliability and verification tests

Item performance tests are often confused with certain accelerated reliability demonstrations. It is not unusual for a customer to present the procedures along with reliability requirements. Some even claim that if the specified tests are performed, reliability requirements would be met.

Verification tests are designed to verify the ability of an item to perform in accordance with the specified environmental extremes, with adequate durability and reliability. If a specific reliability demonstration test is required dictating a particular set and length of tests with a required sample size it usually does not represent a true reliability test and no demonstrated reliability can be claimed if that test was a success (without a failure). Even though those tests can represent some duration in life, there can be no correlation made between performance verification and item reliability.

Completion of verification tests proves that the item conforms to the design specifications so that it can perform when subject to the listed extreme stresses. The sample size typically is inadequate for any reliability demonstration or robustness to manufacturing variation, and the fact that the small item samples are subject to limited test sequences does not allow any statements about their reliability for all stresses expected to be experienced in their use.

6 Accelerated testing strategy in product development

6.1 Accelerated testing sampling plan

For a qualitative accelerated test (Type A test) the sample size is determined by the number of stresses and the number of identified failure modes. It can be necessary for an item to be removed from the test either because the destruct limit has been found or because the item is necessary for failure (mode) analysis. In some cases the item may be repaired and the test continued. Therefore a number of spare modules and spare parts should be available during the HALT. But it is recommended not to count on a repair being possible. Therefore the test should be planned for at least one sample per stress type. For a classical HALT this means one for cold temperature, one for high temperature, one for vibration, one for temperature cycling and one for combined temperature cycling and vibration. In total this is five. To account for more than one failure mode another two to five samples are recommended, so the total recommended sample size is seven to ten items. If that number of items is not available repairs can be made during the test.

For a quantitative accelerated test (Types B and C tests) the number of items are mainly determined by whether the purpose of the test is to estimate the average constant risk (exponential failure distribution assumed) or the purpose is to estimate the time to failure (life time) for the items.

For the exponential case the advantage is that the accumulated test time can be increased by increasing the sample size as the accumulated test time is calculated as sample size multiplied with test time. In this case it is assumed that testing one item for 1 000 h gives the same result as testing 1 000 items for one hour each. Obviously this is not the case. Therefore both the sample size and the test time need to be chosen so as to have a realistic picture of the failure mode (time to the different failure modes) as well as the differences of strength from item to item (number of samples in the test). A typical sample size for an accelerated component test is 77 samples for 1 000 h (see JESD47B [2]). For the exponential case, test plan standards like IEC 61123 and IEC 61124 can be used. If a weak distribution is suspected the sample size should be so large that at least one weak item is with high probability expected in the test. The accumulated test time can be multiplied with the estimated acceleration factor in order to estimate the equivalent number of operating hours in the field. The average failure rate can be estimated using IEC 60605-6 [18].

For the case where the purpose of the test is to estimate the time to failure (life time), the test time shall be long enough to give enough time to estimate the time to failure for the different failure modes. Each failure mode has to be calculated separately (see IEC 61649 and IEC 61710). For a test analysed using the Weibull distribution at least five to ten failures should be expected. Since a Weibull test is often stopped once one third of the tested items have failed the sample size should be 15 to 30 items. If more than one failure mode is expected these numbers should be increased with the expected failure modes. If a weak distribution is suspected the sample size should be so large that at least one weak item is with high probability expected in the test. For example if a weak population of 5 % is suspected the sample size should be at least 30 items. In order to reduce the test time and the number of items that fail (e.g. are destroyed) during the test, sudden death test can be used (see IEC 61649).

6.2 General discussion about test stresses and durations

Often the test methods of the IEC 60068 series [12] are used. These standards give different test severities but no guidance on which severity to use. Some guidance can however be found in the IEC 60721 series.

When comparing test conditions with field conditions it will seldom be possible to simulate the field conditions since they vary with user, climatic conditions, etc. Therefore representative or worst case conditions should be chosen. Some tests operate with the term "severe user" which is a user defined so that only a small percentage, for example 1 % of the users, operates the item under higher stress conditions.

When testing for life time, for example using a test of Type C, the test is usually extended to more loading cycles or longer time than the item is expected to encounter in the field in order to take into account the variations in the stress and strength distribution and ensure a proper confidence in the estimated reliability. This is called multipliers of the stress duration or life time ratio L_v (see 5.7.2.7 and Annex B).

Since the conditions of usage vary from user to user, geographically and over time the test conditions have to be simplified. For practical reasons the stress types are often applied in sequence instead of simultaneously. If the stress types are tested on different samples the test will not detect the effect of interactions between the stress types. Therefore it is recommended to combine stresses when possible. However, this usually requires more complicated and expensive test equipment. When stress types are applied sequentially it is important to combine the stresses to test cycles where the different stress types are applied in sequence for example during one day or one week. This test cycle is then repeated the required number of times. It will often also be a consideration that the test is reproducible. This is important for test laboratories that test equipment for approval. An example is a drop test of an item. If the test is performed so that the item always hits in the same angle, the test will be very reproducible, but will not simulate the conditions in the field, where the angle at which the item hits will be random.

6.3 Testing components for multiple stresses

Normally components are tested for each stress type separately (see JESD47B [2]). However, in some cases, a combined test is used in order to test for the combined effect of stresses. One example is preconditioning of components by exposing them to three times a thermal cycle equal to the soldering profile. Even though the component is not soldered in this preconditioning, the temperature cycling affects the interior of the components in a way similar to the soldering process. Another example of a combined test is thermal cycling after a moisture sensitivity level test to see if delamination in the components propagates (see JESD22-A113 [19] and JESD22-A104 [20]). Often the component testing will target a specific failure mode in order to verify that the failure mode is not present in the component, or the time to failure is acceptable. Component tests are often made on test structures instead of on functioning components in order to save test effort and qualify the technology used for a family of components. For components accelerated tests of Types B and C are recommended, unless the component test is done as a part of root cause investigation in which case Type A tests can be recommended.

6.4 Accelerated testing of assemblies

Assemblies are often tested for each stress type separately. But since there are more interactions possible in an assembly than in a component, combined stresses are more important for assemblies. Often assemblies have a size and a function suitable for a HALT test since HALT tests often do not work well with small items (components) or large items (systems). For assemblies accelerated tests of Types A, B and C should be considered. Often the maximum applicable stress in a Type B or C test is determined by the weakest component in the assembly.

6.5 Accelerated testing of systems

Systems are often tested with combined stresses using tests of Types B and C. Often these stresses are combined in a test cycle. If the components and assemblies have been tested previously, the test on system level will mainly test the integration of the components and the assemblies. Usually the system will also include embedded software and this shall be taken into account in the test (see IEC 62429). In many cases the exponential time to failure assumption is made since the sample size is small and ideally there should be no failures or only a few failures in the test. Often tests on system level are used for reliability growth testing (see IEC 61014 [13] and IEC 61164 [17]).

6.6 Analysis of test results

For qualitative accelerated testing (Type A tests) the result is the failure mode and the stress conditions at which they were observed. A thorough failure analysis is required to find the root cause of the failure and estimate by an engineering evaluation if the failure mode can occur at lower stress levels in the field due to the variations of the strength and stress distributions (see 5.1.1.2). The purpose of the HALT test is to identify the few weaknesses in the item that need to be improved for the whole item to be sufficiently robust. The tests of Type A do not give an estimate of life time or failure rate for the item.

For quantitative accelerated tests (Types B and C) the acceleration factor shall be estimated to link the test time with the equivalent time in the field. Each failure mode shall be analysed separately. Therefore a failure analysis is required for all failures. Failures need to be classified as relevant or non-relevant. The non-relevant failures are those failures that cannot happen in the field, this includes failures caused by error of the test equipment or from the operation of the test equipment. Once an estimate has been made for each failure mode observed, the failure probability and time to failure can be added to estimate the failure probability of the item as a function of time (see 5.2.2.1) based on the relevant failures. Statistical tools that can be used for analysis include IEC 61123, IEC 61124, IEC 60605-6 [18], IEC 61649 and IEC 62429.

7 Limitations of accelerated testing methodology

There are several major limitations to accelerated reliability testing methodologies shown in the following list (which is not exhaustive):

- Determination of acceleration factors is very complex and can be cost and time prohibitive. Thus, accelerated testing duration and reliability results (values), which are dependent on acceleration factors, have limited precision.
- It can be very difficult at times to speculate which stresses contribute in combination to a specific failure mode and to what degree. Therefore the acceleration factor for combined influences also can be over or underestimated.
- Items to be tested can be too large, or too expensive. In either case, the sample size may be limited for a reasonable confidence level in test.
- Test equipment, which includes automated test monitoring, can be too complex to be affordable or manageable.
- Some means of test acceleration will possibly not be attainable because of large thermal masses of the tested items or because of limited stress rating. Thus testing can also become time and cost prohibitive due to lack of efficient acceleration.
- In HALT, the number of test samples is frequently small, and will possibly not be representative of the average strength of all of the items, so that its destruct design limits can also be different, pointing to wrong conclusions. An opposite case is also possible, where the test unit can be of higher strength than that of the average samples.
- In components testing, usually the curves are constructed based on times to failures, and those are used for determination of test acceleration and for information on components reliability. When the components are small and have failed catastrophically (burned or greatly changed physical properties), it often is not possible to determine in which failure mode they did fail, therefore, the results can be fitted with the wrong distributions, resulting in the wrong reliability information.
- Accelerated testing of items yields information on only stresses and their combination that are considered for test preparation. The test results cannot be used if the item is used in a different manner or in different environments. A re-test would be required.
- The results of quantifying reliability through acceleration cannot always be predictive on an individual item since it can operate at different stress levels than was tested.

Annex A (informative)

Highly accelerated limit test (HALT)

A.1 HALT procedure

Table A.1 illustrates the differences between classical accelerated tests and HALT tests.

Table A.1 – Comparison between classical accelerated tests and HALT tests

Test type	Sample size	Test time	Number of failures	Analysis
Classical test	Large (typically 30 to 60)	Very long (months)	Zero or few failures (typically less than 5)	The test is planned so all observed failures should be relevant for field conditions
HALT test	Small (typically 10)	Very short (days)	Several failures (typically 10 or more)	Each failure shall be analysed to evaluate whether it is relevant for field conditions

Figure A.1 illustrates how FMEA (see IEC 60812 [6]) gives input to HALT and receive results from HALT. One advantage of HALT is that it can identify failure modes that were not expected when making the FMEA.

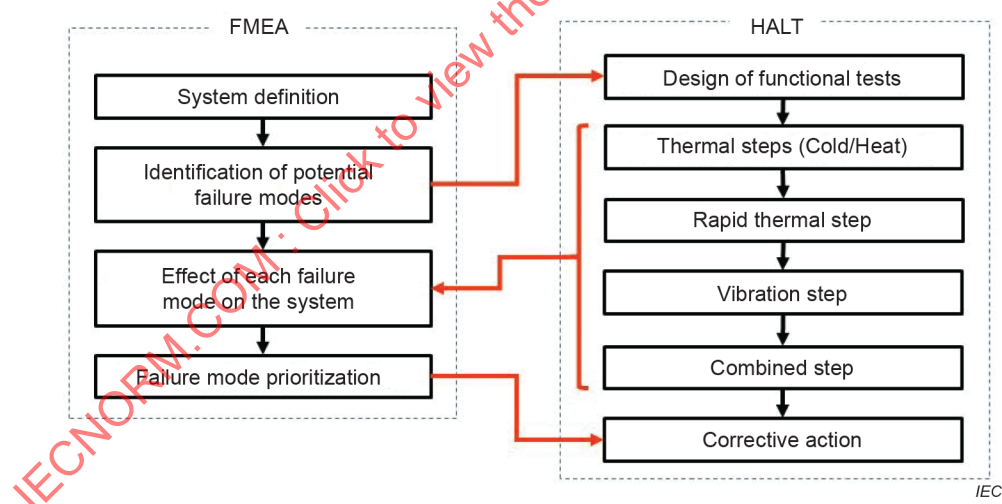


Figure A.1 – How FMEA and HALT supplement each other

A.2 HALT step-by-step procedure

A typical procedure for HALT is as follows:

- Step 1: Determine the stress level where the test will be stopped if the unit under test (UUT) has not failed.

- Step 2: Set-up: mount the UUT in the HALT chamber and make the necessary connections for power supply, signals in and out, connections to monitor the function of the UUT, etc. The stress level on the UUT should be monitored by sensors (e.g. temperature sensors, accelerometers). Care should be taken that the connections can survive the stresses applied in test. In some cases part of the UUT that need not be exposed to high stresses, are placed outside the chamber, so HALT is not applied to them.
- The item should be mounted to the HALT vibration fixture so that the desired vibrations or shock profiles are applied to the UUT without being significantly dampened. The fastening or fixture should not protect the UUT from rapid air movements in the chamber. In some cases it can be necessary to remove enclosures to allow free access of the chamber air to the interior of the UUT. It can also be necessary to remove plastic enclosures or parts or components that cannot survive the high temperature or vibration acceleration during the test.
- Step 3: Initial testing: the UUT shall be functionally operational prior to HALT. The monitoring devices also need to be tested for their proper functionality. Connections to the UUT also need to be checked for their integrity and capability to withstand the stresses in the HALT chamber, for example high air flow.
- Step 4: Increase the applied stress to the desired level. If the UUT is continuously monitored, the stress level may be increased continuously. If continuous monitoring is not possible, the stress levels shall be increased in steps, allowing the UUT to stabilize at each level before it is functionally tested to gather the possible failure information (if a failure did occur). The stress level is then reduced to see if the function of the UUT is resumed, possibly after a reset. If the functionality resumes, then the stress level where the UUT stopped functioning is the operating limit (OL).
- Step 5: The stress level is increased until the UUT can no longer resume functioning even when the stress level is decreased. This stress level is the destruct limit (DL). In some cases the function can be resumed when the stress is removed even though there is a permanent damage (e.g. a crack). Therefore a so called detection screen is used where the UUT is subjected to a weak vibration level during the functional testing to activate intermittent failures. The UUT is then inspected and if necessary removed from the test chamber so that enough information can be collected to determine the failure mode, and if possible the root cause of the failure. In some cases the UUT will be permanently removed for failure analysis. In that case a new UUT should be mounted and the test continued. Where possible the fault in the UUT should be repaired, and the weak part of the design should be strengthened (e.g. by support or filling material) or protected (e.g. by directing cool air to the position or isolating the item against cold air as relevant). In some cases the part of the weaker design can be protected from the high stress or even moved out of the test chamber with connections to the rest of the UUT inside. In this way the test should be allowed to continue to find the next weakest part of the design.
- Step 6: Continue until the DL has been found or the limit determined in Step 1 has been reached.
- Step 7: Repeat the procedure from Step 2 to Step 6 with another type of stress (e.g. hot air).
- NOTE The traditional HALT uses the following sequence of stresses: low temperature, high temperature and cycling between high and low operating temperatures.
- Step 8: Repeat Step 2 to Step 6 with cycling between UOL and LOL. Thermal cycling should avoid failure modes observed at temperature stress steps, therefore the operating levels UOL and LOL are used.
- Step 9: For the traditional HALT now repeat Step 2 to Step 5 with vibration or shock pulses.
- Step 10: For the traditional HALT combine thermal cycling (Step 8) and vibration (Step 9).
- Step 11: Repeat Step 2 to Step 5 for the combined stresses.
- Step 12: Perform failure analysis to determine which failure modes can occur at lower stress in the field use. Estimate the margin of the design taking into account the worst field conditions and the variations in the manufacturing processes.

Step 13: Report result. When the design improvements are implemented, it is recommended for the UUT to be retested, if possible, to verify improvement (IEC 60300-3-5).

Depending on the type of item and its sensitivity, the order of test stresses can be changed.

A.3 Example 1 – HALT test results for a DC/DC converter

Examples in Table A.2, Table A.3 and Table A.4 are from [21].

The DC/DC converter is designed for installation in an aeroplane.

Table A.2 – Summary of HALT results for a DC/DC converter

Exposure	Result	Remarks	Possible cause	Action
Low temperature	LOT –70 °C (start-up) LOT –76 °C (operation) LDT Not found	Weakness: start-up unstable	Unstable start-up of 5 V and 3,3 V at low temperature Characteristics changed – Ripples	None Limit of technology
High temperature	UOT +125 °C UDT Not found	Weakness: 12 V disappeared	Internal temperature limit causes shutdown	Limit set in software
Vibration	OVL 294,3 m/s ² RMS 588,6 m/s ² RMS VDL 588,6 m/s ² RMS	Loose screw Unstable voltage	Screw too loose Hand-solder failed	Apply Loctite ² Solder processes
Temperature cycling –65 °C to +120 °C 4 min to 10 min dwell time	No weaknesses found after more than 20 cycles			
Combined vibration and temperature cycling 40 g RMS, 50 g RMS and 60 g RMS –65 °C to +120 °C		3 components fell off PWB Problems with 5 V DC		Review fixing processes Further investigation required
SOURCE: Reference [21], reproduced with permission of the authors.				

NOTE To enable the DUT to be tested during the test the levels in the combined vibration and temperature cycling test has been reduced.

A.4 Example 2 – HALT test results for a medical item

The medical item is designed for diagnostic use at a hospital.

² Loctite is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

Table A.3 – Summary of HALT results for a medical system

Exposure	Result	Remarks	Possible cause	Action
Low temperature	LOT –35 °C (module) LOT 0 °C (PC) LDT Not found	–20 °C. Output unstable. –35 °C. System stops		Error not found but similar problems seen in production at +10 °C
High temperature	UOT +59 °C +60 °C +70 °C UDT Not found +60 °C +70 °C UDT Not found	Stops after switching task. Fan does not start. 3,3 V shorted. Keyboard error		Oscillator failure To be analysed Component failure To be analysed Component failure
Vibration	OVL 49,05 m/s ² RMS OVL 196,2 m/s ² RMS OVL 490,5 m/s ² RMS VDL 294,3 m/s ² RMS	Keyboard error Output not updated Lines on screen No keyboard response Front end error Module stopped		Component as at +70 °C Reworked component Loose capacitor? Capacitor and cable loose Crystal defect 4 transmitters defect Short in filter
Temperature cycling 5 °C to + 55 °C. 10 min dwell time	No weaknesses found after 6,5 cycles			
Combined vibration and temperature cycling 30 g RMS, 40 g RMS and 50 g RMS 5 °C to +55 °C	98,1 m/s ² RMS and temp. cycle 294,3 m/s ² RMS temp. cycle 294,3 m/s ² RMS and +80 °C 490,5 m/s ² RMS and –20 °C 490,5 m/s ² RMS temp. cycle 490,5 m/s ² RMS temp. cycle	Module stopped Keyboard error Module stopped Language change Unable to start Two functions unstable		Troubleshooting Component and reset failed No test possible SW – battery? Module defect Filter failed Further examination required
SOURCE: Reference [21], reproduced with permission of the authors.				

NOTE To enable the DUT to be tested during the test the levels in the combined vibration and temperature cycling test has been reduced.

When the top 10 list of field failures were compared to the failures found during the HALT test it was seen that all failures except one had also been found during the HALT test. The failure that was not found was due to this part of the item not being tested in the HALT chamber [21].

A.5 HALT test results for a Hi-Fi equipment

The modules were designed for use in a Hi-Fi equipment for domestic use.

Table A.4 – Summary of HALT results for a Hi-Fi equipment

Exposure	Result	Remarks	Possible cause	Action
Low temperature	LOT –55 °C LDT Not found	Noise during change from radio to CD		None
High temperature	UOT Not found UDT Not found	Test stopped at +110 °C due to test cable failure		None
Vibration	OVL 245,25 m/s ² RMS 294,3 m/s ² RMS VDL 343,35 m/s ² RMS	5 components failed 1 component failed		Mounting of components
Temperature cycling –50 °C to +100 °C 30 min dwell time 10 cycles		Incipient stress symptoms at solder joints of heavy components (not critical after 10 cycles)		Solder joints analysed
Combined vibration and temperature cycling 10 g RMS, 20 g RMS, 30 g RMS, 40 g RMS and 50 g RMS –50 °C to +100 °C		Problems regarding CD playing at low temperature		Mounting of 2 components
SOURCE: Reference [21], reproduced with permission of the authors.				

NOTE To enable the DUT to be tested during the test the levels in the combined vibration and temperature cycling test has been reduced.

For more detailed information see [21].

Annex B (informative)

Accelerated reliability compliance and growth test design

B.1 Use environment and test acceleration

To successfully design an accelerated reliability test it is necessary to have a good knowledge of the intended use environment, environmental and operational profile of the item, and item design capabilities. Acceleration of various stresses is a well established technique published in the literature, books and articles. They are based on the assumption that the test demonstrates the strength of an item regarding the applied environmental and operational stresses, and shows whether the UUT did have a related failure (success or life test). When using such tests, the design can be improved to withstand these stresses (reliability growth test). This methodology is briefly discussed in Clause B.2.

B.2 Determination of stresses and stress duration

The item is expected to be reliable regarding each of the applied environmental and operational stresses, thus its overall reliability is the product of individual respective reliabilities. For a predetermined life t_0 , item reliability is then written as:

$$R_{\text{item}}(t_0) = \prod_{i=1}^S R_{\text{Stress}_i}(t_i) \quad (\text{B.1})$$

In the above equation R_{Stress_i} denotes reliability of the item regarding individual stresses (operational or environmental). Environmental stresses here are those climatic (thermal exposure, thermal cycling, humidity, the ramp rate of the use temperature, etc.) and dynamic (vibration – random or sinusoidal or both, shock – such as potholes for vehicles, transportation, door slam, etc.). Their application and levels depend on item use environmental stresses, average and extreme. Other stresses related to item operation which vary with the use profile, are included in the group operational stresses. Examples of such operational stresses are: ON/OFF cycling, power stresses and voltage variations.

For the test, a reliability value is allocated to each of the multiples in the expression for the item reliability. The allocated values to reliability regarding individual stresses differ depending on the item intended use and usage profile and its sensitivity to a particular environmental parameter. Reliability value also should be allocated to the interaction factor. The nominal duration of the test for the actual stresses is calculated based on the cumulative damage model and the stress-strength criteria. Here the equivalent test damage occurs by increasing the magnitude of each of the individual stresses, all within the maximum design limits of the item.

In this accelerated reliability test to simulate real life exposure, all of the test units (n) are subject to each of the stresses in the entire test sequence.

B.3 Overall acceleration of a reliability test

Regardless of the reliability demonstration test type, the main principle is the failure rate acceleration:

$$\lambda_A = AF_{\text{Test}} \times \lambda_0 = \sum_{i=1}^{N_S} \left(AF_i \prod_k AF_k \times \lambda_i \right) \quad (\text{B.2})$$

where

λ_0 is the failure rate that the item has in its use conditions;

λ_A is the accelerated test failure rate;

AF_i is the acceleration factor for each of the increased stresses in test;

λ_i is the failure rate of the item corresponding to the specific stress;

N_S is the number of stresses;

$\prod_k AF_k$ is the product of the acceleration factors of stresses affecting the failure mode i .

The total equivalent test acceleration is:

$$AF_{\text{Test}} = \frac{\sum_{i=1}^{N_S} \left(AF_i \times \prod_k AF_k \times \lambda_i \right)}{\lambda_0} \quad (\text{B.3})$$

$$AF_{\text{Test}} = \frac{\sum_{i=1}^{N_S} \left[AF_i \times \prod_k AF_k \times \left[-\frac{\ln(R_i(t_0))}{t_0} \right] \right]}{\lambda_0} \quad (\text{B.4})$$

Simplified by assumption that equal reliability can be allocated to each of the stresses:

$$\begin{aligned} R_i(t_i) &= R_S(t_0) = \sqrt[N_S]{R_0(t_0)} \\ \lambda_i &= \lambda_s = \text{const.} \\ \lambda_0 &= N_S \times \lambda_s \end{aligned} \quad (\text{B.5})$$

$$AF_{\text{Test}} = \frac{\sum_{i=1}^{N_S} \left(AF_i \times \prod_k AF_k \times \left[\frac{1}{N_S} \times \frac{\lambda_0 \times t_0}{t_0} \right] \right)}{\lambda_0} \quad (\text{B.6})$$

Then the overall acceleration factor becomes:

$$AF_{\text{Test}} = \frac{1}{N_S} \times \sum_{i=1}^{N_S} \left(AF_i \times \prod_k AF_k \right) \quad (\text{B.7})$$

B.4 Example of reliability compliance test design assuming constant failure rate or failure intensity

B.4.1 General

The reliability compliance tests in IEC 61124 are based on the assumption of the constant failure rate or failure intensity. The primary measure of reliability in these tests is mean time to failure, MTTF, or mean time between failures, MTBF; therefore, these tests are applicable for the tests without replacements or repair of the failed units as well as for the tests with replacement or repair of the tested units.

In this example constant failure rate or failure intensity is assumed and the life time-ratio L_V is 1, since no wear-out is assumed. But L_V is retained in the equations to enable computations of cases assuming non constant failure intensity.

In each case, the tests are based on requirements or goals for reliability as well as for producer and customer risk or confidence in the test results. Table B.1 represents an example of the use environment for an automotive electronic device.

Table B.1 – Environmental stress conditions of an automotive electronic device

Parameter	Symbol	Value
Required life	t_0	10 years = 87 600 h
Required reliability	$R_0(t_0)$	0,8
Time ON	t_{ON}	2 h/day = 7 300 h
Temperature ON	T_{ON}	65 °C
Time OFF	t_{OFF}	22 h/day = 80 300 h
Temperature OFF	T_{OFF}	35 °C
Thermal cycling	ΔT_{Use}	45 °C, twice a day
Total cycles	N_{Use}	7 300
Temperature ramp rate	ξ	1,5 °C/min
Vibrations, random	W_{Use}	16,68 m/s ² RMS
Relative humidity	RH_{Use}	50 %
Activation energy	E_a	0,7 eV – for moisture 0,9 eV

NOTE The software program used to calculate this example uses Boltzmann's constant k_B as $8,63 \times 10^{-5}$ eV K⁻¹ in accordance with [22].

To ensure as much synergy among different stresses as possible, it usually is the practice to apply multiple stresses during the same test, as many as the test set-up equipment or facilities allow. Thus it is often the case that the thermal cycling is combined with the thermal exposure, operational cycling and the applied power. In those cases, the stresses are distributed so that they are spread throughout the duration of such a test. Those tests for which it is not possible or practical to perform simultaneously with others, such as humidity and often vibration, it is recommended that the tests are evenly distributed so that the cumulative damage of the stress on the units corresponds to that experienced in use.

For the example given in Table B.1, where the required 10 year reliability was 0,8, the corresponding MTBF is:

$$\Theta_0 = -\frac{t_0}{\ln(R_0(t_0))} \approx 393000h \quad (B.8)$$

Depending on how many failures are experienced in the test, if the SPRT test plan A.10 from IEC 61124 is used, the minimum test time is 3,23 times the MTBF, meaning it can be required that the test duration be 1 268 008 h. If there were 20 test units, then the test would have to continue through for about 63 400 h = 7,2 years (a cost and schedule prohibitive endeavour). Therefore accelerated testing is used.

The reliability of the item regarding each of the stresses is:

$$R_i(t_0) = [R_0(t_0)]^{1/4} = 0,946 \quad (B.9)$$

This example uses the stress conditions shown in Table B.1.

B.4.2 Thermal cycling

$$\Delta T_{Use} = 45 \text{ }^{\circ}\text{C};$$

$$T_{Test} = 105 \text{ }^{\circ}\text{C} \text{ to } -20 \text{ }^{\circ}\text{C} \text{ (the 105 degrees consists of a chamber temperature of 85 }^{\circ}\text{C and a 20 degree temperature rise in the UUT when ON);}$$

$$\Delta T_{Test} = 105 + (20) = 125 \text{ }^{\circ}\text{C};$$

$$\zeta_{Use} = 1,5 \text{ }^{\circ}\text{C/min};$$

$$\zeta_{Test} = 10 \text{ }^{\circ}\text{C/min};$$

$$m = 1,9;$$

$$N_{Test} = N_{Use} \times L_v \times \left(\frac{\Delta T_{Use}}{\Delta T_{Test}} \right)^m \times \left(\frac{\zeta_{Use}}{\zeta_{Test}} \right)^{\frac{1}{3}} \quad (B.10)$$

$$N_{Test} = 557 \text{ cycles.}$$

B.4.3 Thermal exposure, thermal dwell

Normalize the duration at the OFF temperature to the ON conditions:

$$t_{ON_N} = t_{ON} + t_{OFF} \times \exp \left[-\frac{E_a}{k_B} \left(\frac{1}{T_{OFF} + 273} - \frac{1}{T_{ON} + 273} \right) \right] \quad (B.11)$$

$$t_{ON_N} = 15\,055 \text{ h.}$$

Calculate the necessary accelerated test duration:

$$t_{T_{Test}} = t_{ON_N} \times L_V \times \exp \left[-\frac{E_a}{k_B} \times \left(\frac{1}{T_{ON} + 273} - \frac{1}{T_{Test} + 273} \right) \right] \quad (B.12)$$

$$t_{T_{Test}} = 1\,188 \text{ h.}$$

For stress synergism, combine the thermal exposure with the thermal cycling, distributing the thermal exposure over the high temperature of the thermal cycling to determine thermal dwell at the high temperature.

$$t_{TD} = \frac{t_{T_{Test}}}{N_{Test}}$$

$$t_{TD} = 2,13 \text{ h} = 128 \text{ min} \quad (B.13)$$

With the ramp rate measured on the device of 10 °C/min and the stabilization time at high and low temperature of 5 min the duration of the thermal cycle will be:

$$t_{TC} = 2 \times (\text{ramp time}) + (\text{stabilization time} + \text{thermal dwell}) + \text{dwell at cold}$$

$$t_{TC} = 2 \times (125/10) + 128 + 5 = 158 \text{ min} = 2,63 \text{ h} \quad (B.14)$$

B.4.4 Humidity

This test is performed at $RH_{Test} = 95 \%$, and temperature, $T_{RH} = 85 \text{ °C}$.

The duration of humidity exposure is equal to the normalized temperature exposure, t_{ON_N} .

$$t_{RH_{Test}} = L_V \times t_{ON_N} \times \left(\frac{RH_{Use}}{RH_{Test}} \right)^h \times \exp \left[\frac{E_a}{k_B} \times \left(\frac{1}{T_{ON} + 273} - \frac{1}{T_{RH} + 273} \right) \right] \quad (B.15)$$

with

$$h = 3;$$

$$E_A = 0,9;$$

$$t_{RH\text{Test}} = 392 \text{ h.}$$

where parameter h is the exponent for the power law humidity acceleration factor.

Since the humidity test also contributes to the thermal dwell damage there is a need to compensate for this. Equation (17) can be used to estimate the equivalent of 392 h at 85 °C at a temperature of 105 °C. This is 118 h that need to be subtracted from the 1 188 h. Distributed on 557 cycles this means that the 105 °C dwell in each cycle has to be reduced by 13 min out of the 128 min.

B.4.5 Vibration test

The required kilometre age for ten years was 240 000 km, which translates into 150 h per axis vibration at 1,7 g RMS:

$$W_{\text{Use}} = 1,7 \text{ g RMS};$$

$$W_{\text{Test}} = 3,2 \text{ g RMS};$$

$$L_v = 1,0.$$

$$t_{\text{Vib Test}} = L_v \times t_{\text{Vib Use}} \times \left(\frac{W_{\text{Use}}}{W_{\text{Test}}} \right)^w \quad (\text{B.16})$$

with

$$w = 4;$$

$$t_{\text{Vib Test}} = 12 \text{ h per axis.}$$

Vibration, when accelerated, shall have the same profile (same frequency content) as when not accelerated. A different vibration profile would not allow a meaningful acceleration.

B.4.6 Accelerations summary and overall acceleration

For the four tests accelerated in B.4.2, B.4.3, B.4.4 and B.4.5 (the number of stresses $N_S = 4$), the acceleration factors are as follows:

$$AF_{\text{TC}} = \frac{N_{\text{Use}}}{N_{\text{Test}}} = \frac{7300}{557} = 13,1 \quad (\text{B.17})$$

$$AF_{\text{TD}} = \frac{t_{\text{ON}_N}}{t_{\text{TTest}}} = \frac{15055}{1188} = 12,7 \quad (\text{B.18})$$

$$AF_{RH} = \frac{t_{ONN}}{t_{RH_{Test}}} = \frac{15055}{392} = 38,4 \quad (B.19)$$

$$AF_{Vib} = \frac{t_{VibUse}}{t_{Vib_{Test}}} = \frac{150}{12} = 12,5 \quad (B.20)$$

To determine the overall acceleration factor, it will be assumed that vibration and thermal cycling are stresses that would accelerate the same failure modes, while thermal exposure and humidity would accelerate another failure mode.

The overall acceleration factor would then be:

$$AF = \frac{((AF_{TC} \times AF_{Vib}) + (AF_{RH} \times AF_{TD}))}{N_S} \quad (B.21)$$

$$AF = 162,86 \quad (B.22)$$

It is important to notice the difference between the standard practice of multiplying all of the acceleration factors, which would provide an overly estimated overall test acceleration of:

$$AF_{SP} = AF_{TC} \times AF_{Vib} \times AF_{RH} \times AF_{TD} = 8,05 \times 10^4 \quad (B.23)$$

It is intuitively apparent that this standard practice acceleration is extremely unrealistic and can lead to grossly erroneous reliability conclusions.

The acceleration of test then produces the following result:

$$\lambda_0 = -\frac{\ln[R_0(t_0)]}{t_0} = 2,55 \times 10^{-6} \quad (B.24)$$

$$\lambda_{Test} = -\frac{\ln[R_0(t_0)]}{t_0} \times AF = 4,16 \times 10^{-4} \quad (B.25)$$

Or using MTBF:

$$\theta_0 = 3,93 \times 10^5 \text{ h}$$

$$\theta_{\text{Test}} = 2\,416 \text{ h}$$

The compliance test shall then be designed for the above MTBF as a requirement. However, the test will not have to demonstrate the very high required MTBF, $\theta_0 = 3,93 \times 10^5 \text{ h}$, but owing to the test acceleration, the MTBF about 163 times lower, i.e. $\theta_{\text{Test}} = 2\,416 \text{ h}$ or 100 days. But the calendar duration of the test is determined by the number of thermal cycles (557 times $2,63 \text{ h} = 1464 \text{ h}$ or 24 days. To this, the humidity test of 392 h or approximately 17 days and the vibration test lasting $3 \times 12 \text{ h}$ have to be added. In total approximately 43 calendar days.

According to IEC 61124 Test plan A.10, the minimum test time (0 failures) is 3,23 times the MTBF to be verified, assuming a discrimination ratio $D = 1,5$ and the supplier and customer risk $\alpha = \beta = 20 \%$. If 20 items are tested in the accelerated testing the required minimum accumulated test hours is $T = 3,23 \times 2\,416 = 7\,804 \text{ h}$. With 20 items in the test the calendar duration of the compliance test is 390 h (16 days). For comparison with Clause B.5 the test time with three items to test would be 807 h (34 days).

B.5 Example of reliability compliance test design assuming non-constant failure rate or failure intensity (wear-out)

In this example the same data as in Clause B.4 are used. But since possible wear-out should be taken into account in the test, the life time ratio is different from 1. Assuming three items for test ($n = 3$), and $\beta = 2,0$ Figure 11 gives a life time ratio $L_v = 1,5$ for a probability of acceptance $C = 80 \%$ (20 % risk) and a minimum reliability $R = 80 \%$ (20 % failures at the end of life). The factor L_v shall be included in all the equations ((B.10) to (B.16)). This has been chosen in order to facilitate the use of the example for different L_v values ($L_v = 1$ as well as L_v different from 1). But in this case it is easier to multiply the accelerated test time with the L_v factor.

Assuming 0 failures during the test, the required test time is 1,5 times the specified life time for the item (87 600 h). Note that all three items in the test shall be tested for 131 400 h since the accumulated test time cannot be used in this case. With the acceleration factor $AF = 162,86$ the calendar test time would be 538 h – 22 days to verify an item life of 10 years.

NOTE 1 The life time ratio $L_v = 1,5$ has been selected so that it is not necessary to recalculate all equations in Clause B.4. But it does not mean that the method in IEC 62506:2013, Clause B.2 was correct.

Annex C (informative)

Estimating the activation energy, E_a

The following example illustrates how the activation energy can be estimated based on a test.

To estimate the activation energy for a typical component like a power amplifier (size 5 mm × 5 mm × 2 mm), and a typical failure rate of 90 FIT in operating condition, the supplier should, for example, test:

- 500 components for one year at 100 °C and observe one failure. The failure rate can be calculated as 228 FIT;
- another 300 components for one year at 125 °C and observe three failures. The failure rate can be calculated as 1 146 FIT;
- another 300 components for one year at 140 °C and observe nine failures. The failure rate can be calculated as 3 465 FIT.

If all failures are caused by the same failure mode the three failure rates can be plotted in a linear-log plot. If the three data points, with an engineering approximation can be modelled with a straight line, the Arrhenius equation applies, and the activation energy E_a is the slope of the straight line as shown in Figure C.1 below:

$$E_a = k_B \times \frac{\ln[\lambda(T)] - \ln[\lambda(T_0)]}{\frac{1}{T_0} - \frac{1}{T}} \quad (\text{C.1})$$

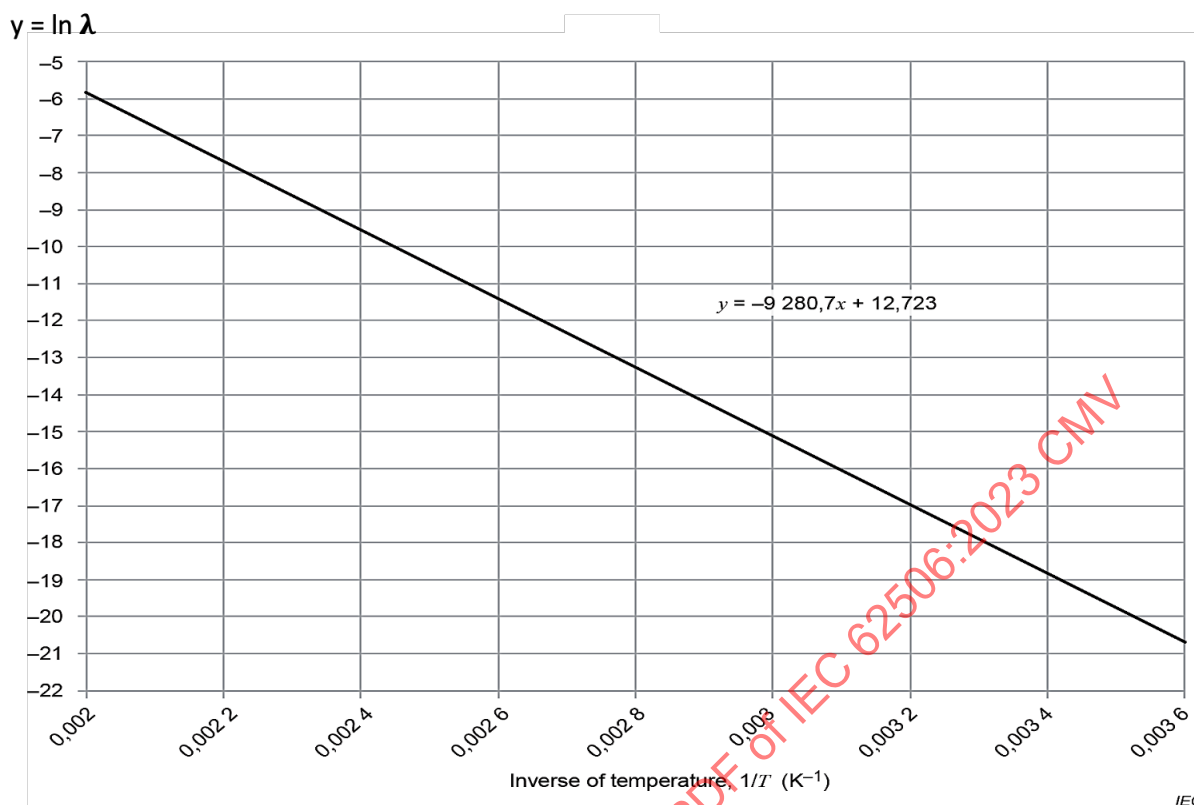


Figure C.1 – Plotting failures to estimate the activation energy E_a

From this example it can be clearly seen that estimating the activation energy is very time- and resource consuming. The activation energy should be estimated for each of the significant failure modes active in the component. Therefore the activation energies for the different failure modes are usually only estimated for a new component technology. Often these tests are made on test structures and not on functional components. The estimated activation energies are then used for all components manufactured using that component technology; therefore the user of components should get information on the activation energy of the dominating failure mode(s) from the component manufacturer.

Annex D (informative)

Calibrated accelerated life testing (CALT)

D.1 Purpose of test

The purpose of a calibrated accelerated life test (CALT) is to estimate the reliability or life time of an item based on three accelerated tests of a few samples. The procedure is adapted from GMW8758 [23]. There exists commercial software that supports the method.

D.2 Test execution

- Step 1 Based on an engineering evaluation determine the maximum stress level that can be applied in the test without the item failing immediately or after a very short time, or fail with a failure mode not expected in the field. This stress level will be higher than the normal stress level and outside the specifications for the item.
- Step 2 Select a stress level of for example 90 % of the level identified in Step 1. This is the high stress level.
- Step 3 Test at least two items at the stress level determined in Step 2 and record the number of cycles to failure or time to failure for each item.
- Step 4 Make a failure analysis of the failures observed in Step 3. If all items fail with the same failure mode then continue with Step 5. If more than one failure mode is observed the test should continue with Step 5 hoping that Step 5 will identify the dominant failure mode so the non dominating failure mode(s) can be treated as suspended items (see IEC 61649).
- Step 5 Reduce the stress level of Step 2 with for example 10 %. This is the medium stress level.
- Step 6 Test at least two items at the stress level determined in Step 5 and record the number of cycles to failure or time to failure of each item.
- Step 7 Identify the dominating failure mode and check that it is relevant for the failures expected in the field.
- Step 8 Plot the failures observed in Step 3 and Step 6 in two Weibull plots and determine the characteristic life for the two test samples (see IEC 61649). Plot only the dominant failure mode and treat any deviating failure modes as suspended items. If there is more than one significant failure mode the test shall be performed and analysed for each failure mode separately.
- Step 9 Plot the two characteristic lives against the stress levels on a log-linear scale if the Arrhenius model is expected to be relevant or on a log-log scale if the inverse power law model is expected to be relevant.
- Step 10 Extrapolate the line through the two points in the plot down to the expected stress level in the field.
- Step 11 Select a stress level that is as close as possible to the expected stress in the field taking into consideration the trade-off between the following two factors: The stress level should be as close to the expected worst case operating conditions ("the severe user") in the field as possible in order to reduce the risk of the extrapolation. On the other hand the stress level should be as high as possible in order to reduce the test time. The chosen stress level is called the low stress level.
- Step 12 Test at least two items at the stress level determined in Step 11 and record the number of cycles to failure or time to failure of each item. If more samples are available it is recommended to test them at this stress level.
- Step 13 Ensure that the same failure mode is dominating the tests at all three stress levels. Other failure modes are regarded as suspensions in this analysis (see IEC 61649). If more than one failure mode is significant they should be analysed separately.

- Step 14 Plot the failures observed in Step 12 in a Weibull plot and determine the characteristic life for the test samples (see IEC 61649). Plot only the dominant failure mode and treat any deviating failure modes as suspended items. If there is more than one significant failure mode the test need to be analysed for each failure mode separately.
- Step 15 Plot all three characteristic lives on the plot made in Step 9 and superimpose the best fit linear regression line through these three points. Extrapolate the line to the expected stress level in the field.
- Step 16 Read the expected characteristic life at the expected stress level in the field.
- Step 17 Estimate the empirical factors of the acceleration model based on the regression line identified in Step 15.
- Step 18 Transpose the cycles or time to failure for the data points from Step 8 and Step 14 to the expected stress level in the field, using the relevant acceleration model equations. There will be a different accelerating factor for each data point.
- Step 19 In the remaining analysis the data points estimated in Step 18 are plotted in a Weibull plot (see IEC 61649) as if all the items were tested at the expected stress level in the field. That means that the cycles or time to failure are the times or number of cycles estimated in Step 18 and the sample size is the total number of items tested including those that were suspended.
- Step 20 Add the confidence limit to the Weibull curve plotted in Step 19 and read the relevant reliability or time to failure at the expected stress level in the field for the tested items.

Annex E (informative)

Example of how to estimate empirical factors

A certain component type has been tested with temperature shock. A group A of 22 samples was tested between -40 °C and $+85\text{ °C}$. One in this group failed after 700 cycles and 2 after 1 000 cycles. A second test has been performed on 21 samples between -40 °C and $+150\text{ °C}$. In this second test group B, 4 failed after 300 cycles, 10 after 400 cycles, and an additional 3 after 500 cycles. The failure mode in all cases was delamination in one of the layers. The failure mode indicates that Weibull distribution should be applied for data analysis.

Data was analysed using the graphical method with a goal that the test data could be fitted with straight lines where the slope would provide the values of shape parameter, and the value of intercept would yield the value of the scale parameter. The derivation of this graphical method starts from the probability of failure:

$$F(c) = 1 - e^{-\left(\frac{c}{\eta}\right)^\beta} \quad (\text{E.1})$$

where

c is the number of thermal cycles (the variable);

β is the shape parameter;

η is the scale parameter.

The number of cycles to failure is plotted in a Weibull diagram according to IEC 61649 (see Figure E.1). Two Weibull curves are parallel with a shape parameter β value of approximately 6. This also indicates that it is the same failure mode in the two tests.

The equation for the probability of failure is rearranged to ultimately derive a straight line as follows:

$$\begin{aligned} 1 - F(c) &= e^{-\left(\frac{c}{\eta}\right)^\beta} \\ \frac{1}{1 - F(c)} &= e^{\left(\frac{c}{\eta}\right)^\beta} \\ \ln\left[\frac{1}{1 - F(c)}\right] &= \left(\frac{c}{\eta}\right)^\beta \\ \ln\left\{\ln\left[\frac{1}{1 - F(c)}\right]\right\} &= \beta \times \ln(c) - \beta \times \ln(\eta) \end{aligned} \quad (\text{E.2) to (E.5)}$$

$F(c)$ is determined as the median rank of numbers of failures:

$$F(c) = \frac{i - 0,3}{n + 0,4} \quad (\text{E.6})$$

where

i is the cumulative number of failures at the observed number of cycles;

n is the total number of items in test.

The data is shown in Table E.1.

Table E.1 – Probability of failure of test samples A and B

c	$F_A(c)$	$F_B(c)$
300		0,172 9
400		0,640 19
500		0,780 47
700	0,031 25	
1 000	0,120 536	

For data plotting see IEC 61649. The Weibull plot is shown in Figure E.1.

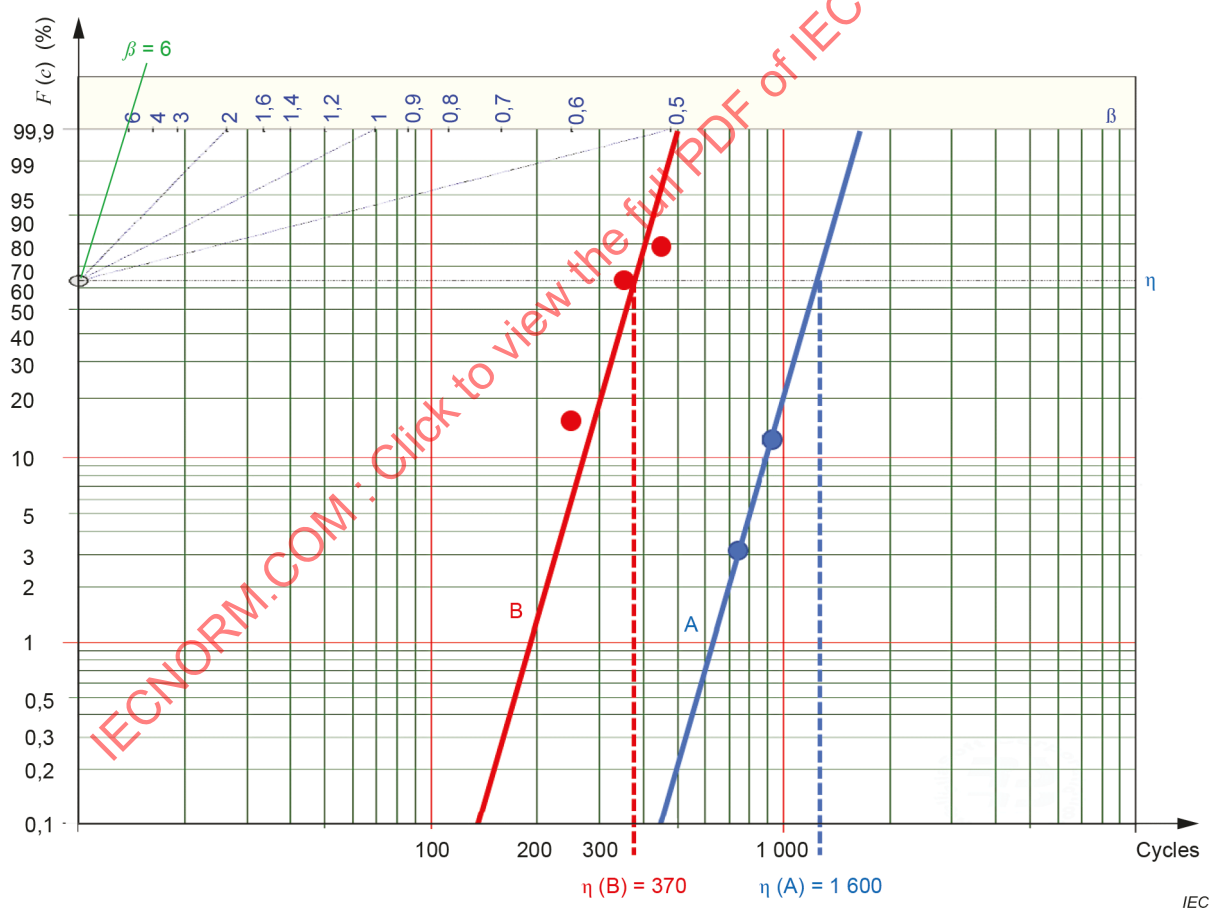


Figure E.1 – Weibull graphical data analysis

Equations of the linear data fit show values of the shape parameters based on the slope, and the intercept is the negative item of the shape parameter and the logarithm of the scale parameter.

Slopes of the two lines fitting test data have very similar values, confirming that the failure modes were indeed identical. The common value of the shape parameter is found to be:

$$\beta = 6,0$$

From the plot, the scale parameters determined for the two tests are as follows:

$$\eta_A = 1\,600 \text{ cycles}$$

$$\eta_B = 420 \text{ cycles}$$

The thermal cycling acceleration, AF_{190_125} between $\Delta T_B = 190\text{ °C}$ and $\Delta T_A = 125\text{ °C}$ is:

$$AF_{\Delta T_B \Delta T_A} = \left(\frac{\Delta T_B}{\Delta T_A} \right)^m = \frac{\eta_A}{\eta_B} \quad (\text{E.7})$$

Solving for the exponent m , which is a characteristic of the test items:

$$m = \frac{\ln\left(\frac{\eta_A}{\eta_B}\right)}{\ln\left(\frac{\Delta T_B}{\Delta T_A}\right)} \quad (\text{E.8})$$

In this example, the value of parameter m is calculated to be

$$m = 3,19$$

To determine a scale parameter for any temperature range of thermal cycling, ΔT , use Equation (E.9):

$$\eta(\Delta T) = \eta_B \times \left(\frac{\Delta T_B}{\Delta T} \right)^m \quad (\text{E.9})$$

To calculate the scale parameter corresponding to the thermal cycling in use of $\Delta T = 50\text{ °C}$ and for the temperature cycling range of 50 °C (in use), the probability of failure as a function of the number of cycles is given by the following Equation (E.10):

$$\eta(50) = 420 \times \left(\frac{190}{50} \right)^{3,19} \quad (\text{E.10})$$

$$\eta(50) = 29\,700$$

Annex F (informative)

Determination of acceleration factors by testing to failure

F.1 Failure modes and acceleration factors

Single acceleration factors are most meaningful when expressing the process acceleration of a single failure mode. The overall acceleration factor from one set of combined stresses to another is determined in the same manner as described in 5.5.

A single stress type is applied at several (a minimum of three) levels, each on a single group of components. The test duration is determined by components' failures, i.e. the test continues until all or the majority of components fail. Times to failure are recorded for each of the components at each of the stress levels, and the appropriate failure distributions are constructed. The scale parameters of those distributions are plotted for each of the stress levels, and the values are then fitted with a function which is best fitted for the values as a function of the applied stress levels. The ratio of the scale parameter versus the ratio of the stress levels determines the acceleration factor.

F.2 Example of determination of acceleration factor

A voltage acceleration factor was determined for a semiconductor (power transistor) by test at three voltages as shown in Table F.1.

Table F.1 – Voltage test failure data for Weibull distribution

Failure no. and voltage	Time to failure h	$F(t)$	$\ln(t)$	$\ln(\ln(1/(1-F(t))))$
1 27 V	100	0,07	4,61	-2,66
2 27 V	180	0,16	5,19	-1,72
3 27 V	240	0,26	5,48	-1,20
4 27 V	290	0,36	5,67	-0,82
5 27 V	335	0,45	5,81	-0,51
6 27 V	377	0,55	5,93	-0,23
7 27 V	420	0,64	6,04	0,03
8 27 V	450	0,74	6,11	0,30
9 27 V	470	0,84	6,15	0,59
10 27 V	485	0,93	6,18	0,99
1 26 V	600	0,07	6,40	-2,66
2 26 V	1 100	0,16	7,00	-1,72
3 26 V	1 580	0,26	7,37	-1,20
4 26 V	2 030	0,36	7,62	-0,82
5 26 V	2 430	0,45	7,80	-0,51
6 26 V	2 810	0,55	7,94	-0,23
7 26 V	3 160	0,64	8,06	0,03
8 26 V	3 460	0,74	8,15	0,30
9 26 V	3 710	0,84	8,22	0,59
10 26 V	3 910	0,93	8,27	0,99
1 25 V	1 800	0,07	7,50	-2,66

Failure no. and voltage	Time to failure t_h	$F(t)$	$\ln(t)$	$\ln(\ln(1/(1-F(t))))$
2 25 V	3 500	0,16	8,16	-1,72
3 25 V	5 000	0,26	8,52	-1,20
4 25 V	6300	0,36	8,75	-0,82
5 25 V	7 450	0,45	8,92	-0,51
6 25 V	8 450	0,55	9,04	-0,23
7 25 V	9 300	0,64	9,14	0,03
8 25 V	10 080	0,74	9,22	0,30
9 25 V	10 730	0,84	9,28	0,59
10 25 V	11 330	0,93	9,34	0,99

The data was plotted as a Weibull distribution, as shown in Figure F.1, and the trend lines were drawn. A good linear fit indicated that the times to failure were Weibull distributed, and the process was the same (very similar shape parameters), meaning that the failure mechanism was the same.

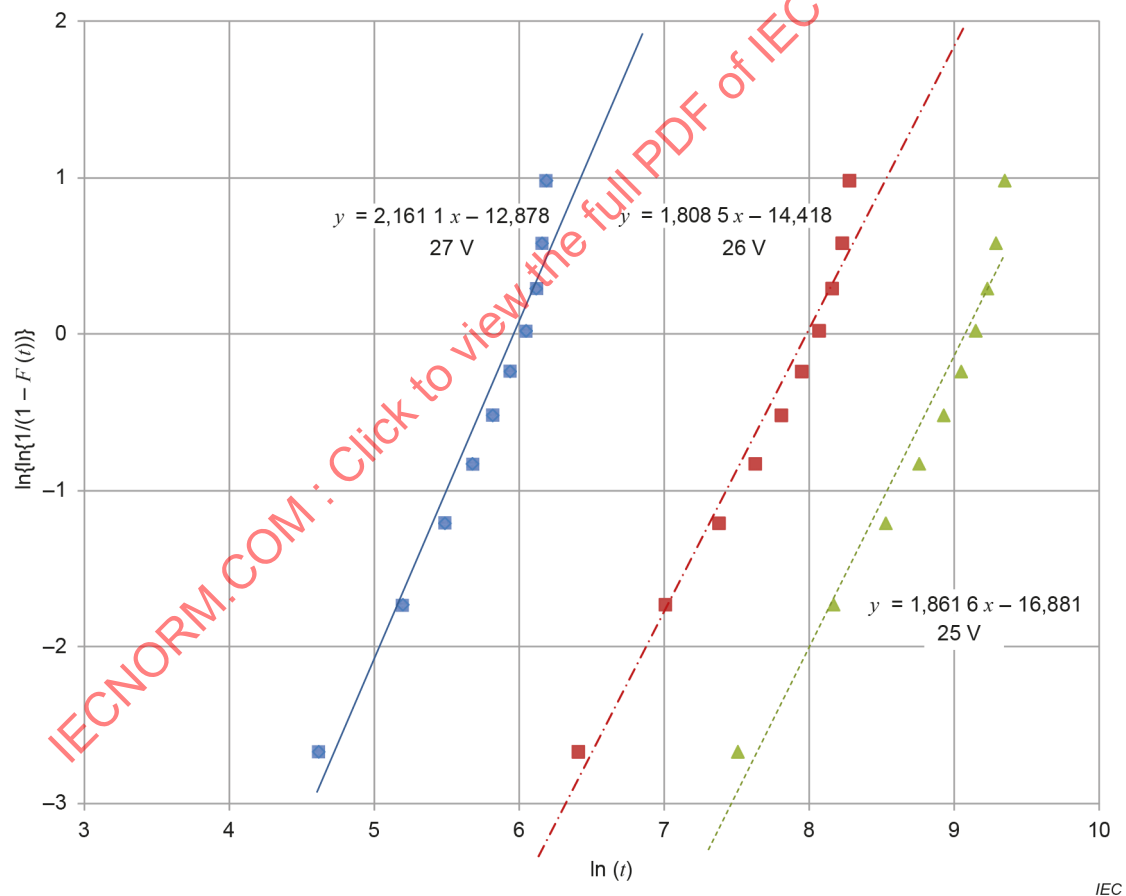


Figure F.1 – Weibull plot of the three data sets

From the equations shown in Figure F.1, the three values of the scale parameter were determined using Equation (F.1):

$$\eta = \exp\left(-\frac{b}{a}\right) \quad (\text{F.1})$$

where a and b are the parameters of the linear equation $y = ax + b$

From Equation (F.1) and Figure F.1 we get:

$$\eta(25 \text{ V}) = 8\,673,3$$

$$\eta(26 \text{ V}) = 2\,899,7$$

$$\eta(27 \text{ V}) = 387,2$$

The acceleration factor therefore is:

$$AF(25 \text{ V to } 26 \text{ V}) = 8\,673 / 2\,899,8 = 2,99$$

$$AF(26 \text{ V to } 27 \text{ V}) = 2\,899,8 / 387,6 = 7,48$$

$$AF(25 \text{ V to } 27 \text{ V}) = 8\,673 / 387,6 = 22,37$$

Note that $AF(26 \text{ V to } 27 \text{ V}) = AF(25 \text{ V to } 26 \text{ V}) \times AF(26 \text{ V to } 27 \text{ V}) = 2,99 \times 7,48 = 22,37$

The values of the scale parameter η as a function of voltage is determined as a power function:

$$\log \eta(V) = B \times V^{-m} \quad (\text{F.2})$$

Taking logarithm two times gives the linear function:

$$\log(\log \eta(V)) = -m \log V + \log B \quad (\text{F.3})$$

Using regression on this function, the values of the regression parameters can be found:

$$m = 5,5182$$

$$B = 2,1537 \times 10^8$$

$$\log B = 8,333\,2$$

Inserting the values in Equation (F.3) gives:

$$\log(\log \eta(V)) = -5,5182 \log V + \log 8,3332 \quad (\text{F.4})$$

With Equation (F.5) the η values for different voltages can be predicted.

$$\eta(V) = AF \times 10^{B \times V^{-m}} \quad (\text{F.5})$$

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Annex G (informative)

Median rank tables 95 % rank

Table G.1 – Median rank tables 95 % rank

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[illegible]

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COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

MÉTHODES D'ESSAIS ACCÉLÉRÉS DE PRODUITS

AVANT-PROPOS

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Cette deuxième édition annule et remplace la première édition parue en 2013. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

- a) les références ont été mises à jour;
- b) les symboles ont été révisés;
- c) les erreurs, principalement en 5.7.2.3 et en Annexe B, ont été corrigées;
- d) les erreurs de calcul dans les exemples à l'Annexe B et à l'Annexe F ont été corrigées.

Le texte de cette Norme internationale est issu des documents suivants:

Projet	Rapport de vote
56/2000/FDIS	56/2016/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à son approbation.

La langue employée pour l'élaboration de cette Norme internationale est l'anglais.

Ce document a été rédigé selon les Directives ISO/IEC, Partie 2, il a été développé selon les Directives ISO/IEC, Partie 1 et les Directives ISO/IEC, Supplément IEC, disponibles sous www.iec.ch/members_experts/refdocs. Les principaux types de documents développés par l'IEC sont décrits plus en détail sous www.iec.ch/publications.

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INTRODUCTION

De nombreuses méthodes d'essai préalables de fiabilité ou de défaillance ont été développées et la plupart d'entre elles sont en cours d'utilisation. Ces méthodes permettent de déterminer la fiabilité du produit ou d'identifier d'éventuels modes de défaillance des produits et ont été considérées comme efficaces pour démontrer la fiabilité:

- essais à durée fixe,
- essais de rapport de probabilité progressifs,
- essais de croissance de la fiabilité,
- essais jusqu'à défaillance, etc.

Bien que très utiles, ces essais sont en général longs, notamment lorsqu'il faut démontrer une fiabilité élevée du produit. La réduction des périodes qui précèdent la mise sur le marché ainsi que la compétitivité de coût des produits rendent d'autant plus impérieuse la nécessité de disposer d'essais accélérés efficaces et efficaces. De ce fait, la durée des essais est raccourcie en appliquant des niveaux de contrainte plus importants ou en augmentant la vitesse d'application des contraintes récurrentes, ce qui permet une évaluation plus rapide et une meilleure fiabilité du produit en décelant ces modes de défaillance et en atténuant leurs effets.

La fiabilité est appréhendée selon deux approches distinctes et différentes:

- la première consiste à vérifier, par des analyses et des essais, qu'il n'existe pas de modes de défaillance potentiels dans le produit qui risquent d'apparaître au cours de la durée de vie prévue du produit, dans les conditions de fonctionnement prévues et dans le profil d'utilisation;
- la seconde consiste à estimer le nombre de défaillances présumées après un certain temps, dans les conditions de fonctionnement prévues et dans le profil d'utilisation.

Les essais accélérés constituent une méthode qui convient dans les deux cas, mais elle est utilisée de manière tout à fait différente. La première approche correspond à des essais accélérés qualitatifs dont l'objectif est d'identifier les modes de défaillance potentiels qui peuvent à terme entraîner des défaillances sur site du produit. La seconde approche correspond à des essais accélérés quantitatifs qui permettent d'estimer la fiabilité du produit sur la base des résultats d'essais de simulation accélérés qui peuvent être corrélés à l'environnement et au profil d'utilisation.

Les essais accélérés peuvent être appliqués à de multiples niveaux matériels et logiciels des entités. Différents types d'essais de fiabilité, tels que les essais à durée fixe, les essais progressifs jusqu'à défaillance, les essais pour une proportion de succès, les essais de démonstration de la fiabilité ou les essais de croissance ou d'amélioration de la fiabilité, peuvent être utilisés comme méthodes d'essais accélérés. Le présent document fournit des recommandations concernant des types choisis d'essais accélérés, couramment utilisés. Il convient que le présent document soit utilisé conjointement aux normes de plans d'essai statistiques telles que l'IEC 61123, l'IEC 61124, l'IEC 61649 et l'IEC 61710.

Il convient que l'équipe de conception de l'entité examine les avantages relatifs des diverses méthodes et de leur applicabilité individuelle ou combinée pour l'évaluation d'un système ou d'une entité donnée (y compris des techniques de fiabilité) avant de sélectionner une méthode d'essai spécifique ou une combinaison de méthodes. Pour chaque méthode, il convient également de tenir compte de la durée de l'essai, des résultats obtenus, de leur crédibilité et des données exigées pour effectuer une analyse significative, ainsi que de l'impact sur le coût du cycle de vie, de la complexité de l'analyse et d'autres facteurs identifiés.

Dans le présent document, le terme "entité" est utilisé comme défini dans l'IEC 60050-192 couvrant les produits physiques, ainsi que les logiciels. Les services et les personnes ne sont cependant pas couverts par le présent document.

MÉTHODES D'ESSAIS ACCÉLÉRÉS DE PRODUITS

1 Domaine d'application

Le présent document fournit des recommandations pour l'application de diverses techniques d'essais accélérés permettant de mesurer ou d'améliorer la fiabilité de l'entité. L'identification des modes de défaillance potentiels qui peuvent être rencontrés lors de l'utilisation d'une entité donnée et la manière d'y remédier contribuent à assurer la sûreté de fonctionnement d'une entité.

L'objectif de ces méthodes est soit d'identifier les faiblesses potentielles de la conception et fournir des informations sur la fiabilité de l'entité, soit d'atteindre l'amélioration nécessaire de la fiabilité et de la disponibilité, dans les deux cas en comprimant ou en accélérant la durée. Le présent document couvre les essais accélérés de systèmes non réparables et de systèmes réparables. Elle peut être utilisée pour des essais de rapport de probabilité progressifs, des essais à durée fixe et des essais d'amélioration/croissance de la fiabilité, lorsque la mesure de la fiabilité peut être différente de la probabilité normale d'occurrence de défaillance.

Le présent document décrit également des méthodes d'essais accélérés ou de déverminage de la production qui permettraient d'identifier les faiblesses induites par une éventuelle erreur de fabrication de l'entité et qui peuvent de ce fait d'en compromettre la fiabilité. Les services et les personnes ne sont cependant pas couverts par le présent document.

2 Références normatives

Les documents suivants sont cités dans le texte de sorte qu'ils constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60050-192, *Vocabulaire Electrotechnique International (IEV) – Partie 192: Sûreté de fonctionnement*, disponible à l'adresse <http://www.electropedia.org>

IEC 60300-3-5, *Gestion de la sûreté de fonctionnement – Partie 3-5: Guide d'application – Conditions des essais de fiabilité et principes des essais statistiques*

IEC 60605-2, *Essais de fiabilité des équipements – Partie 2: Conception des cycles d'essai*

IEC 60721 (toutes les parties), *Classification des conditions d'environnement*

IEC 61123:2019, *Essais de fiabilité – Plans d'essai de conformité pour une proportion de succès*

IEC 61124:2023, *Essais de fiabilité – Plans d'essai de conformité pour un taux de défaillance constant et une intensité de défaillance constante*

IEC 61649:2008, *Analyse de Weibull*

IEC 61709, *Composants électriques – Fiabilité – Conditions de référence pour les taux de défaillance et modèles de contraintes pour la conversion*

IEC 61710, *Modèle de loi en puissance – Essais d'adéquation et méthodes d'estimation des paramètres*

IEC 62429, *Croissance de fiabilité – Essais de contraintes pour révéler les défaillances précoces d'un système complexe et unique*

3 Termes, définitions, symboles et abréviations

3.1 Termes et définitions

Pour les besoins du présent document, les termes et les définitions de l'IEC 60050-192 ainsi que les suivants s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse <https://www.electropedia.org/>
- ISO Online browsing platform: disponible à l'adresse <https://www.iso.org/obp>

NOTE: Les symboles utilisés pour les mesures de fiabilité, de disponibilité et de maintenabilité correspondent, le cas échéant, à ceux définis dans l'IEC 60050-192.

3.1.1

énergie d'activation

E_a

facteur empirique d'estimation de l'accélération, due à une modification de la température absolue

Note 1 à l'article: L'énergie d'activation est en général mesurée en électronvolts par degré Kelvin.

3.1.2

déverminage de détection

exposition à de faibles niveaux de contrainte afin de détecter des défauts intermittents

3.1.3

compression d'événements

augmentation de la fréquence de répétition des contraintes afin qu'elles soient beaucoup plus élevées que celles rencontrées sur le terrain

3.1.4

essai aux limites hautement accéléré

HALT

essai destiné à identifier les modes de défaillance les plus probables pour le produit dans un environnement de contrainte ou une séquence d'essais définis

Note 1 à l'article: L'acronyme HALT est quelquefois considéré comme étant l'abréviation de "highly accelerated life test" (sa désignation erronée) qui signifie essai de durée de vie hautement accéléré. Cependant, en tant qu'essai accéléré non mesurable, il ne fournit pas d'informations concernant la durée de vie, mais sur l'amplitude des contraintes qui représentent les limites de la conception.

3.1.5

audit sous contraintes hautement accéléré

HASA

outil de surveillance du processus permettant de soumettre aux essais un échantillon de lots de production afin de détecter les faiblesses d'un produit, dues à la fabrication

3.1.6

déverminage sous contraintes hautement accéléré

HASS

déverminage destiné à identifier les défauts latents d'un produit dus au processus de fabrication ou à des erreurs du contrôle

3.1.7

entité

sujet que l'on considère

Note 1 à l'article: L'entité peut être une pièce isolée, un composant, un dispositif, une unité fonctionnelle, un équipement, un sous-système ou un système.

Note 2 à l'article: L'entité peut être composée de matériel, de logiciel, de personnel ou d'une quelconque de leurs combinaisons.

Note 3 à l'article: L'entité est souvent composée d'éléments dont chacun peut être considéré individuellement. Voir "sous-entité" (IEV 192-01-02) et "niveau dans l'arborescence" (IEV 192-01-05).

Note 4 à l'article: L'IEC 60050-191:1990 (supprimée; remplacée par l'IEC 60050-192:2015) identifiait les termes français "dispositif" et "individu" et le terme anglais "entity" comme synonymes, ce qui n'est pas vrai pour toutes les applications.

Note 5 à l'article: Dans l'IEC 60050-191:1990 (supprimée; remplacée par l'IEC 60050-192:2015), la définition de l'entité est une description plus qu'une définition. La nouvelle définition permet une substitution valable au terme tout au long du présent document. Le contenu de l'ancienne définition forme la nouvelle Note 1 à l'article.

Note 6 à l'article: Dans le présent document, les personnes et les services sont exclus.

[SOURCE: IEC 60050-192:2015, 192-01-01, modifié – La Note 6 à l'article a été ajoutée]

3.1.8

durée de vie

<d'une entité non réparable> intervalle de temps depuis la première utilisation jusqu'à ce que les exigences de l'utilisateur ne soient plus satisfaites

Note 1 à l'article: La fin de vie est généralement appelée défaillance du composant.

Note 2 à l'article: La fin de vie est souvent définie comme étant l'instant où un pourcentage spécifié des composants est défaillant, par exemple sous forme d'une valeur B_{10} ou L_{10} pour 10 % de défaillances accumulées.

3.1.9

déverminage de précipitation

profil de déverminage destiné à précipiter, par des défaillances, la transformation de défauts latents en défauts révélés

3.1.10

essai sous contrainte échelonnée

essai au cours duquel la contrainte appliquée augmente, après chaque intervalle spécifié, jusqu'à ce qu'une défaillance se produise ou qu'un niveau de contrainte prédéterminé soit atteint

Note 1 à l'article: L'intervalle peut être spécifié par le nombre d'applications de la contrainte, par des durées ou par des séquences d'essai.

Note 2 à l'article: Il convient que l'essai ne modifie ni les modes ou mécanismes fondamentaux de défaillance, ni leur fréquence relative.

[SOURCE: IEC 60050-192:2015, 192-09-10]

3.1.11**facteur d'accélération d'essai**

rapport de la rapidité de réponse aux contraintes du spécimen à l'essai dans les conditions accélérées, à la rapidité de réponse aux contraintes dans des conditions opérationnelles spécifiées

Note 1 à l'article: Les deux rapidités de réponse aux contraintes se rapportent au même intervalle de temps de la durée de vie des entités soumises à essai.

Note 2 à l'article: Des mesures de la rapidité de réponse aux contraintes sont, par exemple, le temps de fonctionnement avant défaillance, l'intensité de défaillance et la rapidité d'usure.

[SOURCE: IEC 60050-192:2015, 192-09-09]

3.1.12**compression temporelle**

retrait de la durée d'exposition d'un essai donné, à des niveaux de contrainte faibles ou considérés non dommageables à des fins d'accélération

3.2 Symboles et abréviations

ADT	Accelerated Degradation Test(ing) (essai de dégradation accéléré)
<i>AF</i>	acceleration, Acceleration Factor (accélération, facteur d'accélération)
<i>AF</i> _{Test}	accélération globale au cours d'un essai donné
CALT	Calibrated Accelerated Life Testing (essai de durée de vie accéléré étalonné)
<i>B</i> ₁₀	Durée de vie, temps où 10 % des entités ont échoué
<i>C</i>	Confiance
CD	Compact Disc (lecteur CD dans un équipement de haute-fidélité)
DL	Destruct Limit (limite de destruction)
DSL	Design Specification Limit (limite de spécification de conception)
FIT	Failure In Time (taux de défaillance) (défaillances pour 10 ⁹ h)
HALT	Highly Accelerated Limit Test (essai aux limites hautement accéléré)
HASA	Highly Accelerated Stress Audit (audit sous contraintes hautement accéléré)
HASS	Highly Accelerated Stress Screening Test (essai de déverminage sous contraintes hautement accéléré)
HAST	Highly Accelerated Stress Test (essai sous contraintes hautement accéléré)
<i>L</i>	Charge
<i>L</i> _v	Life time ratio (rapport de durée de vie)
LDL	Lower Destruct Limit (limite inférieure de destruction)
LDT	Lower Destruct Temperature (température inférieure de destruction)
LOL	Lower Operating Limit (limite inférieure de fonctionnement)
LOT	Lower Operating Temperature (température inférieure de fonctionnement)
LRTL	Lower Reliability Test Limit (limite inférieure des essais de fiabilité)
MTBF	Mean Operating Time Between Failures (temps moyen de fonctionnement entre défaillances)
MTTF	Mean Operating Time To Failure (temps moyen de fonctionnement avant défaillance)
OL	Operating Limit (limite de fonctionnement)
OVL	Operation Vibration Limit (limites de vibration en fonctionnement)
<i>P</i> _A	Acceptance Probability (probabilité d'acceptation)

PDF	Probability Density Functions (fonctions de densité de probabilité)
PWB	Printed Wiring Board (circuit imprimé)
$R(t)$	Reliability as a function of Time (fiabilité en fonction du temps; probabilité de survie jusqu'à l'instant t)
RTL	Reliability Test Level (niveau d'essai de fiabilité)
S	Strength (robustesse)
SL	Specification Limit (limite de spécification)
SPRT	Sequential Probability Ratio Test (essai de rapport de probabilité progressif)
t_0	instant désigné instant 0
t_L	durée spécifiée, par exemple la durée de vie
THB	Temperature Humidity Bias Test (essai de différentiel température/humidité)
TTF	Time To Failure (durée de fonctionnement avant défaillance)
UDL	Upper Destruct Limit (limite supérieure de destruction)
UDT	Upper Destruct Temperature (température supérieure de destruction)
UOL	Upper Operating Limit (limite supérieure de fonctionnement)
UOT	Upper Operating Temperature (température supérieure de fonctionnement)
URTL	Upper Reliability Test Limit (limite supérieure des essais de fiabilité)
UUT	Unit Under Test (unité en essai)
VDL	Vibration Destruct Limit (limite de vibration de destruction)
$\lambda(S)$	taux de défaillance en fonction d'une contrainte donnée
$\lambda(t)$	taux de défaillance en fonction du temps

4 Description générale des méthodes d'essai accéléré

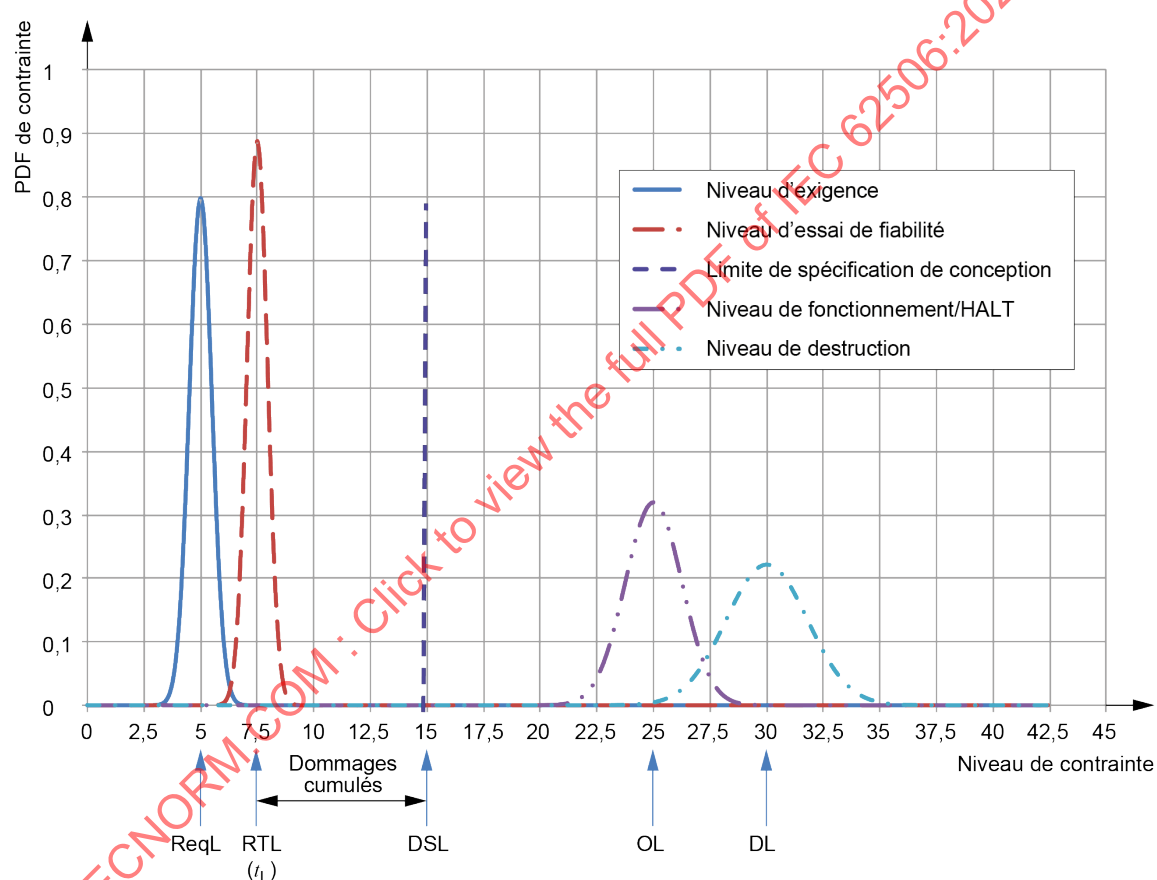
4.1 Modèle de cumul des dommages

Quels que soient les types d'essais accélérés, ils sont fondés sur le principe des dommages cumulés. Les contraintes que subit l'entité au cours de sa durée de vie entraînent des dommages progressifs qui s'accumulent pendant toute sa durée de vie. Ce dommage peut ou non entraîner des défaillances de l'entité sur le terrain.

La stratégie utilisée pour tout type d'essais accélérés est de produire, en augmentant les niveaux de contrainte imposés au cours des essais, des dommages cumulés équivalents à ceux prévus au cours de la durée de vie de l'entité pour le type de contrainte escompté. La détermination des limites de destruction de l'entité, sans estimation de la fiabilité, fournit des informations quant à l'existence éventuelle d'une marge suffisante entre ces limites de destruction et les limites de spécification de l'entité qui permettent ainsi de s'assurer que l'entité reste fonctionnelle pendant sa durée de vie prédéterminée sans défaillances pour ce qui concerne ce type de contrainte spécifique. Cette technique peut, mais ne quantifie pas nécessairement, la probabilité de survie de l'entité au cours de sa durée de vie prévue et permet de s'assurer que les réajustements nécessaires apportés à la robustesse de l'entité permettraient d'éliminer cette défaillance lorsque l'entité est utilisée. Si des marges suffisantes sont déterminées, non liées à la probabilité de survie, alors l'essai est de type qualitatif. Si, au cours des essais, la probabilité de survie est évaluée, l'amplitude de la contrainte d'essai est corrélée à la probabilité de survie de l'entité à ce type de contrainte au cours de sa période de vie prédéterminée et l'essai est de type quantitatif.

La Figure 1 présente le principe des dommages cumulés pour des essais accélérés tant qualitatifs que quantitatifs.

Dans la Figure 1, pour plus de simplicité, toutes les contraintes, les limites de fonctionnement, les limites de destruction, etc., sont données en valeurs absolues. Les valeurs extrêmes, supérieure et inférieure, de la spécification sont fournies pour une entité donnée, c'est-à-dire les limites de spécification supérieure et inférieure (ou basse), USL et LSL, ainsi que les limites de conception correspondantes (DSL), UDL et LDL, les limites supérieure et inférieure de fonctionnement, UOL et LOL, ainsi que les limites supérieure et inférieure des essais de fiabilité, URTL et LRTL. Cela est justifié par le fait que les contraintes opposées négatives peuvent également causer des dommages cumulés avec probablement un mécanisme de défaillance différent et ainsi la relation entre les limites prévues et spécifiées peut être représentée de la même manière que pour des contraintes élevées ou positives. À titre d'exemple, des extrêmes de température froide peuvent produire des modes de défaillance identiques ou différents dans une entité. Pour des raisons de simplification, les valeurs thermiques positives et négatives, ou toute autre contrainte, ne sont pas représentées de manière séparée à la Figure 1, ainsi les amplitudes des contraintes sont soit positives soit négatives et présentées en valeurs absolues uniquement pour les limites supérieures ou inférieures.



IEC

Figure 1 – Fonctions PDF pour dommages cumulés, dégradation et types d'essais

Le graphique à la Figure 1 représente la robustesse exigée d'une entité vis-à-vis d'une contrainte donnée, pour l'ensemble de sa durée de vie, du début de vie (par exemple au moment de la fabrication de l'entité), t_0 , à la fin de vie, t_L . Il est également présumé que la robustesse et les contraintes d'essai ont une distribution gaussienne.

Les différents types d'essais accélérés peuvent désormais être représentés en utilisant la Figure 1 comme modèle conceptuel.

Les essais fonctionnels sont réalisés dans l'étendue de la spécification des exigences et le niveau de la spécification. Il convient qu'il n'y ait dans ce domaine aucune défaillance au cours de l'essai; la conception est validée de manière à permettre le fonctionnement dans les limites supérieure et inférieure de spécification. Les essais accélérés des types B et C (4.2.3 et 4.2.4), c'est-à-dire les essais de dégradation accélérés (ADT) ou les essais de dommages cumulés peuvent être représentés comme étant la distance entre la limite de spécification de conception (DSL) et le niveau auquel il convient d'effectuer l'essai de démonstration de la fiabilité (RTL). Lorsque la dégradation réduit les performances au-dessous des spécifications des exigences, l'entité peut être déclarée comme défaillante si ce comportement est défini comme une défaillance. Lorsque les essais de l'entité sont effectués à l'instant t_0 , il convient qu'aucune défaillance n'apparaisse pour des niveaux de contrainte allant jusqu'à la limite de spécification de conception (DSL) comprise.

Il convient que la spécification de conception de l'entité tienne compte d'une certaine dégradation au cours de sa durée de vie, qui résulte des dommages cumulés des contraintes prévues pendant sa durée de vie; ainsi sa limite est la limite de spécification de conception (DSL) qui est supérieure à la limite exigée (RL) pour obtenir la marge nécessaire. Après la dégradation de l'entité résultant des dommages cumulés dus aux contraintes prévues, l'essai de fiabilité fournit des informations sur l'existence d'une marge entre le niveau d'essai (qui prouve la robustesse résiduelle) et l'exigence. Cette marge est une mesure de la fiabilité à la fin de la période exigée, t_L .

La résistance ultime de la conception est beaucoup plus élevée que les spécifications de conception; il s'agit du niveau sélectionné pour les essais accélérés qualitatifs lorsque l'objectif est la détermination des faiblesses de conception qui peuvent compromettre la fiabilité de l'entité au cours de sa durée de vie, c'est-à-dire les faiblesses qui peuvent apparaître au cours de la durée de vie de l'entité au fur et à mesure de sa dégradation. Ainsi, au cours de l'essai qualitatif, la robustesse est démontrée à la limite de fonctionnement (OL).

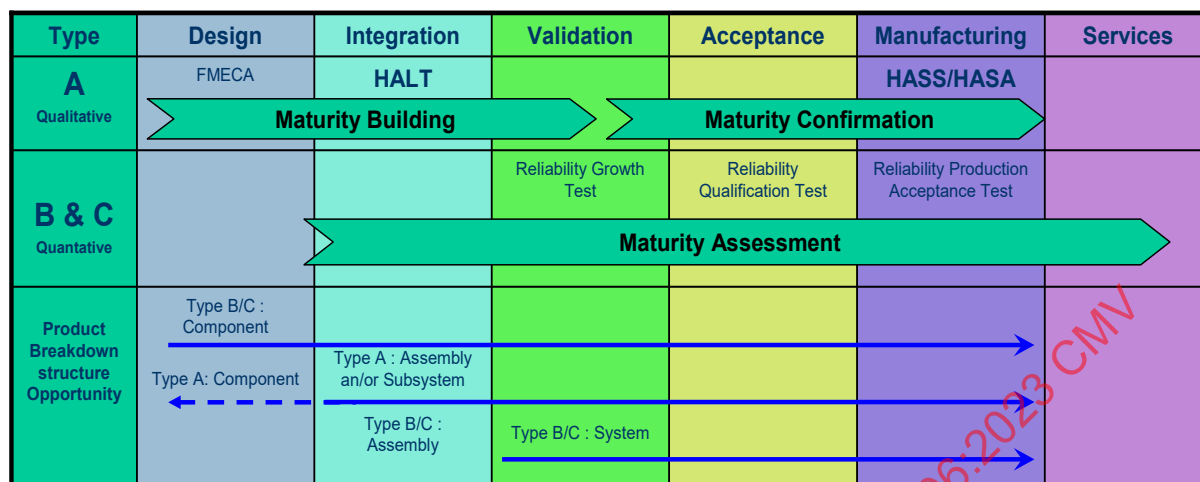
La limite de destruction est supérieure à la limite de fonctionnement (elle est située au-delà) et est désignée DL. C'est là qu'une défaillance permanente est observée. Si la OL ou la DL est proche de la DSL ou si l'écart-type de la loi de distribution de la OL ou la DL est élevé, l'essai indique alors une faiblesse potentielle de la conception, comme représenté à la Figure 1.

La fiabilité de l'entité est définie par une fonction du temps, sur une période prédéterminée, t_L .

La loi normale cumulée de la marge (différence des moyennes des contraintes divisée par leur écart-type commun) entre la robustesse spécifiée (dans des conditions d'utilisation) qui est représentée par l'exigence et le niveau d'essai de fiabilité (RTL) détermine la fiabilité de l'entité. Le niveau d'essai et sa durée sont choisis de manière à engendrer au cours de l'essai des dommages cumulés correspondant à la dégradation due aux dommages cumulés pendant la durée de vie de l'entité. La marge calculée donne la fiabilité exigée de l'entité, qui est dans ce cas une mesure quantitative.

Le Tableau 1 constitue un résumé des essais énumérés et la mise en correspondance de leurs applications avec le cycle de vie de l'entité.

Tableau 1 – Mise en correspondance des types d'essais avec le cycle de développement de l'entité



Anglais	Français
Type	Type
Design	Conception
Integration	Intégration
Validation	Validation
Acceptance	Acceptation
Manufacturing	Fabrication
Services	Services
A	A
Qualitative	Qualitatif
FMECA	AMDEC
HALT	HALT
Maturity Building	Élaboration de maturité
Maturity Confirmation	Confirmation de la maturité
HASS/HASA	HASS/HASA
B&C	B&C
Quantitative	Quantitatif
Reliability Growth Test	Essai de croissance de la fiabilité
Reliability Production Acceptance Test	Essai d'acceptation en production de la fiabilité
Maturity Assessment	Évaluation de la maturité
Product Breakdown structure Opportunity	Possibilité de panne structurelle du produit
Type B/C : Component	Type B/C: composant
Type A: Component	Type A: composant
Type A: Assembly an/or Subsystem	Type A: ensemble et/ou sous-système
Type B/C: Assembly	Type B/C: ensemble
Type B/C: System	Type B/C: système

Le Tableau 1 fournit aux utilisateurs du présent document une synthèse leur permettant de mieux comprendre les différentes méthodes exigées pendant tout le cycle de vie de l'entité.

4.2 Classification, méthodes et types d'accélération d'essai

4.2.1 Généralités

En se fondant sur le modèle de cumul des dommages, les informations attendues de l'essai et les hypothèses d'utilisation de l'entité, les méthodes d'essais accélérés peuvent être divisées en trois groupes:

- type A: essais accélérés qualitatifs: pour la détection du mode de défaillance ou du phénomène;
- type B: essais accélérés quantitatifs: pour la prévision de la distribution des défaillances en utilisation normale;
- type C: essais quantitatifs de compression temporelle et d'événements: pour la prévision de la distribution des défaillances en utilisation normale.

4.2.2 Type A, essais accélérés qualitatifs

Les essais accélérés de type A sont conçus pour identifier les éventuelles faiblesses de conception, ainsi qu'une faiblesse due au processus de fabrication. Par conséquent, leur représentation à la Figure 1 peut être considérablement plus élevée, au-dessus de OL. L'objectif de ce type d'essai n'est pas de quantifier la fiabilité de l'entité, mais d'induire ou de précipiter l'apparition, au cours de l'essai, des problèmes de performance globale de l'entité qui risquent d'apparaître en utilisation sur le terrain, à un certain moment au cours de la durée de vie de l'entité, et d'entraîner une défaillance de l'entité. L'amélioration de la conception de l'entité ou des processus de fabrication permet d'éliminer ces défaillances en élaborant une entité plus résistante ou plus robuste qui est présumée être plus fiable sur le terrain, même lorsqu'elle est soumise aux contraintes extrêmes ou répétitives définies dans les spécifications de conception.

Des essais de type A peuvent également être appliqués pour détecter d'autres faiblesses ou des défaillances latentes, non seulement pour la fiabilité, mais aussi pour d'autres attributs de sûreté de fonctionnement.

Les processus de développement de l'entité qui utilisent ce type d'essai augmentent la fiabilité de l'entité en réduisant les modes de défaillance et en augmentant la robustesse de l'entité sans chercher à démontrer un objectif de fiabilité ou à mesurer une amélioration de la fiabilité. Ces essais sont souvent réalisés à des niveaux de contrainte tellement élevés qu'il convient de pouvoir idéalement observer les défaillances (DL à la Figure 1), bien au-delà des limites de la spécification de conception. L'objectif est d'identifier les modes de défaillance, les maillons faibles de la conception et la marge entre limites fonctionnelles, la limite de fonctionnement (OL) et la limite de destruction (DL), comme représenté à la Figure 1. La marge entre la limite de spécification et la limite de fonctionnement permet de s'assurer que les faiblesses ont été identifiées au cours d'essais HALT, voir 5.1.1, et qu'elles n'apparaîtront pas comme des défaillances au cours de la durée de vie prévue de l'entité, t_L .

NOTE Les autres essais de type A sont les essais marginaux et les essais de contraintes excessives.

4.2.3 Type B: essais accélérés quantitatifs

Les essais de type B utilisent des méthodes d'étude des dommages cumulés pour déterminer la fiabilité de l'entité estimée jusqu'à la fin de la durée de vie prévue de l'entité. La marge nécessaire entre les dommages cumulés prévus et l'exigence donne une mesure de la fiabilité. Ces essais sont ainsi accélérés pour obtenir les dommages cumulés exigés en des périodes beaucoup plus courtes que la durée de vie prévue de l'entité. Les essais accélérés de type B utilisent les facteurs d'accélération quantifiables fondés sur les caractéristiques physiques des défaillances (ou modes de défaillance) particulières et établissent un rapport entre la durée d'exposition aux contraintes spécifiques pendant l'essai et dans l'environnement d'utilisation. La distribution des défaillances ou des modes de défaillance est déterminée à partir d'informations recueillies lors d'essais accélérés séparés. Ces résultats d'essais constituent la base d'un modèle de cycle de vie fonctionnel et peuvent être utilisés pour quantifier l'accélération d'essais utilisables si nécessaire et le cas échéant, pour divers calculs de fiabilité. Il est possible de cette manière d'estimer la fiabilité de l'entité par estimation de la fiabilité ou de la probabilité d'occurrence de modes de défaillance différents pour chaque niveau des contraintes prévues. Si cela est nécessaire pour l'analyse des données à partir d'autres types d'essais (par exemple essais de croissance de la fiabilité ou de démonstration de la fiabilité), le facteur établi d'accélération d'essai peut être utilisé pour recalculer les données de durée de fonctionnement avant défaillance à partir des essais accélérés, de manière à représenter les durées avant occurrence de défaillances dans l'environnement d'utilisation et d'appliquer ces résultats aux calculs de fiabilité. À la Figure 1, ces essais sont représentés comme des niveaux d'essais de fiabilité (RTL).

Une autre manière d'obtenir des informations à partir de ce type d'essai est de soumettre à essai des échantillons d'entités pour des modes de défaillance spécifiques et pour des environnements de défaillance spécifiques. Cela permet de déterminer les lois de distribution des défaillances applicables et les facteurs d'accélération appropriés, qui peuvent ensuite être utilisés pour calculer la probabilité d'occurrence du mode de défaillance particulier. Ces informations peuvent être utilisées pour des essais futurs, ainsi que pour des essais Weibayes (loi de Weibull à 1 paramètre, voir IEC 61649). Le niveau de contrainte des essais de type B peut être représenté à la Figure 1 comme étant supérieur à l'exigence, mais inférieur au niveau de contrainte qui serait appliqué lors d'essais HALT. Ce niveau de contrainte peut se trouver entre la limite de spécification de conception et le niveau de contrainte de DL. La durée d'application des contraintes doit être suffisante pour engendrer une marge de dommages cumulés au-delà des dommages cumulés produits par les contraintes prévues au cours de la durée de vie de l'entité.

La réduction de la durée d'essai est en général obtenue par une augmentation de la contrainte opérationnelle ou d'environnement au-delà des contraintes spécifiées en utilisation. L'augmentation de niveau de ces contraintes produit un effet de dommages cumulés équivalent à ceux qui sont prévus au cours de la durée de vie de l'entité, mais sur une période considérablement réduite.

L'essai de dégradation accéléré (ADT) applique une méthode pour laquelle la dégradation d'une entité est mesurée en fonction du temps ou des cycles de contrainte. La dégradation est tracée et extrapolée jusqu'à ce que le paramètre atteigne un niveau inacceptable (défaillance). Cette méthode est très utile pour les défaillances qui ne se produisent pas de manière soudaine, mais se développent progressivement. Les niveaux de contrainte appliqués au cours de l'essai peuvent correspondre aux limites de fonctionnement nominal ou le plus défavorable prévues en utilisation sur le terrain ou l'essai peut être accéléré en augmentant les contraintes d'essai comme décrit en [1]¹.

1 Les chiffres entre crochets renvoient à la Bibliographie.

4.2.4 Type C: essais quantitatifs de compression temporelle et d'événements

4.2.4.1 Utilisation des essais de type C

Les essais de type C sont le plus souvent utilisés pour estimer la durée de vie des composants lorsque le mode de défaillance dominant est l'usure en utilisation quotidienne, tels les commutateurs, les claviers, les relais, les connecteurs ou les paliers. Les données obtenues à partir de ces essais sont souvent analysées en utilisant la loi de Weibull, et souvent sous la forme de l'essai dit "de mort subite", voir IEC 61649.

De même, les essais de compression temporelle de type C sont souvent utilisés pour identifier:

- les problèmes d'intégration système (comme l'intégration ou l'interaction entre logiciel et matériel);
- les modes de défaillance spécifiques à l'état de fonctionnement, par exemple les cycles de fonctionnement de tout événement comportant un cycle mécanique et électrique;
- les modes de défaillance spécifiques à des environnements comportant de larges domaines de contrainte, mais pour lesquels il est défini un seuil tel que les expositions à des contraintes inférieures à ce seuil n'ont pas de contribution significative à l'endommagement de l'entité.

Les compressions temporelles ou les compressions d'événements permettent d'accélérer les contraintes en durée ou en fréquence d'application sans augmentation de leur niveau.

Une description approfondie de chacune des méthodes d'essais accélérés ci-dessus est fournie à l'Article 5.

4.2.4.2 Compression temporelle

La compression temporelle est une accélération d'essai qui peut être appliquée dans certaines circonstances, lorsque les essais tiennent compte uniquement de la durée pendant laquelle une entité est réellement fonctionnelle ou fonctionne dans un état qui génère des dommages significatifs (également appelée élimination des "expositions non dommageables"). Ce type d'accélération peut être appliqué dans des circonstances où les contraintes opérationnelles et leurs dommages cumulés sont notablement plus élevés que ceux qui apparaissent dans d'autres modes opérationnels, par exemple non opérationnel ou de veille. Pour appliquer cette méthode, il convient que les dommages cumulés au cours de périodes de moindres contraintes soient insignifiants par rapport aux dommages cumulés au cours des périodes de contraintes élevées qui, physiquement, ne sont peut-être pas facilement justifiées (voir IEC 60605-2).

4.2.4.3 Compression d'événements

Lorsqu'une contrainte est répétitive, comme des cycles MARCHE/ARRÊT, l'essai peut être accéléré par une répétition rapide des contraintes (compression d'événements). Cela est notamment utile dans le cas où le niveau de contrainte proprement dit ne peut pas être accéléré. De cette manière, le nombre d'opérations demeure le même et c'est le cas également de l'effet des dommages cumulés. Il convient de s'assurer que le niveau de répétition plus élevé des contraintes ne génère pas de modes de défaillance qui n'apparaîtraient pas en fonctionnement normal, comme l'autoéchauffement d'une pièce en plastique, des vibrations non amorties avant la charge suivante et des séquences logicielles qui ne se terminent pas avant le signal suivant.

5 Modèles d'essais accélérés

5.1 Type A: essais accélérés qualitatifs

5.1.1 Essais aux limites hautement accélérés (HALT)

5.1.1.1 Généralités

Le présent document présente chaque type de méthodes d'essais accélérés couramment utilisées en décrivant ses avantages et inconvénients perçus ainsi que les précautions d'application nécessaires.

Les essais de type A ne représentent pas uniquement l'essai HALT classique, ils traduisent également d'autres types d'essais hautement accélérés tels que les essais en autoclave, les essais de chocs thermiques, les essais marginaux, les essais de contraintes excessives et autres essais accélérés quantitatifs, voir JESD47B [2] et [3]).

NOTE 1 L'essai HALT classique utilise uniquement des contraintes thermiques et dues à des vibrations.

La Figure 1 représente un modèle de rapport entre les spécifications, les limites de conception et les stratégies d'essai de la méthode HALT.

NOTE 2 L'acronyme HALT a malencontreusement été considéré comme signifiant "Highly Accelerated Life Test" (essai de *durée de vie* hautement accéléré). Cependant, étant par nature un essai accéléré qualitatif, HALT ne mesure pas la durée de vie d'une entité, même si l'expression "durée de vie" est induite par le fait que les défaillances obtenues lors des essais HALT ne seraient pas rencontrées au cours de la durée de vie de l'entité soumise à l'essai. L'essai vérifie effectivement les limites de robustesse d'une entité et ainsi le terme "limite" semble bien approprié.

Lorsque la démonstration de la fiabilité ou les essais de croissance de la fiabilité sont accélérés, il est nécessaire de démontrer l'existence d'une marge entre les dommages cumulés induits par les contraintes appliquées lors de l'essai et les dommages cumulés dus aux contraintes prévues au cours de la durée de vie de l'entité ou à tout autre moment prédéterminé pour lequel la fiabilité est à démontrer. Les résultats d'essai favorables pour les marges appliquées donnent des informations sur la fiabilité de l'entité audit moment prédéterminé, exprimées par des critères de robustesse en fonction de la contrainte. Les résultats d'essai prouvent la robustesse démontrée tandis que la fiabilité est le complément de la zone commune aux deux courbes, de charge et de robustesse, représentées à la Figure 2 (la zone commune aux deux distributions de charge et de robustesse est associée à la probabilité de défaillance de l'entité; plus cette zone est grande, plus la probabilité de défaillance est élevée).

À la Figure 1, les spécifications des exigences sont traduites en spécifications de conception. La figure représente en outre la manière dont la marge de conception est vérifiée par les essais HALT.

Pour estimer la marge entre les spécifications de conception et l'UUT, il est nécessaire d'augmenter les niveaux de contrainte jusqu'à apparition des défaillances au cours des essais de type A. Les marges vérifiées au cours de ces essais HALT sont représentées par une limite de contrainte de fonctionnement (OL), ainsi que par une limite de destruction (DL). Cela indique également les marges de variations des matériaux et des processus de fabrication, en cours de fabrication.

5.1.1.2 Principes fondamentaux des essais HALT

La méthodologie des essais HALT est de précipiter rapidement des défaillances afin d'identifier et de pallier les faiblesses de conception d'une entité, de manière à en augmenter la robustesse en utilisation sur le terrain. Ce type d'essai accéléré n'est pas destiné à mesurer, mais à augmenter la fiabilité de l'entité en éliminant les modes de défaillance ayant la marge la plus faible entre contrainte opérationnelle (charge) et robustesse de l'entité (Figure 2 et Figure 3). Ce type d'essai accéléré identifie uniquement les modes de défaillance potentiels et permet d'orienter le développement et l'amélioration des processus pour les agents d'agression choisis. C'est grâce à l'expérience tirée des essais HALT que la plupart des produits sont très robustes vis-à-vis des contraintes appliquées, même si quelques composants ou détails de conception sont notablement plus faibles que le reste. L'idée sous-jacente d'un essai HALT est de trouver ces quelques composants ou détails de conception et de les rendre aussi robustes que le reste de l'entité.

La Figure 2 représente l'interaction entre distribution de la robustesse et des contraintes. Il est présumé que les contraintes sur le terrain dues à diverses applications, conditions climatiques, etc. peuvent être modélisées par une distribution des charges. Ces contraintes sont ici présentées en distribution normale. La robustesse des entités varie en fonction des différences de matières premières et de processus de fabrication. Le modèle de robustesse correspondant est également représenté à la Figure 2 comme une distribution normale.

La zone commune aux distributions de charge et de robustesse est associée à la probabilité de défaillance de l'entité. Plus cette zone est grande, plus la probabilité de défaillance est élevée. La Figure 2 représente un graphique de la marge de conception classique, les critères de robustesse en fonction des contraintes, mais dans le contexte de 5.1.1.2, il ne tient pas compte du modèle de cumul des dommages et, par conséquent, il est applicable à l'essai initial de courte durée qui permettrait de mesurer la résistance ultime de la conception de l'entité. De même, si un contrôle qualité poussé de l'entité maintient une très étroite distribution de la robustesse (ce qui peut être une mesure très onéreuse et chronophage), il n'y aurait pas chevauchement des distributions, ce qui signifie que pour le mode de défaillance spécifique, les défaillances sur le terrain seraient peu probables.

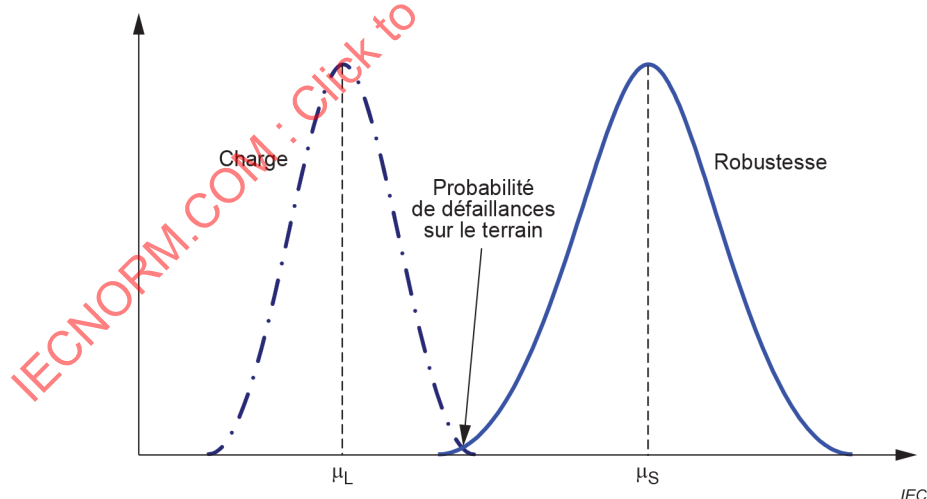


Figure 2 – Relations entre fonctions PDF de la robustesse de l'entité en fonction de la charge en cours d'utilisation

La Figure 3 représente l'importance des marges de conception. La marge de conception ne doit pas seulement couvrir la réduction de la robustesse due au vieillissement, à l'usure et à la fatigue, mais elle doit également couvrir les variations de robustesse causées par les matières premières, les composants et les processus de fabrication et d'assemblage. La Figure 3 a) représente un cas avec une marge de conception insuffisante, la Figure 3 b) un cas avec une marge de conception suffisante. La courbe de charge représente les charges utilisées pendant les essais, représentant les charges sur le terrain. La courbe de robustesse est une courbe PDF qui couvre toutes les entités produites, allant des échantillons d'essai précoces aux entités produites en série. Les échantillons d'essai sont souvent fabriqués dans un laboratoire d'essais de prototypes spécial avec des conditions de fabrication optimales et qu'ils bénéficient d'une attention maximale de l'encadrement. Ils sont donc typiques de la robustesse moyenne ou plus (cercles bleu clair). Plus tard, lorsque les entités sont produites en série, des variations de robustesse dues aux matières premières, aux composants et aux processus de fabrication entraînent souvent une plus faible robustesse des entités produites ("queue" gauche de la distribution de robustesse, cercles bleu foncé). Lors de l'examen de l'essai d'acceptation de la conception à la Figure 3 a), le niveau d'essai est H1, la contrainte maximale prévue sur le terrain. Les échantillons d'essai (cercles bleu clair) réussissent cet essai et la conception est approuvée. Cependant, une fois que la production en série commence, certaines entités dans la queue gauche de la distribution de robustesse (cercles bleu foncé) sont produites, et certaines d'entre elles provoquent des défaillances sur le terrain. La Figure 3 b) représente un essai HALT effectué sur la conception. Si la conception survit au niveau de contrainte H1, la contrainte est augmentée à H2, H3 et H4. À la Figure 3 a), une défaillance aurait déjà été constatée à H2, si un essai HALT avait été effectué, mais à la Figure 3 b), aucune défaillance n'est constatée même au niveau de contrainte H4. La conclusion est donc que la conception représentée à la Figure 3 b) offre une marge suffisante, tandis que la conception représentée à la Figure 3 a) présente une marge insuffisante. Cela n'aurait pas été détecté si un essai HALT n'avait pas été effectué.

Il s'agit là de la justification des essais sous contrainte échelonnée et des essais HALT qui assurent une marge appropriée par rapport aux contraintes prévues au cours de la durée de vie de l'entité. De cette manière, il est possible de réaliser ces essais sur un nombre beaucoup plus faible d'échantillons d'essai que celui qui est nécessaire pour des essais classiques.

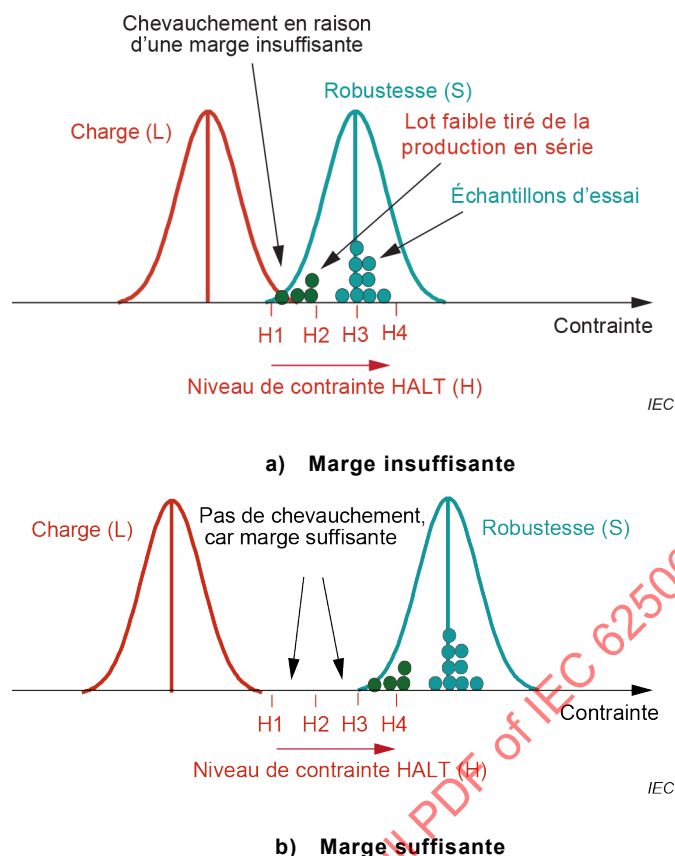


Figure 3 – Comment l'essai HALT détecte la marge de conception

L'essai HALT est un essai exploratoire et qualitatif d'amélioration de la conception et il convient donc de l'accepter en tant que tel. Il identifie le mode de défaillance du maillon le plus faible de la conception pour le ou les types de contraintes concernés. Si le mode de défaillance est lié aux contraintes rencontrées dans l'environnement d'utilisation de l'entité, les niveaux de contrainte ne peuvent être estimés que par des cirières techniques qui tiennent compte de la marge entre les courbes de charge et de robustesse et qui inclut la marge supplémentaire induite par les variations attendues du processus de fabrication et de l'environnement d'utilisation prévu. Le Tableau A.1 représente la comparaison entre les essais HALT et un essai accéléré classique. Une procédure par étape est donnée à l'Article A.2 et des exemples dans le Tableau A.2, le Tableau A.3 et le Tableau A.4.

Sachant que le maillon le plus faible cède en premier, l'application de l'essai HALT se poursuit afin de détecter le deuxième, le troisième et les autres maillons faibles suivants. Cette procédure se poursuit jusqu'à ce qu'aucun mode de défaillance pertinent ne soit observé ou jusqu'à ce que soient atteintes les limites technologiques du système soumis à l'essai.

L'essai HALT est conçu pour aller au-delà de l'environnement d'utilisation de l'entité et de ses spécifications de conception. Les contraintes sont appliquées pendant de courtes durées et l'objectif est de précipiter les défaillances latentes et de renforcer l'entité dans toute la mesure où cela est économiquement et techniquement réalisable. L'essai HALT identifie les modes de défaillance, mais non leur dépendance temporelle.

L'UUT doit être surveillée du point de vue fonctionnel au cours de l'essai, afin de détecter les éventuelles pertes de fonctions. S'il n'est pas possible d'assurer une surveillance continue, l'entité est à soumettre aux essais en maintenant constant le niveau de contrainte. L'Annexe A représente une procédure type d'essai HALT.

L'amplitude des contraintes n'est pas le centre d'intérêt de l'essai HALT; le véritable centre d'intérêt d'un programme d'essais HALT efficace est l'amélioration de l'entité et la réponse devant être apportée par l'organisme aux défaillances. Il convient que l'amélioration de l'entité se poursuive jusqu'à obtenir une entité robuste et rentable dont aucune partie de la conception n'est notablement plus faible que le reste de l'entité. L'objectif est de continuer à améliorer l'entité jusqu'à un niveau justifié par l'analyse de rentabilisation et l'utilisation d'une technologie efficace.

Les limites de fonctionnement et de destruction de l'entité peuvent être représentées comme des distributions sur un axe des contraintes, comme représenté à la Figure 4, pour les deux limites, supérieures et inférieures (LOL, UOL, LDL et UDL).

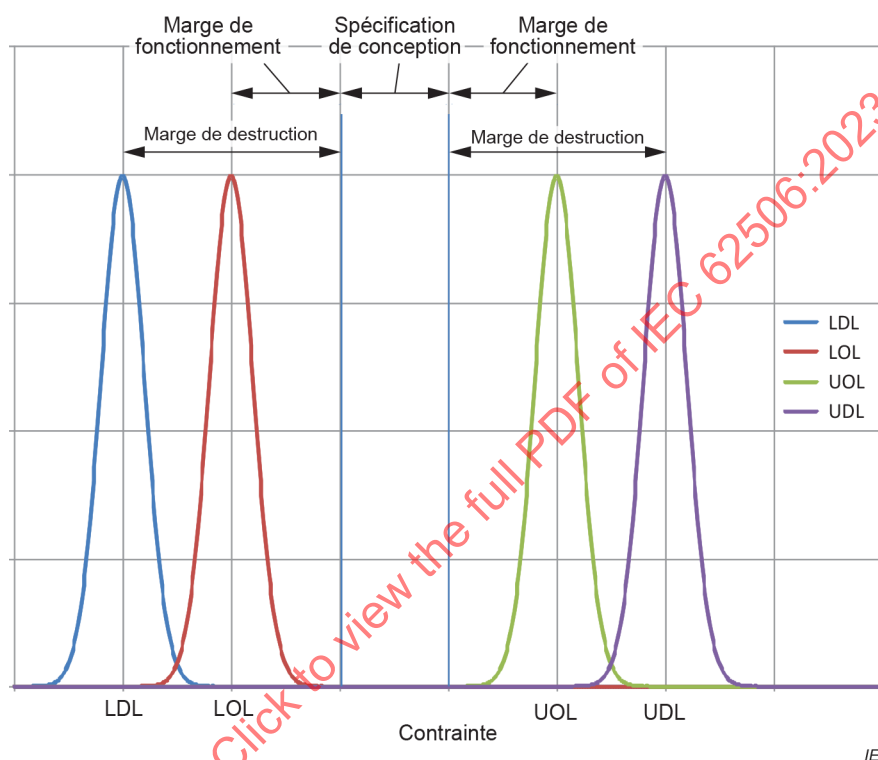


Figure 4 – PDF des limites de fonctionnement et de destruction en fonction de la contrainte appliquée

Dans l'exemple à la Figure 4, les deux limites de contrainte affectent une entité donnée. Cet exemple peut être la contrainte thermique; dans ce cas, les performances de l'entité sont affectées par les températures aussi bien élevées que basses. Il est possible que ces effets ne soient pas symétriques, étant donné que les limites pour les températures élevées peuvent se situer à une distance différente de celles des températures basses par rapport à la contrainte de conception nominale. Même si ces essais sont réalisés sur des prototypes à un stade de production précoce, ils peuvent fournir des informations sur les modes de défaillance liés à la conception. La Figure 4 montre que toutes ces limites peuvent varier comme l'indiquent les lois de distribution. Ces lois de distribution peuvent avoir des écarts-types différents et la détermination de l'essai HALT a pour objectif de donner une indication des marges qui permettent à l'entité finale de subir ces variations sans défaillance sur le terrain.

Bien que la Figure 4 décrive une contrainte thermique, la méthode HALT peut également s'appliquer avec succès à d'autres types de contraintes. Dans le cas d'autres types de contraintes, il est possible qu'il n'y ait pas de limites inférieures comme dans le cas de contraintes mécaniques, mais il peut y avoir d'autres contraintes telles que des contraintes électriques ou même l'humidité.

5.1.1.3 Types de contraintes et application

Les contraintes principalement ou généralement appliquées dans les essais HALT sont les suivantes:

- la température;
- les cycles thermiques;
- les vibrations ou les chocs;
- la tension électrique;
- une combinaison de vibrations ou chocs et de cycles thermiques.

D'autres contraintes spécifiques à l'entité peuvent également être appliquées telles que la fréquence d'horloge pour les microprocesseurs, les variations de tension ou de puissance, l'exposition à des contaminants ou à des solvants, etc. ou une combinaison de ces contraintes [3].

La vérification des marges et les améliorations apportées à l'entité en réponse aux essais HALT permettent d'augmenter la probabilité de robustesse et de fiabilité de l'entité sur le terrain.

L'Annexe A représente un exemple de niveaux de contrainte types. Les contraintes d'essai HALT sont également appliquées comme décrit en 5.1.1.2 jusqu'à ce que les contraintes maximales préétablies soient atteintes. Ces contraintes maximales sont déterminées comme suit:

- par les limites des matériaux et les limites technologiques des matériaux et des composants utilisés;
- par la contrainte maximale réalisable au moyen des méthodes et équipements disponibles.

À noter qu'il convient que les niveaux de contrainte appliqués ne dépassent pas les limites de résistance à la rupture du matériau si les caractéristiques physiques ou chimiques peuvent varier.

Il est normal qu'il y ait dans l'UUT certains éléments fragiles qui ne sont pas conçus pour les niveaux de contrainte généralement appliqués au cours des essais HALT. Il convient dans toute la mesure du possible de protéger ces éléments fragiles au cours des essais HALT ou ne pas en tenir compte lors de l'évaluation des données d'essai. Les éléments fragiles peuvent être protégés en leur appliquant par exemple une source d'air de refroidissement, en les isolant contre l'air froid, en les suspendant à l'extérieur de l'UUT afin de les isoler des vibrations et des chocs ou même en les retirant de la chambre d'essai HALT et en les munissant de rallonges de raccordement au reste de l'UUT. Les éléments fragiles qui ont été protégés pendant l'essai HALT sont alors à soumettre à un essai séparé, par exemple un essai de composant ou un essai de survie.

Il convient d'étudier chaque défaillance observée au cours des essais HALT et d'effectuer une analyse des causes initiales des défaillances, voir IEC 62740 [4]. Si le mode de défaillance identifié est susceptible d'apparaître sur le terrain où il est prévu que le niveau de contrainte soit beaucoup plus faible que celui appliqué lors des essais HALT, il convient de proposer et de mettre en œuvre une mesure corrective conformément à l'état de la technique et aux décisions de la direction.

5.1.2 Essai sous contrainte hautement accéléré (HAST)

Ce type d'essai peut être considéré comme étant au croisement entre les essais qualitatifs de type A et les essais quantitatifs de type B. Ce type d'essai est communément utilisé dans l'industrie des composants électroniques comme une variante plus efficace (plus courte) que l'essai de différentiel température/humidité (THB) qui dure beaucoup plus longtemps, il s'agit d'un essai en autoclave d'une durée de 1 000 h. Dans le cadre des essais HAST, ces contraintes sont en général la température et l'humidité qui peuvent corroder les orifices d'interconnexion (conducteurs métalliques) des puces et les résistances à couche mince. Les composants sont généralement polarisés au cours de l'essai. Même si ces essais ne fournissent pas des estimations numériques de la fiabilité, ils sont utilisés comme des essais de requalification effectifs, qui permettent de s'assurer que la fiabilité des composants n'est pas compromise par d'éventuelles modifications apportées aux composants, voir JESD22-A110 [5]. La durée des essais HAST dans l'industrie des composants électroniques est en général d'environ 100 h et les niveaux habituels de contrainte pour la température et l'humidité relative sont respectivement de 130 °C et de 85 %.

5.1.3 Déverminage ou audit sous contrainte hautement accéléré (HASS/HASA)

5.1.3.1 Applicabilité et principe du HASS/HASA

HASS et HASA ne sont pas considérés comme des essais, car il n'y a pas de critères de réussite ou d'échec. Ils sont cependant inclus dans le présent document, car ils appliquent des contraintes accélérées pour détection ou déverminage des défauts. HASS est utilisé pour déverminer des unités de production en utilisant des contraintes beaucoup plus élevées que celles prévues en utilisation normale ou lors de l'expédition de l'entité, mais avec des niveaux plus faibles que ceux qui peuvent réduire notablement la durée de vie de l'entité sur le terrain. Ces niveaux sont déterminés sur la base des conclusions et constatations du programme d'essais HALT. Le déverminage peut être effectué sur l'ensemble (100 %) des unités de production ou sur un échantillon. L'objectif du déverminage est de détecter les éventuels défauts de fabrication latents qui pourraient éventuellement apparaître lors de l'utilisation normale de l'entité. La détection des défauts latents, suivie par une analyse des défaillances et les actions correctives nécessaires (vérifiées par un essai conçu pour détecter le mode de défaillance spécifique), réduit le nombre de défaillances latentes. L'amélioration de la fiabilité sur le terrain qui en résulte est due à la réduction du nombre de composants mis en service présentant des défauts de fabrication latents et non à une modification de la fiabilité inhérente à la conception. HASS est idéalement adapté à la production pilote ou aux montées en charge de la production, c'est-à-dire à un moment où le taux de production est faible et qu'il est possible d'effectuer facilement un déverminage à 100 %. HASS peut se poursuivre en fonctionnement normal pour des entités très critiques qui sont fabriquées en petits volumes.

Les niveaux de contrainte utilisés en HASS ou HASA permettent un déverminage de précipitation des défauts. Le déverminage de précipitation consiste à appliquer des contraintes combinées dont les niveaux s'inscrivent tout juste dans les limites opérationnelles. L'objectif de ce déverminage est de précipiter la transformation de défauts de fabrication en défaillances intermittentes ou permanentes. Pour détecter les défaillances, il est recommandé de surveiller les fonctions des UUT pendant le déverminage, sachant qu'il est possible que certaines anomalies opérationnelles ne soient pas décelées lors des vérifications opérationnelles réalisées après les essais. Par ailleurs, le moment où, au cours du déverminage de précipitation, d'éventuelles défaillances fonctionnelles intermittentes peuvent être détectées n'est pas connu. Le déverminage de précipitation peut combiner plusieurs types de contrainte et différents niveaux de contrainte. Comme pour les essais HALT, des défaillances intermittentes peuvent être vérifiées en utilisant un déverminage de détection, voir Article A.2, Étape 4. Il convient d'assurer une surveillance constante afin d'obtenir une couverture fonctionnelle aussi complète que possible. Il convient d'optimiser la couverture et l'efficacité de la surveillance avant de commencer le processus de développement du déverminage. Il convient que le processus de surveillance facilite l'analyse des causes initiales.

Le déverminage de précipitation type exige une durée d'application des contraintes relativement courte de 3 min à 1 h. Un supplément de temps est exigé pour le montage du matériel d'essai et de surveillance.

HASA est un outil de surveillance du processus, utilisé lorsqu'un échantillon de lot de production est exposé au déverminage de précipitation afin de détecter les défauts possibles. HASA est souvent réalisé avant la libération du lot de production. Lorsque le processus de fabrication atteint sa maturité, HASS est souvent supplanté par HASA. HASA est par ailleurs réduit, voire écarté, lorsque l'efficacité des contrôles de production est bien établie.

5.1.3.2 Sélection des contraintes et de leurs amplitudes

Il convient de sélectionner les contraintes de manière à ne pas compromettre, du point de vue fonctionnel, les propriétés du matériau ou la durée de vie du matériel non défectueux. Les niveaux initiaux sont déterminés à partir des informations obtenues lors d'essais HALT.

Le déverminage de précipitation est réalisé à des niveaux de contrainte légèrement inférieurs aux limites de fonctionnement, sachant que les caractéristiques fonctionnelles de l'UUT sont à surveiller pendant le déverminage. En général, la contrainte de température est réduite de 5 °C et le niveau de vibration de 2 g en valeur efficace (19,62 m/s²). Avant d'utiliser le déverminage de précipitation en HASS ou HASA, il convient de s'assurer qu'il ne réduit pas notablement la durée de vie de l'entité sur le terrain. Cela peut être effectué, par exemple en exposant 10 fois un échantillon donné au déverminage de précipitation.

5.1.4 Aspects techniques de HALT et de HASS

5.1.4.1 Avantages de HALT et de HASS

Les avantages de HALT et de HASS sont les suivants:

- marges de conception augmentées et vérifiées de manière sélective pour améliorer la fiabilité;
- faible effectif d'échantillons pour la détermination d'un mode de défaillance spécifique;
- détermination rapide des modes de défaillance déterminants pour des agents d'agression spécifiques et contraintes facilement combinées (la durée de l'essai est en général de 3 jours);
- analyse de compromis efficacement réalisée et détermination des actions correctives nécessaires;
- vérification rapide des actions correctives;
- déverminage efficace de la production à court terme;
- élimination des composants faibles ou défectueux (HASS) en les séparant de la population principale (amélioration de la qualité et de la fiabilité).

5.1.4.2 Inconvénients de HALT et de HASS

Les inconvénients de HALT et de HASS sont les suivants:

- a) stimulation possible des modes de défaillance susceptibles de ne pas être observés en utilisation normale de l'entité;
- b) sur-amélioration potentielle de la marge de conception (surconception);
- c) fiabilité résultante inconnue;
- d) confiance statistique des résultats d'essai limitée (sur ou sous-estimation des marges de conception);
- e) absence de couverture par les essais de tous les effets interactifs des modes de défaillance multiples;
- f) irréalisables pour les grandes entités, les petites entités et les entités présentant des fragilités diverses;
- g) nombre limité de types de contraintes (principalement température, vibrations, chocs et cycles thermiques);
- h) inaptitude à évaluer les limites de conception pour une contrainte influencée par la synergie avec d'autres types de contraintes non prévues par les types d'essais HALT.

5.2 Types B et C – Méthodes d'essais accélérés quantitatifs

5.2.1 Objectif des essais accélérés quantitatifs

L'objectif des essais accélérés quantitatifs est d'estimer une ou plusieurs mesures de fiabilité, par exemple le taux de défaillance, la probabilité de défaillance ou de survie, la durée de fonctionnement avant défaillance (TTF). L'objectif des essais accélérés quantitatifs est bien souvent la détermination de la durée de vie de composants ayant une durée de vie limitée (usure), ou la détermination (quantification) et l'amélioration de la fiabilité des systèmes et des composants. L'analyse de Weibull est à cet effet très utile, voir IEC 61649.

5.2.2 Fondement physique des méthodes d'essais accélérés quantitatifs de type B

5.2.2.1 Généralités

L'objectif des essais accélérés du type B est de mesurer la fiabilité et de vérifier les performances de fiabilité acceptables de l'entité sur une courte durée. Ainsi, l'objectif de ces essais accélérés est d'accélérer le taux de cumul des dommages pour des mécanismes pertinents de défaillance par contraintes répétitives et par usure (un mécanisme de défaillance pertinent est un mécanisme susceptible d'apparaître dans des conditions normales du cycle de vie d'un produit).

Il est nécessaire, pour accélérer les essais, d'avoir une connaissance approfondie des mécanismes de défaillance potentiels, ainsi que des contraintes opérationnelles et d'environnement de l'entité ou du système. Cette connaissance peut également être acquise par une analyse des modes de défaillance de l'entité conçue, associée au profil d'utilisation prévu de l'entité, en utilisant par exemple une analyse AMDE (voir IEC 60812 [6]). Des mesures efficaces peuvent alors être prises, non seulement pour prévenir la manifestation de ces défaillances lorsque les entités sont soumises à des contraintes du cycle de vie ou d'utilisation prédéterminées, mais également afin de précipiter ces défaillances de manière efficace au cours des essais accélérés pour l'amélioration de l'entité. L'expérience a montré que les essais accélérés d'usure ou de fiabilité sont précieux pour l'évaluation de la fiabilité de systèmes électroniques, électromécaniques et mécaniques exigeant une haute fiabilité. L'application de contraintes élevées est en général destinée à :

- a) faire en sorte que la conception soit plus robuste et améliorer le processus de fabrication par des essais systématiques sous contrainte échelonnée et en augmentant les marges de contrainte au moyen d'actions correctives (essais de croissance de la fiabilité);
- b) réaliser des essais de durée de vie accélérés en laboratoire afin de mesurer et de vérifier la fiabilité en service.

L'étendue de l'accélération, appelée de manière générale facteur d'accélération (AF) est définie comme étant le rapport de la durée de vie dans les conditions d'utilisation à la durée de vie dans les conditions d'essai accéléré. Ce facteur d'accélération est nécessaire pour pouvoir extrapoler de manière quantitative une mesure de fiabilité (telle que la durée de fonctionnement avant défaillance et les taux de défaillance) de l'environnement d'essai accéléré vers l'environnement d'utilisation, avec un certain degré de confiance raisonnable. Le facteur d'accélération dépend des paramètres matériels (par exemple les propriétés du matériau, l'architecture de l'entité) de l'UUT, des conditions de contrainte en utilisation, des conditions d'essais accélérés sous contrainte et du mécanisme de défaillance applicable. Ainsi, chaque mode de défaillance pertinent (en presumant qu'il résulte d'un mécanisme de défaillance) pour l'UUT concernée, dispose de son propre facteur d'accélération et les conditions d'essai (par exemple le cycle d'utilisation, le niveau de contrainte, l'historique des contraintes, la durée des essais) doivent être adaptées en fonction de ce facteur d'accélération.

Les caractéristiques physiques appréhendées pour les défaillances signifient que chaque mode de défaillance est traité séparément et la marge du point de vue de la durée de vie ou de la fiabilité exigée est vérifiée pour chacune de ces caractéristiques. Cette approche est telle que chaque mode de défaillance dispose de sa propre loi de distribution des défaillances et de son propre taux de défaillance. Dans d'autres cas, le résultat est combiné à une fiabilité estimée pour l'ensemble des entités.

Lors de la planification d'un essai, il convient d'énumérer les modes de défaillance potentiels de l'entité. L'essai est ensuite planifié selon les niveaux et les durées de contrainte de sorte qu'il convient de pouvoir observer les modes de défaillance au cours de l'essai s'ils sont présents dans l'entité. Pour cette planification, les facteurs empiriques obtenus d'entités précédentes, des fournisseurs de composants ou des ouvrages de référence, peuvent être utilisés pour estimer le facteur d'accélération de l'essai. À l'issue de l'essai, les modes de défaillance réels sont connus et l'essai peut être analysé pour chaque mode de défaillance séparément. Il est recommandé d'utiliser un montage d'essai capable d'estimer les facteurs empiriques à partir de l'essai proprement dit, voir Annexe E et Annexe F.

Les essais de type B peuvent être exécutés en augmentant le niveau des diverses charges telles que les charges thermiques (par exemple température, cycles thermiques et taux de variation de la température), les charges chimiques (par exemple humidité, produits chimiques corrosifs tels que les acides et les sels), les charges électriques (par exemple tension, intensité, puissance en régime établi ou transitoire) et les charges mécaniques (par exemple déformations mécaniques cycliques quasi statiques, vibrations et chocs ou impulsions ou impacts). L'environnement de l'essai accéléré peut comporter une combinaison de ces diverses charges. L'interprétation des résultats pour les charges combinées et leur extrapolation aux conditions du cycle de vie exige une connaissance quantitative des interactions relatives des différentes contraintes d'essai et la contribution de chaque type de contrainte au dommage global.

5.2.2.2 Avantages de l'essai de type B

Les essais accélérés sous contrainte fournissent des informations quantitatives sur la fiabilité des entités en essai:

- ce type d'essai peut être conçu:
 - pour les modes de défaillance sélectionnés (par exemple à partir d'une analyse AMDE) pour évaluer avec une confiance raisonnable la fiabilité globale;
 - pour les contraintes combinées, de manière à simuler les effets interactifs de ces contraintes et obtenir une évaluation réaliste de la fiabilité de l'entité;
- l'accélération des essais peut être efficacement réalisée pour que l'essai représente les dommages cumulés en utilisation.

5.2.2.3 Inconvénients de l'essai de type B:

- risque que l'accélération des contraintes puisse dépasser les caractéristiques physiques des matériaux utilisés dans l'entité et donne lieu à des dommages imprévus;
- risque que l'accélération des contraintes combinées fasse subir à l'entité des dommages supplémentaires imprévus qui n'auraient pas lieu dans les conditions d'utilisation réelles;
- le référentiel applicable aux essais accélérés n'est pas une contrainte unique, mais considère généralement plusieurs contraintes qui varient en fonction de l'utilisateur et de l'emplacement. Cela nécessite d'être pris en compte dans le cadre de la quantification des résultats.

5.2.3 Essais de type C, compression temporelle (C_1) et des événements (C_2)

5.2.3.1 Essais de type C_1

5.2.3.1.1 Généralités

La compression temporelle est réalisée en éliminant le "temps à l'arrêt" (par exemple le temps non opérationnel ou le temps avec de faibles niveaux de contrainte) par compression du cycle d'utilisation en tenant uniquement compte du temps d'activité. En outre, lorsque les entités sont exposées à une grande variété de contraintes, il arrive souvent que les contraintes les plus élevées (les contraintes primaires) génèrent le plus de dommages et certains niveaux de contrainte d'utilisation, comparés aux contraintes primaires, sont présumés n'entraîner que des dommages négligeables. Il peut être présumé que toute exposition à un niveau de contrainte inférieur à un seuil de dommage donné génère des dommages négligeables et qu'elle peut être retirée du programme d'essai. Cela est notamment vrai pour les fatigues mécaniques et cette hypothèse s'applique souvent à des essais accélérés de fatigue structurelle, voir IEC 60605-2.

Un exemple de compression du cycle d'utilisation est l'application d'une durée d'essai de 24 h par jour, alors que l'entité, dans son environnement d'utilisation réel, ne fonctionne que 8 h par jour, ce qui donne un facteur de compression temporelle de 3. Chaque durée d'essai d'un jour équivaut à une utilisation réelle de 3 jours.

5.2.3.1.2 Avantages des essais de compression temporelle

Les entités ayant une durée d'utilisation minimale ou un temps de fonctionnement court par rapport au temps calendaire peuvent être soumises aux essais au cours d'une période d'essai très raisonnable par rapport à la durée de vie exigée (par exemple du matériel bureautique, des automobiles, des machines de récolte). Un chasse-neige est, par exemple, utilisé pendant une seule saison et une fois par an et seulement s'il y a suffisamment d'accumulation de neige pour que son usage soit nécessaire. Même lorsqu'il est utilisé, il est prévu qu'il soit actif pendant en moyenne 2 h à 3 h. Il est soumis à plusieurs contraintes primaires dommageables, telles que les vibrations, les contraintes du moteur, l'usure des lames. Pendant le reste de l'année, il est rangé dans un abri et protégé contre les principaux agents atmosphériques. Ainsi, un chasse-neige qui a une durée de vie exigée de dix ans, mais qui n'est effectivement utilisé que quatre fois par mois pendant trois mois, pendant une durée de 2 h, peut être soumis à des essais de durée d'utilisation exigée de 240 h. Par conséquent, une durée d'essai d'environ 300 h constitue une bonne marge pour démontrer la haute fiabilité du chasse-neige.

La durée de l'essai aux contraintes nominales étant relativement courte, il n'y a aucune raison d'augmenter les contraintes et, par conséquent, il n'est pas nécessaire de déterminer les facteurs d'accélération des contraintes sous peine de soumettre l'UUT à des contraintes excessives.

5.2.3.1.3 Inconvénients des essais de compression temporelle

Le fait de se concentrer exclusivement sur le temps opérationnel signifie la prise en compte de l'environnement opérationnel uniquement, avec les modes de défaillance correspondants, tandis que les modes de défaillance en environnements "non opérationnels" peuvent être omis. Ces derniers peuvent se révéler plus dommageables pour l'entité, sachant qu'ils résultent de contraintes qui sont peut-être beaucoup plus faibles que celles auxquelles l'entité est soumise en utilisation, mais appliquées pendant des durées beaucoup plus longues, de sorte qu'elles peuvent générer des dommages cumulés identiques, voire supérieurs à ceux des contraintes appliquées en cours d'utilisation.

En prenant toujours le même exemple du chasse-neige et en tenant compte des 87 600 h de sa durée de vie de dix ans, le chasse-neige est exposé à des températures extrêmement basses pendant environ 20 000 h, ce qui entraîne un mode de défaillance par fragilisation des matériaux, à des températures extrêmement élevées, pendant environ 6 000 h, ce qui entraîne un vieillissement des pièces en plastique, de la peinture et des adhésifs, ainsi qu'à environ 7 200 cycles thermiques entraînant de multiples dommages structurels, outre l'humidité appliquée pendant au moins 30 000 h par an, ce qui entraîne une corrosion importante. Des essais effectués uniquement dans les conditions opérationnelles ne tiendraient pas compte des effets de ces environnements non opérationnels.

Pour les entités soumises à des durées d'activité beaucoup plus courtes que les périodes d'inactivité (temps à l'arrêt), il est nécessaire de combiner les essais à accélération temporelle des périodes opérationnelles à des essais qui accélèrent les périodes de passivité, par exemple essais de corrosion, essais d'humidité. Dans certains cas, l'entité peut être préconditionnée avant les essais de compression temporelle, en appliquant certaines contraintes subies pendant les périodes de passivité, comme l'humidité, le stockage dans des conditions de froid extrême, le rayonnement solaire ou des charges mécaniques telles que des vibrations et des chocs simulant les conditions de non-fonctionnement. L'objectif de ce préconditionnement est de simuler l'interrelation des modes de défaillance en utilisation active avec les modes de défaillance prévus en stockage, qui, à leur tour, affectent grandement les modes de défaillance en utilisation. Par exemple, la corrosion du chasse-neige pourrait grandement affecter l'influence des vibrations appliquées à la structure de l'entité.

5.2.3.2 Essais de type C₂

5.2.3.2.1 Généralités

Les essais de compression d'événements appliquent des répétitions d'événements à des taux beaucoup plus élevés que ceux subis par l'entité en utilisation réelle. Par exemple, les cycles MARCHE/ARRÊT de l'unité mentionnée ci-dessus (le chasse-neige) peuvent être comprimés en un essai de plusieurs heures, en appliquant de manière répétitive des cycles MARCHE/ARRÊT. Par conséquent, les 120 cycles MARCHE/ARRÊT exigés au cours de la durée de vie de 10 ans, avec une marge suffisante permettant de démontrer la fiabilité, seraient un essai très court.

Les essais de type C₂ peuvent être associés aux essais de compression temporelle pour obtenir une accélération supplémentaire des essais. Cela peut donner lieu à un essai très court avec démonstration d'une "haute fiabilité"; cependant, cette accélération combinée doit être accompagnée de nombreuses précautions importantes. Par exemple, l'application rapide de contraintes répétées peut affecter les résultats d'essai par variation des dommages cumulés.

Les essais de compression d'événements peuvent également être combinés aux essais d'accélération des contraintes pour raccourcir encore plus la durée de l'essai. Il convient de prendre les précautions nécessaires lors de la préparation de ces essais, car la compression temporelle peut influencer l'accélération des contraintes. Par exemple, des cycles MARCHE/ARRÊT rapides entraînent le passage à l'état ARRÊT pendant une très courte période, ce qui ne laisse pas à l'UUT le temps de se refroidir correctement. Cela peut entraîner une accélération thermique supplémentaire de l'UUT et une défaillance précipitée. De même, ce type d'accélération peut omettre les défaillances dues à la non-utilisation, comme la détérioration des matériaux.

5.2.3.2.2 Avantages de l'essai de type C₂

L'avantage de l'essai de type C₂ est qu'en une courte période, en accélérant la répétition des contraintes, il est possible de reproduire les dommages cumulés sur une durée beaucoup plus courte qu'en utilisation normale.

5.2.3.2.3 Inconvénients de l'essai de type C₂

Ce type d'essai peut également générer des effets négatifs par application de contraintes continues entraînant des défaillances précipitées qui, normalement, ne seraient pas apparues. Par exemple, l'application d'un frottement continu à des pièces mécaniques, qui entraîne une usure par frottement en fonctionnement, peut produire de la chaleur qui pourrait précipiter une défaillance, alors qu'en usage normal, celle-ci serait retardée par des périodes de refroidissement. Un autre exemple peut être la fatigue du métal, due à la répétition des contraintes si ces dernières sont appliquées sans donner au matériau le temps de relaxation nécessaire.

5.3 Mécanismes de défaillance et conception des essais

L'importance d'une bonne analyse des défaillances doit être fortement soulignée. Il est essentiel de comprendre les mécanismes de défaillance pour concevoir et réaliser avec succès des essais de durée de vie accélérés ou autres, tels que les préconisent les méthodes de conception et de prédiction de la fiabilité fondées sur les caractéristiques physiques des défaillances (à condition que lesdites prédictions soient fondées sur les caractéristiques physiques de la méthode d'évaluation des défaillances). Pour cela, une méthode rationnelle permettant de corrélater quantitativement les résultats des essais accélérés à la fiabilité ou aux taux de défaillance dans des conditions d'utilisation, en utilisant une transformée d'accélération scientifique, doit être identifiée. Il est nécessaire de déterminer quantitativement l'importance de la compression temporelle d'essai réalisée au cours d'un essai accéléré, en se fondant sur les caractéristiques physiques des modes de défaillance pertinents. Les essais de durée de vie accélérés tentent de réduire la durée nécessaire à l'observation des défaillances. Dans certains cas, il est possible de les réaliser sans modifier réellement l'équation du taux instantané de défaillance. Cependant, si la fonction de danger varie, elle est appelée "modèle de danger proportionnel". Mathématiquement, la différence entre les deux est perceptible dans les deux équations ci-dessous, pour une loi de Weibull dans laquelle $H_{AL}(t)$ est la fonction de danger cumulé pour la durée de vie accélérée, $H_{PH}(t)$ est la fonction de danger cumulé pour le modèle de danger proportionnel, AF est un facteur d'accélération dû à un certain type de stimulus et $(t/\eta)^\beta$ est le danger cumulé non modifié pour une loi de Weibull (t = temps, η = durée de vie caractéristique et β = paramètre de forme).

$$H_{AL}(t) = \left(\frac{AF \times t}{\eta} \right)^\beta \quad (1)$$

$$H_{PH}(t) = AF \times \left(\frac{t}{\eta} \right)^\beta \quad (2)$$

Dans la fonction $H_{AL}(t)$, le temps est une relation linéaire de la fonction d'accélération. Dans la fonction $H_{PH}(t)$, la fonction de danger proprement dite est modifiée. En réarrangeant l'équation pour $H_{PH}(t)$, il apparaît que le temps est une fonction non linéaire du facteur d'accélération. La différence entre ces deux types d'essais accélérés est que $H_{AL}(t)$ exige uniquement que soit connu le rapport de la durée d'essai réelle au temps calendaire (durée non accélérée) résultant du stimulus environnemental appliqué, tandis que $H_{PH}(t)$ exige que soit connue la manière dont le facteur AF varie en fonction du paramètre β . Pour la loi de Weibull, dont la distribution exponentielle est un cas particulier, la distribution résultante demeure dans les deux cas une loi de Weibull.

L'Équation (1) s'applique en général lorsque l'accélération est effectuée au taux de répétition augmenté des contraintes répétitives appliquées comme les cycles de fonctionnement. Il est préférable d'utiliser l'Équation (2) lorsque l'accélération est appliquée aux états physiques de l'unité en essai, comme l'accélération thermique, où le facteur d'accélération proprement dit dépend de la distribution.

Pour résumer le raisonnement ci-dessus, il est possible d'affirmer que l'accélération des contraintes assure une réduction de la durée de fonctionnement avant défaillance en augmentant les niveaux des contraintes au-delà de celles prévues en utilisation normale de l'entité.

5.4 Détermination des niveaux de contrainte, profils et combinaisons en utilisation et en essai – Modélisation des contraintes

5.4.1 Généralités

Il est également important de comprendre les contraintes opérationnelles et d'environnement qui génèrent le mode de défaillance sur la base des caractéristiques physiques de la défaillance. Cette modélisation des contraintes sert de point de référence de départ de l'accélération. La manière dont ce référentiel est traité est extrêmement importante lorsque les contraintes varient en fonction de l'utilisation de l'entité.

5.4.2 Méthode pas-à-pas

La procédure suivante s'applique:

- a) identifier les facteurs de contrainte pertinents sur le terrain, y compris durant le stockage et le transport, voir série IEC 60721;
- b) déterminer les types de contraintes à accélérer, celles qui sont utilisées avec leurs valeurs nominales et celles qui peuvent être omises, par exemple parce qu'elles sont couvertes par d'autres essais;
- c) déterminer si les contraintes peuvent être appliquées simultanément, de manière à inclure des interactions de contraintes ou si elles sont à appliquer successivement, par exemple au cours d'un cycle d'essai, voir IEC 60605-2;
- d) déterminer si le facteur d'accélération (AF) peut être estimé à partir de l'essai ou estimer les facteurs d'accélération sur la base des équations d'accélération et des facteurs empiriques applicables;
- e) déterminer l'effectif d'échantillons, voir IEC 61649, IEC 61123 et IEC 61124;
- f) réaliser l'essai, voir IEC 60300-3-5;
- g) procéder à l'analyse des défaillances;
- h) analyser l'essai, séparément pour chaque mode de défaillance, voir IEC 61649, IEC 61710 et IEC 61124;
- i) consigner les résultats d'essai, voir IEC 60300-3-5.

5.5 Méthode d'accélération de contraintes multiples – Essais de type B

Dans le cas où deux contraintes ou plus sont à l'origine d'interactions affectant la durée de vie du composant ou de l'entité (fiabilité), l'accélération d'essai est effectuée en augmentant chaque contrainte différente sur la base de modèles appropriés aux contraintes concernées. Dans ce cas, les taux de défaillance représentant chacun des mécanismes de défaillance sont accélérés séparément et il convient d'estimer séparément la fiabilité globale (R) ou la probabilité de défaillance (F). Cela peut être exprimé sous la forme générale suivante:

$$R = \prod_{i=1}^{N_S} R_i \quad (3)$$

où

R_i représente l'influence d'une contrainte i sur la fiabilité de l'UUT lorsque les contraintes sont indépendantes;

R représente la fiabilité de l'UUT;

N_S est le nombre total de contraintes indépendantes.

Le cas particulier des risques concurrents est décrit dans l'IEC 61649:2008, Annexe G.

Si la durée de fonctionnement avant défaillance de tous les composants ou entités peut être modélisée par la distribution exponentielle, cela peut être simplifié de la manière suivante:

$$AF \times \lambda_{Entité} = \sum_{i=1}^{N_S} AF_i \times \lambda_{Entité} (\text{Contrainte}) \quad (4)$$

Dans le cas de la loi de Weibull, lorsque toutes les distributions des modes de défaillance ont le même paramètre de forme, le paramètre d'échelle d'une entité soumise à des contraintes combinées est le suivant:

$$\frac{1}{\eta_{item}^{\beta} (\text{Stress})} = \frac{1}{\eta_U^{\beta}} + \sum_{i=1}^{N_S} \frac{1}{\eta_i^{\beta} (\text{Stress})} \quad (5)$$

où

β est le paramètre de forme de la loi de Weibull;

$\eta_{Entité}$ est le paramètre d'échelle d'une entité pour la combinaison de contraintes différentes;

η_U est le paramètre d'échelle de base;

η_i sont les paramètres d'échelle déterminés pour des contraintes différentes.

En cas de paramètres de forme différents, la distribution qui en résulte peut être différente de la loi de Weibull et la complexité des relations correspondantes dépasse le domaine d'application du présent document.

Il est à noter que la loi de Weibull peut être uniquement utilisée lorsqu'il s'agit d'accélérer des modes de défaillance uniques, car elle comporte une dépendance des durées de fonctionnement avant défaillance, sachant que la modélisation de Weibull n'est pas applicable au mélange de différents modes de défaillance. Les durées de fonctionnement avant défaillance ne sont pas liées dans le cas de modes de défaillance différents, même si un seul composant est concerné.

L'Équation (4) présente une méthode plutôt précise d'expression du taux de défaillance global de l'entité avec application des contraintes. Il est présumé que le taux de défaillance de la pièce ou du composant est la somme d'un taux de défaillance de base, résultant de modes de défaillance indéterminés liés aux défauts intrinsèques de la pièce, et des taux de défaillance attribués aux modes de défaillance sensibles à des contraintes particulières et qui sont accélérés par ces contraintes. Ainsi, les taux de défaillance représentant des contraintes différentes peuvent être déterminés par des essais de contraintes séparés. Les accélérations de contraintes différentes s'appliquent donc à chacun de ces modes de défaillance liés à une défaillance particulière.

Si chaque type de contrainte accélère un seul mode de défaillance, le facteur d'accélération affecte chaque mode de défaillance séparément. S'il est présumé qu'il existe une distribution exponentielle, ce qui est souvent le cas lorsque les ensembles et les systèmes sont soumis à des essais pour plusieurs modes de défaillance différents, le taux de défaillance d'une entité après accélération est le suivant:

$$AF \times \lambda_{\text{item}} = \sum_{i=1}^{N_S} AF_i \times \lambda_{\text{item}}(\text{Stress}) \quad (6)$$

Ayant à l'esprit que plusieurs contraintes peuvent accélérer le même mode de défaillance, l'accélération d'essai à partir de l'Équation (6) devient l'Équation (7):

$$\lambda_A = AF_{\text{Test}} \times \lambda_0 = \sum_{i=1}^{N_S} \left(\left(\prod_k AF_k \right)_i \times \lambda_i \right) \quad (7)$$

où

λ_0 est le taux de défaillance de l'entité dans des conditions d'utilisation;

λ_A est le taux de défaillance de l'essai accéléré;

$\left(\prod_k AF_k \right)_i$ est le produit des facteurs d'accélération des contraintes, i , affectant le mode de défaillance k ;

λ_i est le taux de défaillance de l'entité correspondant à la contrainte spécifique;

N_S est le nombre de contraintes;

AF_{Test} est le facteur d'accélération du taux de défaillance de l'entité dans des conditions d'utilisation pour produire le taux de défaillance global de l'essai accéléré.

$$AF_{\text{Test}} = \frac{\sum_{i=1}^{N_S} \left(\left(\prod_k AF_k \right)_i \times \lambda_i \right)}{\lambda_0} \quad (8)$$

Si le taux de défaillance, λ_i , est défini en matière de fiabilité à un instant prédéterminé t_1 , $R_i(t_1)$ dans ce cas l'accélération d'essai est la suivante:

$$AF_{\text{Test}} = \frac{\sum_{i=1}^{N_S} \left(\left(\prod_k AF_k \right)_i \times \left[-\frac{\ln(R_i(t_1))}{t_1} \right] \right)}{\lambda_0} \quad (9)$$

Si toutes les contraintes affectent tous les modes de défaillance, les facteurs d'accélération résultants (AF_i) peuvent être multipliés. Cela peut être une manière plus facile ou plus simple de calculer le taux de défaillance total de la pièce sous la forme de son taux de défaillance de base, modifié par plusieurs contraintes d'environnement composées:

$$\lambda_{\text{Entité}}(\text{Contrainte}) = \lambda_0 \times \prod_{i=1}^{N_S} AF_i \quad (10)$$

L'Équation (10), bien que largement utilisée dans l'industrie, prend pour hypothèse que chaque contrainte appliquée accélère le taux de défaillance de base et que la contrainte suivante appliquée accélère le taux de défaillance total accéléré par la contrainte précédente et ainsi de suite. Cette approche simpliste peut entraîner une surestimation des effets des contraintes multiples sachant que les mécanismes de défaillance sont différents et que certains ne sont pas accélérés par toutes les contraintes.

La surestimation de l'accélération entraîne une surestimation de la probabilité de défaillance ou donne des essais qui sont abusivement courts et inappropriés.

La meilleure manière d'obtenir un calcul réaliste de l'accélération d'essai est de rechercher les contraintes qui influencent effectivement les mêmes modes de défaillance, auquel cas elles peuvent être multipliées.

5.6 Accélération de contraintes uniques et multiples pour des essais de type B

5.6.1 Méthode d'accélération de contraintes uniques

5.6.1.1 Généralités

Avec cette méthode, l'accélération d'essai est réalisée avec une seule contrainte. Ces modèles sont des modèles de contraintes au cours de la durée de vie du produit, dans lesquels les dommages par unité de temps d'essai sont accélérés de manière appropriée en augmentant le niveau des contraintes. Les trois relations les plus fréquemment utilisées sont les suivantes:

- le modèle de loi de puissance inverse (IPL), utilisé pour l'accélération de l'essai lorsque des contraintes autres qu'une température constante sont prises en compte, comme des contraintes électriques, mécaniques, chimiques (corrosion);
- le modèle du taux de réaction d'Arrhenius, utilisé pour des contraintes à température constante, fondé sur l'effet de la température absolue sur un mécanisme de défaillance;
- le modèle d'Eyring, utilisé dans les cas où l'accélération est obtenue avec les niveaux de contrainte de température et d'humidité.

Quel que soit le modèle d'accélération, les données d'essai peuvent être analysées au moyen de modèles d'analyse établis permettant de déterminer les paramètres caractéristiques de durée de vie accélérée. Les facteurs d'accélération permettent de déterminer les paramètres correspondant aux environnements d'utilisation qui sont employés si nécessaire pour obtenir des projections de fiabilité. Il convient dans toute la mesure du possible de vérifier les modèles d'accélération en traçant les courbes de données d'essai.

5.6.1.2 Loi de puissance inverse

5.6.1.2.1 Généralités

La loi de puissance inverse est applicable:

- aux contraintes dynamiques telles que les chocs (tout type d'impulsions) et les vibrations (sinusoïdales et aléatoires);
- aux contraintes climatiques telles que les cycles thermiques, les variations de température (chocs et cycles thermiques), l'humidité, le rayonnement solaire ou toute autre contrainte climatique à dommages cumulés.

Le modèle de loi de puissance inverse [7] est très simple à comprendre et à utiliser et très facilement adaptable à toute distribution des défaillances. Il est possible d'utiliser des solutions graphiques (ajustement optimal au jugé) et les paramètres peuvent également être déterminés en utilisant la méthode du maximum de vraisemblance.

Avec la loi de puissance inverse, la caractéristique qui représente la fiabilité de l'entité en fonction du temps, telle que la durée de vie caractéristique, la durée de vie moyenne, le temps moyen avant défaillance, est représentée de la manière suivante:

$$L(S) = C^{-1} \times S^{-m} \quad (11)$$

où

S est la contrainte;

C est la constante (> 0) à déterminer;

m est le paramètre dépendant du comportement en contrainte, également à déterminer;

$L(S)$ est la durée de vie ou autre durée temporelle prédéterminée en fonction de la contrainte.

Le modèle de loi de puissance est simple lorsqu'il est exprimé ou tracé sous forme logarithmique: une ligne droite dont la pente représente la valeur du paramètre m , et l'intersection avec l'axe des y est fonction de la constante C :

$$\ln[L(S)] = -m \times \ln(S) - \ln(C) \quad (12)$$

La loi de puissance inverse est applicable à toutes les distributions couramment utilisées en matière de fiabilité.

Le facteur d'accélération d'essai est alors:

$$AL_{S_{IPL}} = \frac{L(S_{Use})}{L(S_{Test})} = \frac{C^{-1} \times S_{Use}^{-m}}{C^{-1} \times S_{Test}^{-m}} = \left(\frac{S_{Test}}{S_{Use}} \right)^m \quad (13)$$

où

$AL_{S_{IPL}}$ est l'accélération de la contrainte par la loi de puissance inverse;

$L(S_{Use})$ est la durée de vie en fonction des contraintes en utilisation réelle;

$L(S_{Test})$ est la durée de vie en fonction de la contrainte appliquée au cours de l'essai.

Dans l'Équation (13), les indices "Test" et "Use" représentent respectivement la condition d'essai accélérée et la condition d'utilisation non accélérée.

Le paramètre C de l'accélération d'essai s'annule, mais le paramètre m doit être déterminé pour l'entité et le type de contrainte.

S'il n'est pas déjà connu, le paramètre m peut être déterminé par des essais réalisés sur le même composant ou la même entité à divers niveaux de contrainte jusqu'à défaillance (Annexe E et Annexe F). Les données d'essai sont ensuite analysées pour déterminer la distribution et les paramètres correspondants. Le paramètre de la distribution qui correspond à la durée de vie est ensuite tracé en fonction de la contrainte en coordonnées bilogarithmiques, et la pente de la ligne droite détermine la valeur du paramètre m tandis que l'intersection négative donne la valeur de la constante C .

Le processus, qui semble simple lorsqu'il est décrit, peut devenir pénible pour des entités plus complexes qu'un composant unique, car l'essai peut nécessiter beaucoup de temps et un grand nombre d'échantillons. Par ailleurs, l'utilisation de facteurs d'accélération d'essai grossièrement estimés peut donner lieu à d'importantes erreurs de conception des essais accélérés.

Lorsque la courbe contrainte-durée de vie est extrapolée bien au-delà des points d'essai, la courbe contrainte-durée de vie prévisionnelle peut correspondre à une estimation plus prudente de la durée de vie sachant que la courbe contrainte-durée de vie réelle pour le mode de défaillance spécifique peut présenter une pente plus basse.

La loi de puissance inverse est en général applicable aux contraintes de chocs thermiques, électriques et mécaniques (statiques et dynamiques) et à l'humidité.

Pour accélérer l'essai de durée de vie d'un composant avec une contrainte spécifique, il convient de bien comprendre et de regrouper les défaillances correspondant au même mode de défaillance afin de s'assurer que les contraintes appliquées génèrent le même mécanisme de défaillance. Par exemple, l'essai d'accélération d'un condensateur en céramique pour puce électronique avec des électrodes en nickel, réalisé par une augmentation de la tension, peut présenter deux mécanismes de défaillance différents: défaillance par claquage et par mouvement des lacunes d'oxygène, qui entraînent toutes deux un court-circuit du condensateur. Ces deux mécanismes peuvent apparaître comme étant le même mode de défaillance, car il serait difficile de les distinguer si les défaillances n'étaient pas analysées. L'un des indicateurs de la présence de deux mécanismes de défaillance différents peut être une loi de Weibull bimodale résultante, voir IEC 61649.

Pour chacune des distributions, les limites de confiance des paramètres et les fonctions de durée de vie et de fiabilité peuvent être déterminées en utilisant des données statistiques appropriées, comme celles décrites dans l'IEC 61649. Du fait du faible effectif d'échantillons, il convient d'utiliser avec précaution les limites statistiques appliquées à la courbe contrainte-durée de vie; il est en effet possible d'obtenir des résultats incorrects de la courbe contrainte-durée de vie extrapolée.

5.6.1.2.2 Avantages du modèle de loi de puissance inverse

Le principal avantage de ce modèle réside dans sa simplicité et la facilité avec laquelle il permet de déterminer les paramètres obtenus d'un essai, à condition de pouvoir facilement séparer les modes de défaillance. Il présente également l'avantage d'être largement utilisé ce qui permet de trouver les valeurs spécifiques des paramètres dans les ouvrages de référence pertinents.

5.6.1.2.3 Inconvénients du modèle de loi de puissance inverse

Ce modèle présente les inconvénients suivants:

- la simplicité du modèle peut entraîner des erreurs de correspondance avec les paramètres relatifs à la durée de vie des différentes distributions;
- bien souvent, en raison de contraintes temporelles et économiques, il n'est pas possible de déterminer les paramètres de la loi de puissance inverse, d'où l'utilisation des valeurs moyennes communes qui peuvent induire en erreur;
- pour être statistiquement défendables, les essais de défaillance exigent un grand nombre d'échantillons à soumettre à chacune des contraintes choisies. Les composants soumis aux contraintes faibles peuvent exiger une durée d'essai plus longue et il convient qu'ils aient également un niveau de fiabilité élevé, il peut être nécessaire de disposer d'un effectif d'échantillons important et l'essai peut prendre beaucoup de temps;
- il convient de choisir avec précaution la valeur présumée du paramètre m , empruntée à une entité apparemment similaire.

5.6.1.3 Modèle d'Arrhenius

5.6.1.3.1 Généralités

Le modèle d'Arrhenius [7] est fondé sur l'expression du taux de réaction en fonction du type de composant et de son mode de défaillance, ainsi que de la température absolue, T . Ce modèle prend pour hypothèse que le taux de réaction dépend de manière exponentielle de la température absolue.

Le taux de réaction est exprimé comme suit:

$$\rho(T) = K \times e^{-\frac{E_a}{k_B \times T}} \quad (14)$$

où

K est la constante (qui n'est pas fonction de la température);

E_a est l'énergie d'activation (eV);

k_B est la constante de Boltzman = $8,617\,385 \times 10^{-5}$ eV/K;

T est la température absolue (K);

$\rho(T)$ est le taux de réaction en fonction de la température absolue.

Une durée de vie fiable en fonction de la température peut être exprimée comme suit:

$$L(T) = C \times e^{\frac{D}{T}} \quad (15)$$

Pour représenter l'équation ci-dessus comme une ligne droite:

$$\ln[L(T)] = \frac{D}{T} + \ln(C) \quad (16)$$

où

T est la température absolue variable mesurée en degrés K (température absolue);

D est la pente de la ligne droite ($= E_a/k_B$);

$\ln(C)$ est l'intersection de la ligne droite avec l'axe Y.

Le facteur d'accélération est alors calculé pour l'environnement d'utilisation et d'essai comme le rapport des deux taux de réaction:

$$AF = \frac{\rho(T)}{\rho(T_0)} = \frac{K \times e^{-\frac{E_a}{k_B \times T}}}{K \times e^{-\frac{E_a}{k_B \times T_0}}} = e^{\left[\frac{E_a}{k_B} \left(\frac{1}{T_0} - \frac{1}{T} \right) \right]} \quad (17)$$

Les taux de défaillance en fonction de la température absolue, T , peuvent être corrélés au taux de défaillance à une température absolue spécifiée, T_0 , de la manière suivante:

$$\lambda(T) = C \times e^{-\frac{E_a}{k_B \times T}} \quad (18)$$

Le taux de défaillance, λ_0 , à une température spécifiée, T_0 , est égale à:

$$\lambda(T_0) = C \times e^{-\frac{E_a}{k_B \times T_0}} \quad (19)$$

La division des Équations (18) et (19) donne la relation suivante:

$$\lambda(T) = \lambda_0(T_0) \times e^{\left[\frac{E_a}{k_B} \left(\frac{1}{T_0} - \frac{1}{T} \right) \right]} \quad (20)$$

où

T_0 et T sont les températures absolues dans l'environnement d'utilisation et d'essai, respectivement.

La Figure 5 représente un exemple d'utilisation du modèle d'Arrhenius de détermination de la valeur du taux de défaillance, λ_0 , qui, à une température de 25 °C (298 K), était de 1×10^{-8} défaillances/h, en fonction de la température absolue, T .