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Methods for product accelerated testing

National foreword

This British Standard is the UK implementation of EN 62506:2013. It is identical to IEC 62506:2013.

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Methods for product accelerated testing
(IEC 62506:2013)

Méthodes d'essais accélérés de produits
(CEI 62506:2013)

Verfahren für beschleunigte
Produktprüfungen
(IEC 62506:2013)

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European Committee for Electrotechnical Standardization
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Foreword

The text of document 56/1503/FDIS, future edition 1 of IEC 62506, prepared by IEC/TC 56 "Dependability" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 62506:2013.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2014-03-21
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Endorsement notice

The text of the International Standard IEC 62506:2013 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60812 NOTE Harmonized as EN 60812:2006

IEC 61125:1992 NOTE Harmonized as EN 61125:1993 (not modified).

Annex ZA
(normative)
Normative references to international publications with their corresponding European publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60068	Series	Environmental testing	-	-
IEC 60300-3-1	2003	Dependability management - Part 3-1: Application guide - Analysis techniques for dependability - Guide on methodology	EN 60300-3-1	2004
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	Series	Classification of environmental testing	-	-
IEC 61014	2003	Programmes for reliability growth	EN 61014	2003
IEC 61124 + corr. January	2012 2013	Reliability testing - Compliance tests for constant failure rate and constant failure intensity	EN 61124	2012
IEC 61163-2		Reliability stress screening - Part 2: Electronic components	-	-
IEC 61164	2004	Reliability growth - Statistical test and estimation methods	EN 61164	2004
IEC 61649	2008	Weibull analysis	EN 61649	2008
IEC 61709	2011	Electric components - Reliability - Reference conditions for failure rates and stress models for conversion	EN 61709	2011
IEC 61710		Power law model - Goodness-of-fit tests and estimation methods	EN 61710	
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	EN 62429	

CONTENTS

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 was 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;
– the second approach estimates how many failures can be expected after a given time under the expected operating conditions.

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 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 software. Different types of reliability testing, such as fixed duration, sequential test-to-failure, success test, reliability demonstration, or reliability growth/improvement tests can be candidates for accelerated methods. This standard provides guidance on selected, commonly used accelerated test types. This standard 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 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.

METHODS FOR PRODUCT ACCELERATED TESTING

1 Scope

This International Standard provides guidance on the application of various accelerated test techniques for measurement or improvement of product reliability. Identification of potential failure modes that could be experienced in the use of a product/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, or to achieve necessary reliability/availability improvement, all within a compressed or accelerated period of time. This standard 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 differ from the standard probability of failure occurrence.

This standard also extends to present accelerated testing or production screening methods that would identify weakness introduced into the product by manufacturing error, which could compromise product dependability.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

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

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

IEC 61649:2008, *Weibull analysis*

IEC 61709, *Electronic 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 abbreviations

For the purposes of this document, the term and definitions given in IEC 60050-191:____, as well as the following, apply.

NOTE Symbols for reliability, availability, maintainability and safety measures follow those of IEC 50060-191:1990, where available.

3.1 Terms and definitions

3.1.1
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 and "indenture level", definition 191-41-05.

Note 4 to entry: IEC 60050-191:1990, first edition, identified the term “entity” as a synonym, which is not true for all applications.

Note 5 to entry: The definition for item given in the first edition is a description rather than a definition. This new definition provides meaningful substitution throughout this standard. The words of the former definition form the new note 1.

[SOURCE: IEC 60050-191:—, definition 191-41-01] [1][1]

3.1.2
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 ‘intervals’ 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]

3.1.3
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

1 Figures in square brackets refer to the Bibliography.

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.

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

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
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

3.1.8
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.

3.1.9
event compression
increasing stress repetition frequency to be considerably higher than it is in the field

3.1.10
time compression
removal of exposure time at low or deemed non damaging stress levels from a test for purpose of acceleration

3.1.11
precipitation screen
screening profile to precipitate, through failure, conversion of latent into permanent faults

3.1.12
detection screen
low stress level exposure to detect intermittent faults

3.2 Symbols and abbreviated terms

Symbol/ Abbreviation	Description
$R(t)$	reliability as a function of time; probability of survival past the time t

NOTE 1 IEC 60050-191:1990, definition 191-12-01 uses the general symbol $R(t_1,t_2)$. Time may be substituted by cycles, measure of distance, etc.

$\lambda(t)$	failure rate as a function of time

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

HALT	highly accelerated limit test
HASS	highly accelerated stress screening test
HAST	highly accelerated stress test
HASA	highly accelerated stress audit
$\lambda(S)$	failure rate as a function of a stress
UUT	unit under test
A	acceleration, acceleration factor
A_{test}	overall acceleration in a test
ADT	accelerated degradation testing
DSL	design specification limit
RTL	reliability test level
SL	specification limit
DL	destruct limit
LDL	lower destruct limit
UDL	upper destruct limit
OL	operating limit
UOL	upper operating limit
LOL	lower operating limit
SPRT	sequential probability ratio test
RG	reliability growth
URTL	upper reliability test limit
LRTL	lower reliability test limit
THB	temperature humidity bias test
TTF	time to failure
MTBF	mean operating time between failures
MTTF	mean time to failure
AF	acceleration factor
FIT	failure to time
CALT	calibrated accelerated life testing
ADT	accelerated degradation test
t_0	start of a period of in determination of product destruct life rest
t_L	duration of a predetermined time, e. g. life
SPRT	sequential probability ratio tests

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 in its life cause progressive damage that accumulates throughout the product life. This damage may or may not result in a product'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 life for the type of expected stress. Determination of product destruct limits, without reliability estimation, provides information on whether there exists a sufficient margin between those destruct limits and product specification limits, thus providing assurance that the product will survive its predetermined life period without failure related to that specific stress type. This technique may or may not necessarily quantify a probability of product survival for its life, just assurance that the necessary adjustments in product strength would help eliminate such failure in product 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 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 also cause cumulative damage probably with a differently 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 produce the same or different failure modes in a product. 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.

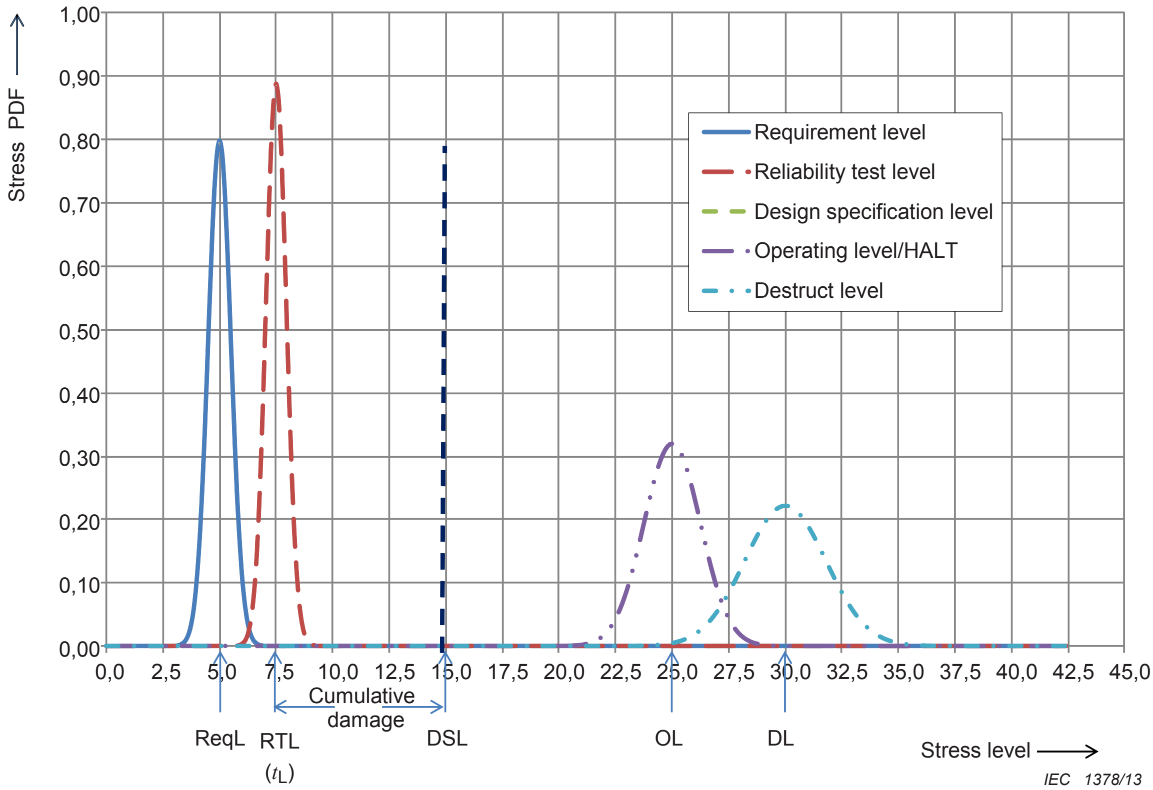


Figure 1 – Probability density functions (PDF) for cumulative damage, degradation, and test types

The graph in Figure 1 shows the required strength of a product regarding a stress for the duration of its lifetime, from beginning of life (e.g. time when the product 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 Type 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 (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 can be declared as failed, if this behaviour is defined as a failure. When testing the product at time t_0 no failures should be expected for stress levels up to and including the design specification level (DSL).

The product design specification should take into consideration certain degradation during the product'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 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 compromise product reliability, i.e. the weaknesses that could occur in the product's life span, as the product 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 OL or DL are close to the DSL or 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 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 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 life span. The calculated value, produces product required reliability, which is then a quantitative measure.

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

Table 1 – Test types mapped to the product 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 →		→	

IEC 1379/13

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

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 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, i.e.. The goal of this type of test is not to quantify product reliability, but to induce or precipitate, during the test, the product's overall performance issues which are likely to take place in the field some time during the product's useful life and result in a product failure. Improvement of the product design or manufacturing processes is executed to preclude those failures, producing a stronger or more robust product, expected to be more reliable in the field even under extreme or repetitive stresses as outlined in the design specifications.

Product development processes using this type of test increase product reliability through the mitigation of failure modes and by increasing product 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) in Figure 1. The margin between the specification limit and the operating limit ensures that the weaknesses are identified in HALT and are not expected to occur as failures during the expected product life, t_L.

4.2.3 Type B: quantitative accelerated tests

Type B tests use cumulative damage methods to determine product reliability projected to the end of the expected product 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 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 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 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 (RTL).

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 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 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 life, but in a considerably reduced time period.

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 this standard [7].

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, e.g. 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.

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 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, e.g. 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 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.

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 standard with its advantages, disadvantages and necessary application cautions.

Type A test is not only the classical HALT but also other highly accelerated test types such as the autoclave, thermal shock, and other quantitative accelerated tests.

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

NOTE The acronym HALT was inadvertently spelled out in the past as highly accelerated *life* test. By its nature of being a qualitative accelerate 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/item, thus the word “limit” is appropriately used in the spelled 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 reliability in that predetermined time as expressed by strength vs. 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).

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 using 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 n 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 in order to increase robustness during the product field use. This type of accelerated test is not intended to measure, but to increase product reliability through the elimination of failure modes with the lowest margin between the field stress (load) and product strength (Figures 2 and 3). This type of accelerated test only identifies potential failure modes and guides the development and improvement processes for the chosen stressors. It is the experience from 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.

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 distribution. It is shown here as a normal distribution. The strength of the products 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 and strength distribution, measures the probability of product failure. The graph in Figure 2 shows the classical design margin, stress vs. strength criteria, but in the context shown in this clause, 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 design. Also, if the extensive product quality control maintains a very narrow strength distribution (which may 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.

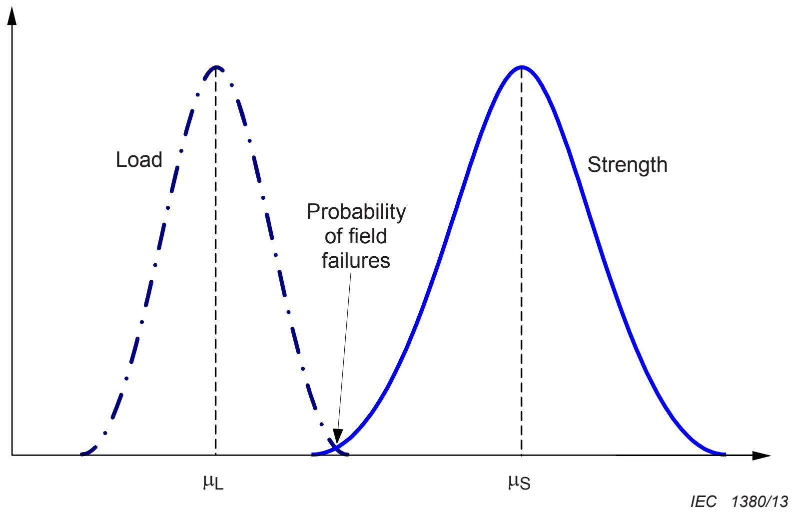


Figure 2 – Relationship of PDFs of the product strength vs. load in use

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, H1 is located.

The narrow spread of this original distribution would make if 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 H3 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.

This is the rationale behind the application of tests such as step-stress 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.

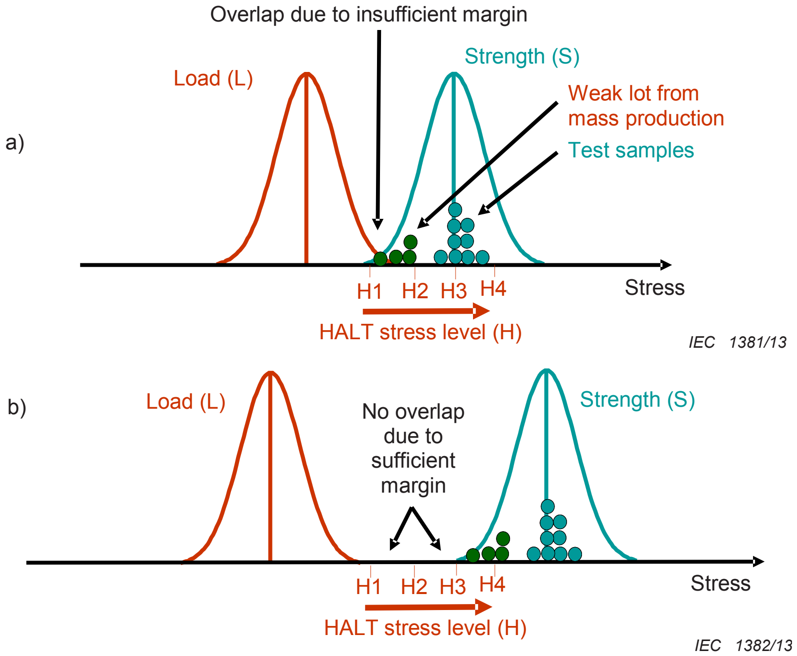


Figure 3 – How uncertainty of load and strength affects the test policy

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 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.

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 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 as much as it is economically and technically feasible. HALT identifies failure modes, but not their time dependency.

The UUT has to be functionally monitored during the test in order to detect the loss of its functions. If continuous monitoring is not possible, the product 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 program is on product improvement activities and organizational response to failures. The product improvement should be continued to the point of a cost-effective rugged product where no part of the design is significantly weaker than the rest of the product. The goal is to keep improving the product to the level justified by the business case and utilization of cost-effective technology.

The operating and destruct limits for the product 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).

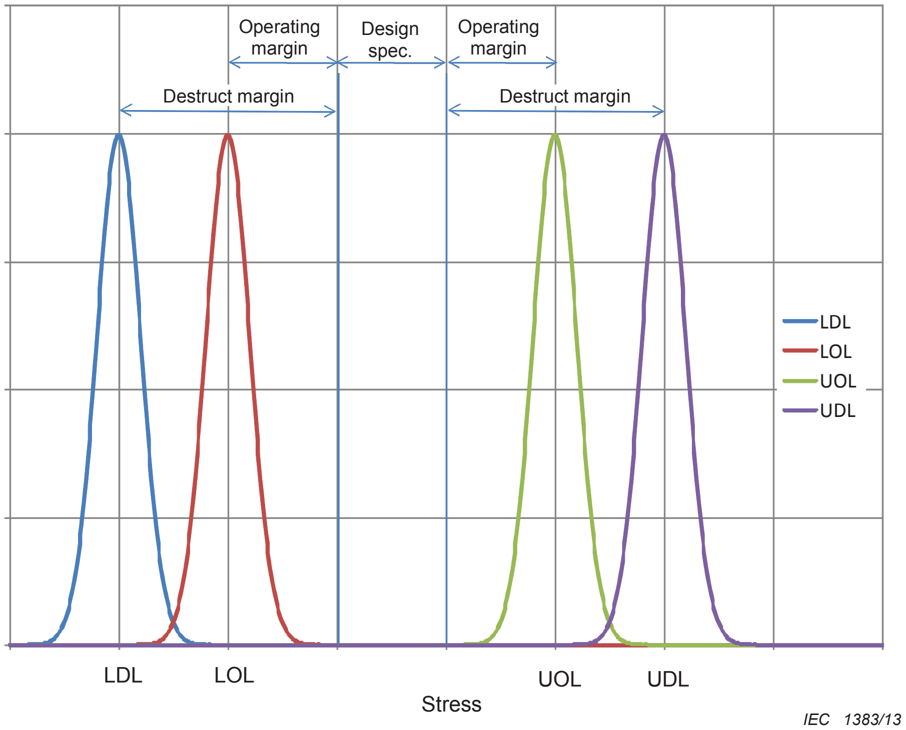


Figure 4 – PDFs of operating and destruct limits as a function of applied stress

Figure 4 is an example where both limits of the stress affect an item. This example could be the thermal stress where both, high and low temperature, affect the performance of the product. These effects may not be symmetrical, as the limits for high and low temperature may 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 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, lower limits may not exist as for example is the case for mechanical stresses, but they may 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/shock;
- voltage;
- combination of vibration/shock and thermal cycling.

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

Verification of margins and product improvements made in response to HALT serve to increase the probability that the product 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 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.

Each failure observed during the HALT should be investigated and root cause failure analysis should be performed. If the identified failure mode is likely to occur in the field where the stress level is expected to be considerably lower than 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 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 [23]. The duration of 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/audit (HASS/HASA)

5.1.3.1 Principle and extent of HASS/HASA

HASS and HASA are not classified as tests. Yet, both are included in this standard because they apply accelerated stress for defect detection/screening. HASS tests are 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 significantly reduce product life in the field. These levels are determined based on the finding from the HALT program. 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. 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.

The stress levels in the HASS/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 some operational abnormalities may 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 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.1, 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 r.m.s. (19,62 m/s^2). Before the precipitation screen is used for HASS/HASA it should be verified that the precipitation screen does not significantly reduce the product 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 3 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 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 large products, small products and products 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 Type 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, e.g. 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 in accelerated testing is to measure the reliability and verify acceptable reliability performance of the product 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 or system. This can also be achieved through failure mode analysis of the designed product associated with the intended product usage profile, e.g. using a FMEA (see IEC 60812 [2]). 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 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 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.

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. For this planning, empirical factors from previous products, 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 setup where the empirical factors can be estimated from the test itself. See Annexes F and G.

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/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:

- 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 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 exceed the physical properties of product materials and cause unforeseen damage;
- a risk that the acceleration of combined stresses may cause additional unforeseen damage to the product that would not have happened in actual use;
- the base line for acceleration testing is not a single stress but is generally a multiple stress that varies with user and location. This needs to be taken 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) by compressing the duty cycle through addressing just the ON time. Furthermore, when products 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 program. 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 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 3 days of actual use time.

5.2.3.1.2 Advantages of time compressed tests

Products 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, etc.). 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 duration of 2 h, can be tested for 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 even be more damaging to the product, since they are a result of stresses that are perhaps considerably lower than those when the product is in use, but are applied for 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 30 000 h per year, causing corrosion. Testing only under operational conditions would disregard the influence of non-operating environments.

For products 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, e.g. corrosion tests, humidity tests etc. In some cases the product 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 influence of applied vibrations on the product structure.

5.2.3.2 Type C_2 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 use. As an example, the ON/OFF cycling of the above-mentioned unit (the snow plough) can be compressed to a test of several h, 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 C_2 tests can be combined with the time compression tests for further test acceleration. This may 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 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 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 neglect the failures due to non-use, such as material deterioration.

5.2.3.2.2 Advantages of the type C_2 test

The advantage of the Type C_2 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 C_2 test

This type of testing may 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 produce heat that would further precipitate a failure that would normally be delayed by periods of cooling. Another example could 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 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 relation 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 the manner in which 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 use.

5.4.2 Step-by-step procedure

The following procedure shall be applied:

a) identify the relevant stress factors from the field, including storage and transportation (see the IEC 60721 series);
b) determine which stress types have to be accelerated, which will be nominal and which can be omitted, e.g. 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, e.g. in a test cycle (see IEC 60605-2);
d) determine if the acceleration factor (A) 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 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 be estimated separately. This can generally be expressed as follows:

$$R = \prod_{i=1}^{N_s} R_i \tag{3}$$

where

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

R represents the reliability of UUT;

N_S is the total number of independent stresses.

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

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

$$\lambda_{\text{item}}(Stress) = \lambda_{\text{U}} + \sum_{i=1}^{N_S} \lambda_i (Stress_i) \tag{4}$$

where

λ_{U} is the unknown failure rate.

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:

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

where

β is the shape parameter of the Weibull distribution;

η_{Item} is the item scale parameter for the combined individual stresses;

η_{b} 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 standard.

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 (3) presents a rather accurate way of expressing the overall item failure rate with applied stresses. It assumes that the part/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 the case when assemblies and systems are tested for multiple different failure modes, the item failure rate as accelerated is:

$$A \cdot \lambda_{Item} = \lambda_U + \sum_{i=1}^{N_S} A_i \cdot \lambda_{Item}(Stress_i) \tag{6}$$

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 the same failure mode the test acceleration from Equation (6) becomes Equation (7):

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

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;
$\left(\prod_k A_k \right)_i$	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}	is the acceleration factor of the failure rate of the item in use conditions to produce the overall accelerated, test failure rate.

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

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

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

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

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

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 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 overestimate 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

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. The acceleration models should if possible be verified by plotting the test data.

5.6.1.1 Inverse power law

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 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 [10].

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

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

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:

$$\ln[L(S)] = -m \times \ln(S) - \ln(C) \tag{12}$$

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

The test acceleration factor is then:

$$A_{S\_IPL} = \frac{L(S_{Use})}{L(S_{Test})} = \frac{C^{-1} \cdot S_{Use}{}^{-m}}{C^{-1} \cdot S_{Test}{}^{-m}} = \left(\frac{S_{Test}}{S_{Use}}\right)^{m} \tag{13}$$

where

A_{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 above, 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 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 become a very tedious process for items that are more complex than a single component, as the test may involve long periods of time and large number of samples. However, using test acceleration factors that are loosely estimated may 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 represent a more conservative estimate of life since the actual stress-life curve for the specific failure mode may 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 exhibit two different failure mechanisms: dielectric breakdown, and movement of oxygen vacancies, both resulting in shorting of the capacitor. The two may 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 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 be incorrect.

5.6.1.1.1 The advantages of the inverse power law model

The primary advantage of his 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 abundant literature.

5.6.1.1.2 The disadvantage of the inverse power law model

The model disadvantages are as follows:

- the simplicity of the model may 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 require a long test time, and should those at the same time have a high level of reliability, the sample size may need to be large, and the test may be lengthy;
- caution should be exercised when accepting an assumed value for the parameter m, borrowed from a seemingly similar product.

5.6.1.2 Arrhenius model

The Arrhenius model 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:

$$\rho(T) = K \times e^{-\frac{E_a}{k_{B \times T}}} \tag{14}$$

where

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

E_a is the activation energy (eV);

k_B is Boltzman's constant = 8,617385 × 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:

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

To represent the above equation as a straight line:

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

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:

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

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:

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

The failure rate λ_0 at a specified temperature T_0 *is*:

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

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

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

where

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

An example of use of Arrhenius model for determination of 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.

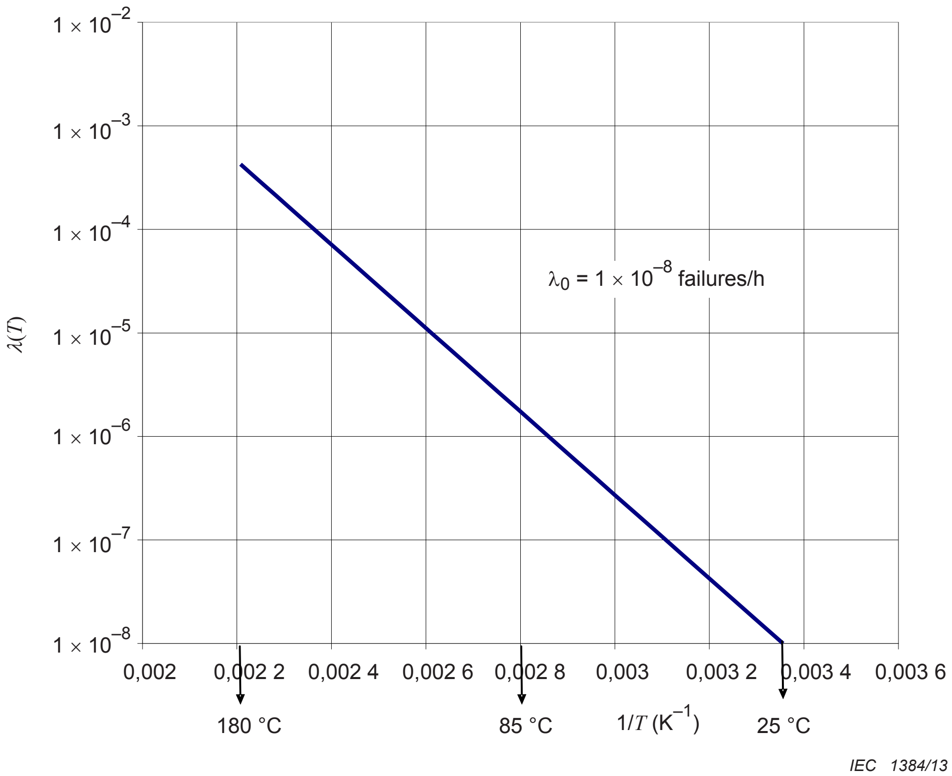


Figure 5 – Line plot for Arrhenius reaction model

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 D, 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:

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

$$E_a = k_B \cdot SLOPE$$

where

λ_0 = 1 ×10^{-8} failures/h;

$\ln(\lambda_0)$ = –18,421;

T_0 = 25 °C = (25 + 273) K = 298 K

$\ln(\lambda_F)$ = –7,764 5;

T_F = 180 °C = (180+273)K = 453 K;

E_a = 0,8 eV

$$SLOPE = \frac{\ln[\lambda(T)] - \ln(\lambda_0)}{\frac{1}{T_0} - \frac{1}{T}}$$

Figure 6 shows determination of the activation energy.

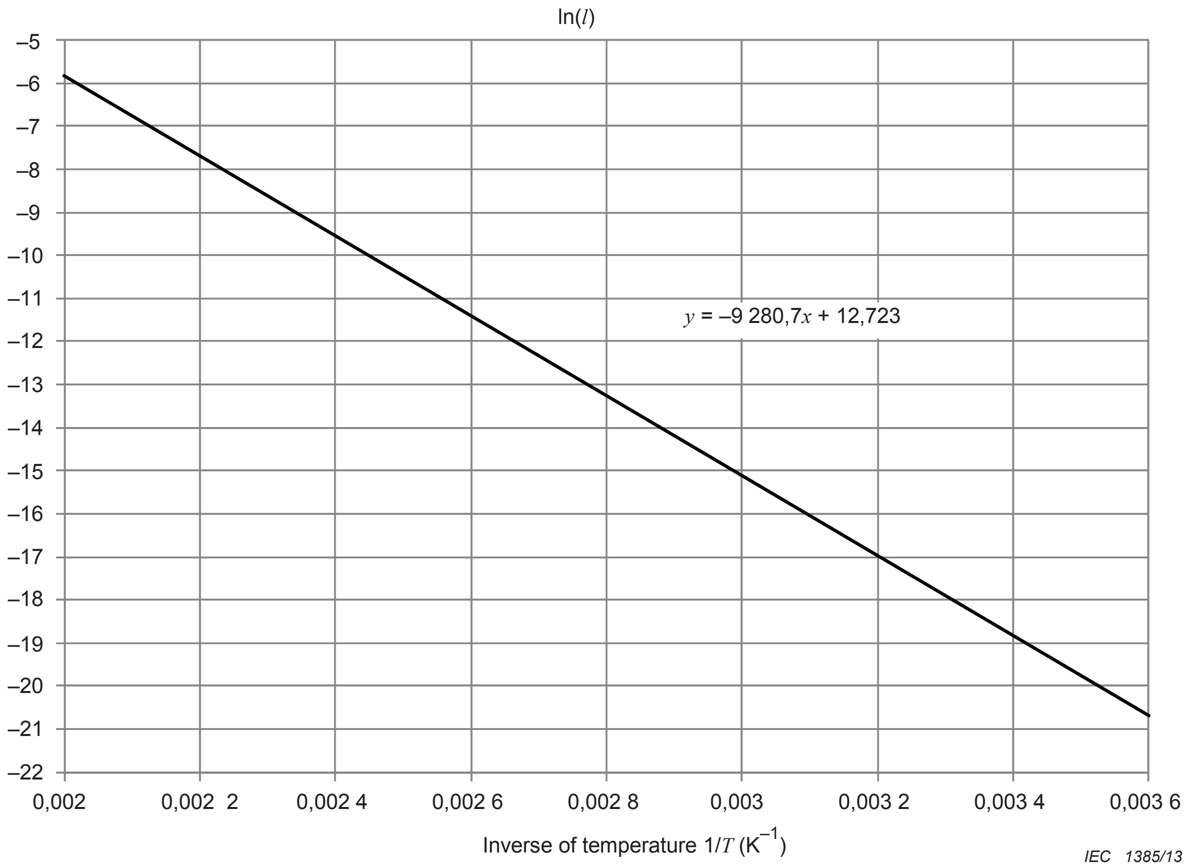


Figure 6 – Plot for determination of the activation energy

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.

5.6.1.2.1 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.

5.6.1.2.2 Model advantages

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.

5.6.1.2.3 Model disadvantages

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 be hard to apply, as the components will often have different thermal activation energies for different failure modes (see JESD85 [26] and Annex G of IEC 61649:2008).

5.6.1.3 Eyring model

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

The function related to expected life is shown as follows:

$$L(S_E) = \frac{1}{S_E} \cdot e^{-\left(A - \frac{B}{S_E}\right)} \tag{22}$$

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 with this model is:

$$A_{S\_E} = \frac{L(S_{E\_Use})}{L(S_{E\_Test})} = \frac{\frac{1}{S_{E\_Use}} \cdot e^{-\left(A - \frac{B}{S_{E\_Use}}\right)}}{\frac{1}{S_{E\_Test}} \cdot e^{-\left(A - \frac{B}{S_{E\_Test}}\right)}} = \frac{S_{E\_Test}}{S_{E\_Use}} \cdot e^{B\left(\frac{1}{S_{E\_Use}} - \frac{1}{S_{E\_Test}}\right)} \tag{23}$$

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 [10].

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.

5.6.1.3.1 Model advantages

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.

5.6.1.3.2 Model disadvantages

As with the Arrhenius model, knowledge of the parameter B is critical for correct test acceleration. For products with moderate complexity, accurate test acceleration may 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 usage profile and those are the cumulative damage or cumulative exposure model.

5.6.2.2 Step stress model

The model most frequently used as 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 [13], [7].

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

$$R(t,S) = e^{-\left(\frac{t}{\eta(S)}\right)^{\beta}} \tag{24}$$

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 probability of failure is

$$F(t,S) = 1 - R(t,S) \tag{25}$$

In the above equations, with an example of the inverse power law model, the characteristic life is:

$$\eta(S) = C^{-1} \times S^{-m} \tag{26}$$

For successive stresses (stress levels) S_i, where i = 1,2,3…

$$F_i(t,S_i) = 1 - e^{-\left(C \cdot S_i^m \cdot t\right)^{\beta}} \tag{27}$$

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, to account for ageing at the previous stress level:

$$\tau_i = (t_i - t_{i-1}) \cdot \left(\frac{S_i}{S_{i-1}} \right)^m + \tau_{i-1} \tag{28}$$

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

$$F_i(t, S_i) = 1 - e^{-\left(C \cdot S_i^m \cdot (t - t_{i-1}) + \tau_{i-1}\right)^\beta} \tag{29}$$

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 life measure as described in the related standards on confidence limits, dependent on the established distribution.

5.6.2.2.1 Model advantage

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

5.6.2.2.2 Model disadvantage

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 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 lifetime according to Miners 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:

$$\frac{n_1}{N_1}+\frac{n_2}{N_2}+....+\frac{n_i}{N_i}+....+\frac{n_m}{N_m}=1 \tag{30}$$

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_1/N_1 is the damage ratio (fraction of life) at the i-th stress level.

Replacing number of cycles by the lifetimes:

$$\frac{l_1}{L_1}+\frac{l_2}{L_2}+....+\frac{l_i}{L_i}+....+\frac{l_m}{L_m}=1 \tag{31}$$

where

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

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

l_1/L_1 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:

$$\begin{aligned} l_1 &= \alpha_1 \times L \\ l_2 &= \alpha_2 \times L \\ l_i &= \alpha_i \times L \end{aligned} \tag{32}$$

where

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

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

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

$$\frac{\alpha_1 \times L}{L_1}+\frac{\alpha_2 \times L}{L_2}+....+\frac{\alpha_i \times L}{L_i}+....+\frac{\alpha_m \times L}{L_m}=1$$

$$L=\frac{1}{\frac{\alpha_1}{L_1}+\frac{\alpha_2}{L_2}+....+\frac{\alpha_i}{L_i}+...\frac{\alpha_m}{L_m}} \tag{33}$$

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.

The stress vs. 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 5.6.1.1 is 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 and in [17].

5.6.4.2 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 which periods in the mission profile can be time compressed and how much (IEC 60605-2);

Step 3: estimate the acceleration factor(s) for the potential failure modes (see 5.2.2.1);

Step 4: determine the sample size (see IEC 61649);

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

Step 6: perform failure analysis;

Step 7: analyse test results for each failure mode separately (see IEC 61649);

Step 8: 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 standard.

5.7.1.2 Product and component use profile

Often the manufacturers choose to test a product in an accelerated test that simulates environmental stresses as they are experienced in the field. Some of the reasons for such tests may 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. There are instances where, due to space or performance constraints, one or more components in that product may be insufficiently derated which may not provide adequate stress vs. strength margin. In these instances, product reliability may be highly dependent on the manner of its use, operational and environmental stresses, their combination and sequence.

A product 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 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. This goal may be expressed as a percent failed products at the end of 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 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 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 be estimated separately. This can be expressed in general form for a combination of n independent stresses as:

$$R_{equipment} = \prod_{i=1}^{n} R_i \qquad (34)$$

For the failure probability:

$$F_{equipment} = 1 - \prod_{i=1}^{n} \left(1 - F_i\right) \qquad (35)$$

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

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 in a segment of time (part of a use profile where a specific stress combination exists) t_k is:

$$R_{Item}(Stress, t_k) = \prod_{j=1}^{m} \left[\prod_{i=1}^{n} R_p(Stress_i . t_k) \right]_j \qquad (36)$$

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

$$R_{Item}(Stress, t_0) = \prod_{k=1}^{w} \left\{ \prod_{j=1}^{m} \left[\prod_{i=1}^{n} R_p(Stress_i . t_k) \right]_j \right\} \qquad (37)$$

where

$$t_0 = \sum_{k=1}^{w} t_k \tag{38}$$

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

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

$$\lambda_{a\_Item}(Stress, t_0) = -\frac{\ln\left[R_{Item}(Stress, t_0)\right]}{t_0} \tag{39}$$

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 Reliability demonstration or life tests

5.7.2.1 Applicable test types

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;
– test to failure (usually for components or small assemblies and individual failure modes);
– reliability improvement/growth tests, which are usually prepared for a predetermined time period;
– sequential probability ratio tests (SPRT).

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 program is prepared in view of the reliability for the specific use profile then the results of the test program are valid for that specified use profile only. If reliability estimates for other use profiles are needed for the same product, 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 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 and component reliability in regards to operational and environmental stresses as a function of predetermined time (lifetime) t_0, can be expressed as follows:

$$R(t_0) = R_U(t_0) \times \prod_i R_{S\_i}(t_0) \times \prod_i R_{E\_i}(t_0) \tag{40}$$

In the above equation $R_E(t_0)$ denotes reliability of the item regarding environmental stresses for the time duration t_0, while $R_S(t_0)$ denotes reliability regarding operational stresses. Factor $R_U(t_0)$ is used to represent 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 not be a valid assumption.

Equation (40) can be generalized to be written in the form:

$$R_{Iten}(t_0) = \prod_{i=1}^{N_S} R_{Stress_i}(t_i) \tag{41}$$

If $R_{Item}(t_0)$ is the product reliability goal or the product 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 reliability. Simplified for illustration the allocated individual reliabilities may be assumed to be the same.

$$\begin{aligned} R_{Item}(t_0) &= \left(R_{Stress_i}(t_i)\right)^{N_S} \\ R_{Stress_i}(t_i) &= \sqrt[N_S]{R_{Item}(t_0)} \end{aligned} \tag{42}$$

The allocated values to reliability regarding individual stresses differ depending on the product 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 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 have different prevalent or extreme stresses. As an example, in some countries such as Northern Scandinavia, Canada and Russia, low temperature may be one of the highest stresses, while New Mexico, Africa and India it may be high temperatures. In Singapore and Japan the most pronounced stress may be humidity and in New Delhi it may 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). 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 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. Such environmental tests are described in the IEC 60068 series.

Often, products are tested with a stress cycle in order to expose the product 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, e.g. of 1 week duration.

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:

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

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;
$\mu L_{\_i}$	is the mean duration of that load (stress) application in use;
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:

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

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:

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

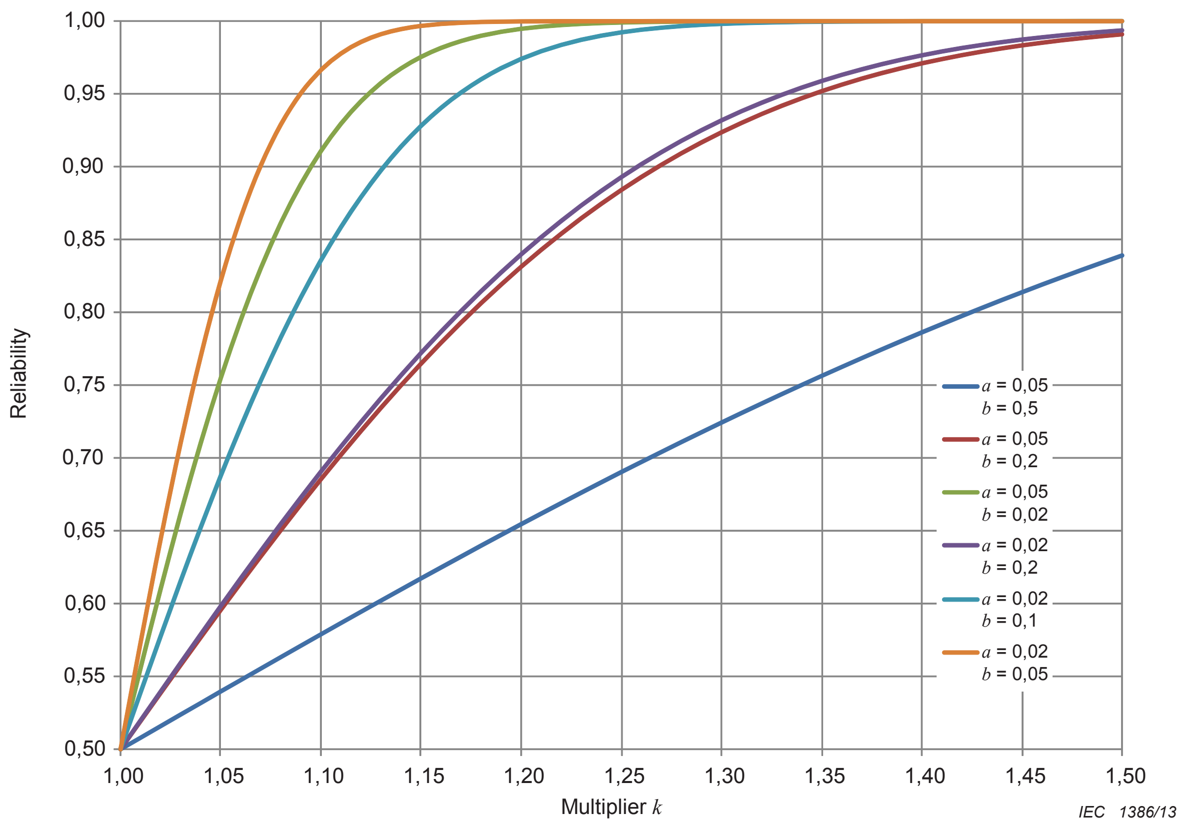
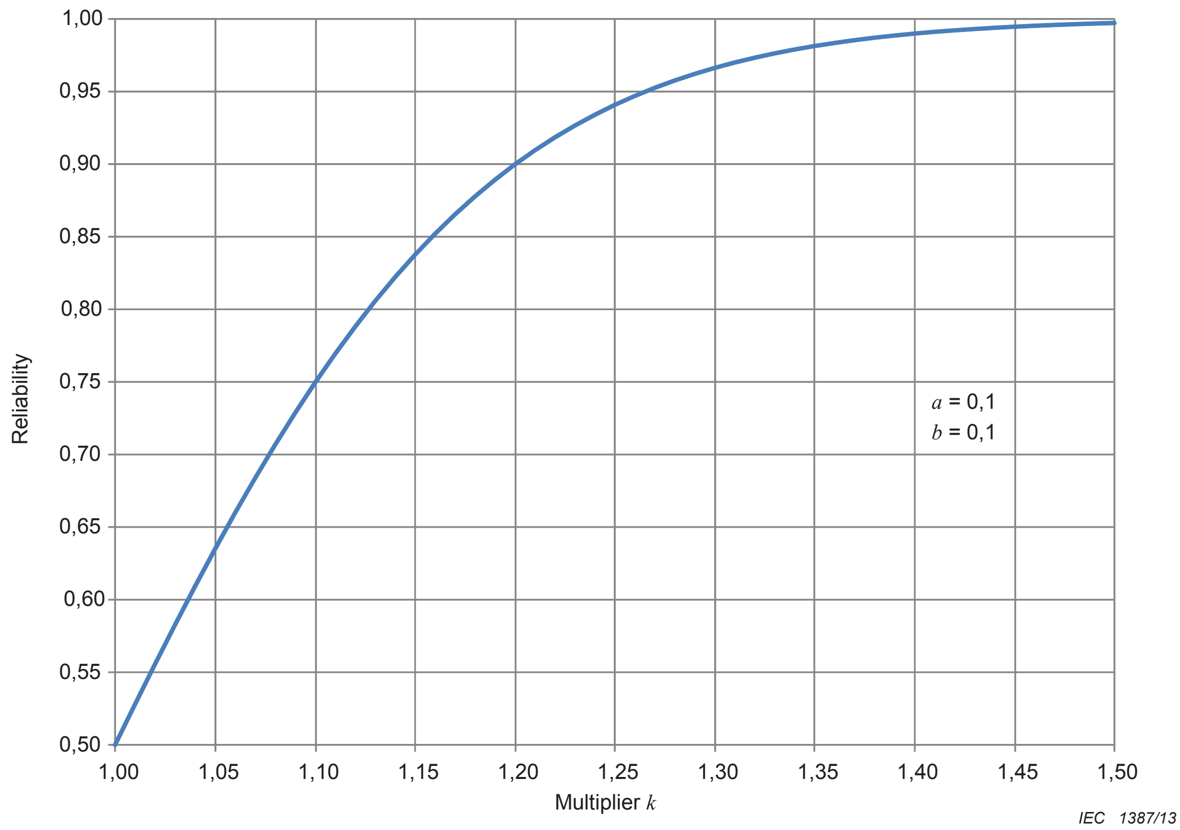


Figure 7 – Multiplier of the test stress duration for demonstration of required reliability for compliance or reliability growth testing

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 specific acceleration factors for the various expected stresses need to be known. These need to be obtained through tests-to-failure at different stress levels for the specific components (see Annexes F and G).

The above program 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 will be estimated based on the number of failures in the test;
– as a reliability growth/improvement test based on an assumed growth rate.

When it is a success test, the results are simply and easy to interpret. Without failures, the test demonstrates the reliability requirement with applied confidence intervals.

If this test is to allow a certain number of failures, then 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 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, r, having in mind the total duration of the applied stresses, required confidence and the required demonstrated reliability (see IEC 62429).

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 JESD47 [26]. 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 be expected that the physical characteristics may 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 be an indicator that perhaps the stress level was too high and has changed physical characteristic of that component or that the manufacturing process was flawed. If that happened within the component rating it could mean that the component rating needs to be re-evaluated.

Usual environments 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 estimated life of the components. It is testing to failures that provides meaningful results while testing with no failures may 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 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 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. If that test is accelerated, it may provide information only for the normalized to in use level (life equivalent) time. The fact that the multiple components were tested does not improve the test results, only the degree of confidence (see JESD47 and JESD85 [26],[28]).

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. The re-calculations are done using appropriate acceleration models (see IEC 61709).

This information is provided at a given temperature and environment as well as other specified stresses.

The stated failure rate is often the average failure rate over the useful life 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. 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).

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 B10 or L10 life) or 1 % failures (often denoted as B1 or L1 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. 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 determination of item reliability with regard to individual failure modes, which is the case for components (piece parts).

Given the high reliability (or MTTF/MTBF) of the products, 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 the term MTBF is used for both MTTF and itself.

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:

$$\lambda_0 = -\frac{\ln[R(t_0)]}{t_0} \tag{46}$$

where

t_0 is the expected operating time.

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

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

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 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.

Total equivalent test acceleration factor is then (Krasich acceleration model for constant failure rate [10]):

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

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

Reciprocal of the accelerated failure rate from Equation (46) will yield the MTBF, m_0, which can be determined from tests.

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

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 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 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 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 e.g. 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 analysis methods used for reliability growth test type is applied (see IEC 61164).

When analysis is carried out in this manner, the order of stress application does not skew the test results, as the failure 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 change.

For some tests where the intention is to understand the stress limits of the product, 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 tests are performed, reliability requirements would be met.

Verification tests are designed to verify 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 represent some duration in life, there can be no correlation made between performance verification and product reliability.

Completion of validation 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. An item may have to be removed from the test either because the destruct limit has been found or because the item is needed 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 5. To account for more than one failure mode another 2 to 5 samples are recommended, so the total recommended sample size is 7 – 10 items. If that number of items are not available repairs must be made during the test.

For a quantitative accelerated test (Type B and C test) 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 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 JESD 47B [26]). 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 h in the field. The average failure rate can be estimated using IEC 60605-6.

For the case where the purpose of the test is to estimate the time to failure (life time), the test time have to 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 5 – 10 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 – 30 items. If more than one failure mode is expected these numbers should be multiplied 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 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 a representative or worst case conditions have to be chosen. Some tests operate with the term “severe user” which is a user defined so that only a small percentage e.g. 1 % of the user operates the product under higher stress conditions.

When testing for life time e.g. using test of type C the test is usually extended to more loading cycles or longer time than the product 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 lifetime ratio (see 5.7.2.2 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. If the test is performed so that the product always hit 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 hit will be random.

6.3 Testing components for multiple stresses

Normally components are tested for each stress type separately (see JESD47B) [26]. However in some cases combined test is used in order to test for the combined effect of stresses. One example is pre conditioning of components by exposing them to 3 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]). 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 type 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 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 test often do not work well with small items (components) or large items (systems). For assemblies accelerated tests of Type 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 Type 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 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, IEC 61164 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 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 that need to be improved for the whole product to be sufficiently robust. The tests of type A do not give an estimate of life time or failure rate for the product.

For quantitative accelerated tests (Type B and C) the acceleration factor has to be estimated to link the test time with the equivalent time in the field. Each failure mode has to be analysed separately. Therefore a failure analysis is required for all failures. 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 as a function of time (see 5.2.2.1). Statistical tools that can be used for analysis include IEC 61123, IEC 61124, IEC 60605-6, IEC 61649, IEC 62303 and IEC 62429.

7 Limitations of accelerated testing methodology

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

- Determination of acceleration factors is very complex and cost and time prohibitive. Thus, accelerated testing duration and reliability results (values), which are dependent on acceleration factors, have limited precision.
- It may 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 be over or underestimated.
- Items to be tested may 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 be too complex to be affordable or manageable.
- Some means of test acceleration may 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, and may not be representative of the average strength of all of the items; so that its destruct design limits may also be different, pointing to wrong conclusions. An opposite case is also possible, where the test unit may 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 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 is used in different manner or in different environments. The re-test would be required.
- The results of quantifying reliability through acceleration may not always be predictive on an individual product since it may operate at different stress levels than was tested.

Annex A
(informative)

Highly accelerated limit test (HALT)

A.1 HALT procedure

A typical procedure for HALT is as follows:

Step 1: Determine stress level where the test will be stopped if 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 considerably dampened. The fastening or fixture should not protect the UUT from rapid air movements in the chamber. In some cases it may be necessary to remove enclosures to allow free access of the chamber air to the interior of the UUT. It may also be necessary to remove plastic enclosures or parts/components that cannot survive the high temperature or vibration acceleration during the test.

Step 3: Initial testing: the UUT must 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, e.g., high air flow.

Step 4: Increase the applied stress to the desired level. If the UUT is continuously monitored, the stress level can be increased continuously. If continuous monitoring is not possible, the stress levels have to 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 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 temperature.

Step 8: Repeat Step 2 to Step 6 with cycling between UOL and LOL.

Step 9: For the traditional HALT now repeat step 2 to step 5 with vibration/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 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 the UUT is to be retested if possible to verify improvement (IEC 60300-3-5).

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

A.2 Example 1 – HALT test results for a DC/DC converter

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

Table A.1 – 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 shut down	Limit set in software
Vibration	OVL 294,3 m/s^2 r.m.s. 588,6 m/s^2 r.m.s. VDL 588,6 m/s^2 r.m.s.	Loose screw. Unstable voltage	Screw too loose. Hand-solder failed	Apply Loctite[2] . Solder processes
Temperature cycling –70 °C to +125 °C 4 m in to 10 min dwell time	No weaknesses found after more than 20 cycles			
Combined vibration and temperature cycling 40, 50 and 60 g r.m.s. –70 °C to +125 °C		3 components fell off PWB Problems with 5 V DC		Review of production processes Further investigation required

A.3 Example 2 – HALT test results for a medical product

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

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2 Loctite is an example of a suitable product available commercially. This information is given for the convenience of users of this standard and does not constitute an endorsement by IEC of this/these product(s).

Table A.2 – Summary of HALT results from 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/sec^2 r.m.s OVL 196,2 m/sec^2 r.m.s OVL 490,5 m/sec^2 r.m.s. VDL 294,3 m/sec^2 r.m.s	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. 10 min dwell time	No weaknesses found after 6,5 cycles			
Combined vibration and temperature cycling 30 g, 40 g and 50 g r.m.s. –20 °C to +85 °C	98,1 m/s^2 r.m.s and temp. cycle 294,3 m/s^2 r.m.s temp. cycle 294,3 m/s^2 r.m.s and +80 °C 490,5 m/s^2 r.m.s and –20 °C 490,5 m/s^2 r.m.s temp. cycle 490,5 m/s^2 r.m.s 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

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 not being tested in the HALT chamber.

A.4 HALT test results for a Hi-Fi equipment

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

Table A.3 – 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 r.m.s. 294,3 m/s^2 r.m.s. VDL 343,35 m/s^2 r.m.s.	5 components 1 component		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, 20 g, 30 g, 40 g and 50 g r.m.s. –55 °C to +110 °C		Problems regarding CD playing at low temperature		Mounting of 2 components

For more detailed information see [15].

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, and product design capabilities. Acceleration of various stresses is a well established technique published in the literature, books and articles (see bibliographic references [3, 4, 6, 8, 9, 10, 12,13]). They are based on the assumption that the test demonstrates the strength of a product regarding the applied environments and operational stresses, and shows whether the tested product/item did have a related failure (success/life test). 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 the stress duration

The product 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 reliability is then written as:

$$R_{Item}(t_0) = \prod_{i=1}^{S} R_{Stress_i}(t_i) \tag{B.1}$$

In the above equation $R_{\text{stress},i}$ denotes reliability of the product 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 use environments, average and extreme. Other stresses related to product 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, voltage variations, etc.

For the test, a reliability value is allocated to each of the multiples in the expression for the product reliability. The allocated values to reliability regarding individual stresses differ dependent on the product intended use and usage profile and its sensitivity to a particular environment. Reliability value also must 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.

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:

$$R_i = \Phi\left[\frac{S_i \times \mu_{S\_i} - S \times_i \times \mu_{L\_i}}{\sqrt{\left(S_i \times \mu_{S\_i}\right)^2 + \left(S_i \times \mu_{L\_i}\right)^2}}\right] \tag{B.2}$$

Reduced Equation (B.2) becomes:

$$R_i = \Phi\left[\frac{\mu_{S\_i} - \mu_{L\_i}}{\sqrt{\left(\mu_{S\_i}\right)^2 + \left(\mu_{L\_i}\right)^2}}\right] \tag{B.3}$$

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.

$$R_i(t_0) = \Phi\left[\frac{\mu_{S\_i} - \mu_{L\_i}}{\sqrt{\left(a \times \mu_{S\_i}\right)^2 + \left(b \times \mu_{L\_i}\right)^2}}\right] \tag{B.4}$$

Simplified, Equation (B.4) then becomes:

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

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.

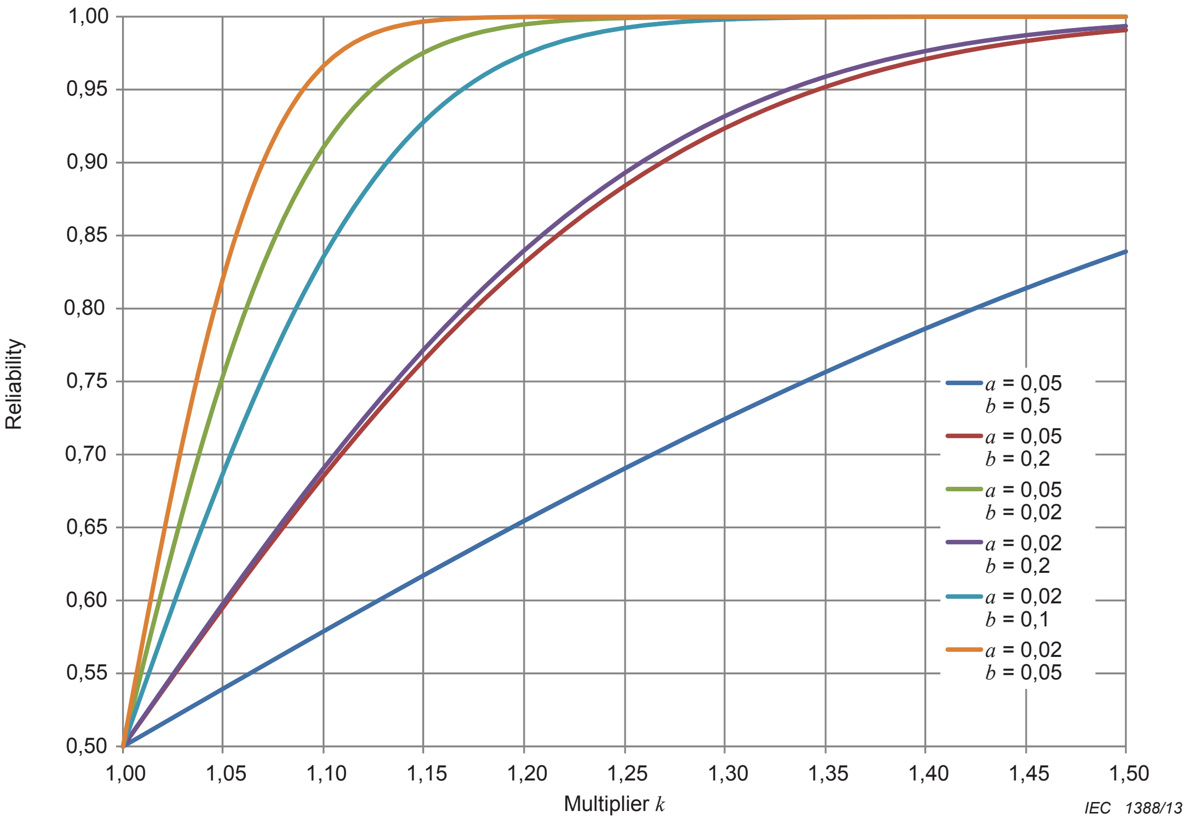


Figure B.1 – Reliability as a function of multiplier *k* and for combinations of parameters *a* and *b*

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 failure rate acceleration:

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

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 acceleration factors of stresses affecting the failure mode i.

Total equivalent test acceleration is:

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

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

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

$$\begin{aligned} R_i(t_i) &= R_S(t_0) = \sqrt[N_S]{R_0(t_0)} \\ \lambda_i &= \lambda_S = const. \\ \lambda_o &= N_S \cdot \lambda_S \end{aligned} \quad \text{(B.9)}$$

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

Then the overall acceleration factor becomes:

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

B.4 Example of reliability compliance test design

B.4.1 General

Reliability compliance tests 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 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/s² r.m.s
Relative humidity	RH_{use}	50 %
Activation energy	E_a	1,2 eV

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 setup 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 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.

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

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

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).

Reliability of the item regarding each of the stresses is:

$$R_i(t_0) = [R_0(t_0)]^{1/4} = 0{,}946 \tag{B.13}$$

This example uses 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.

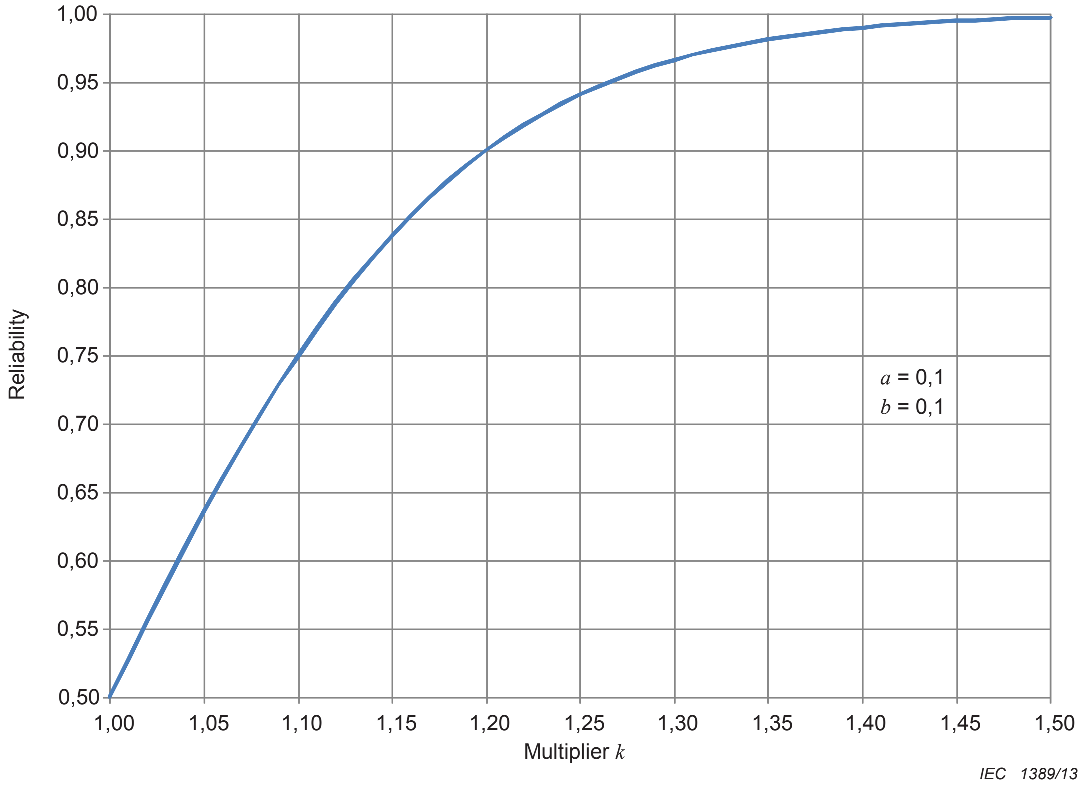


Figure B.2 – Determination of the multiplier *k*

B.4.2 Thermal cycling

ΔT_{Use} = 45 °C

T_{Test} = 105 °C

ΔT_{Test} = 105 – (-20) = 125 °C

ξ_{Use} = 1,5 °C/min

ξ_{Test} = 10 °C/min

m = 2,5

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

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

B.4.3 Thermal exposure, thermal dwell

Normalize duration at the OFF temperature to the ON conditions:

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

$t_{ON\_N} = 8\,754$ hours

Calculate the necessary accelerated test duration:

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

$t_{T\_Test} = 168{,}1\,\text{h}$

For stress synergism, combine 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.

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

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:

$$\begin{aligned} t_{TC} &= 2 \times (\text{ramp time}) + (\text{stablization time} + \text{thermal dwell}) + \text{dwell at cold} \\ t_{TC} &= 2 \times \frac{125}{10} + 22{,}3 + 5 = 52{,}3\,\text{min} = 0{,}875\ \text{h} \end{aligned} \quad \text{(B.18)}$$

B.4.4 Humidity

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

Duration of humidity exposure is equal to the normalized temperature exposure, $t_{\text{ON\_N}}$.

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

$h = 2{,}3$

$t_{RH\_Test} = 300\,\text{h}$

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

B.4.5 Vibration test

Required kilometrage for ten years was 240 000 km, which translates into 150 h per axis vibration at 1,7 g r.m.s.

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

W_{Test} = 3,2 g r.m.s.
k = 1,5

$$t_{Vib\_Test} = k \cdot t_{Vib\_Use} \cdot \left(\frac{W_{Use}}{W_{Test}} \right)^{w} \tag{B.20}$$

With : $w = 4$
$t_{Vib\_Test} =$ 18 hours 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 as above, the acceleration factors are as follows:

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

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

The overall acceleration factor would then be:

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

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:

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

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

The acceleration of test then produces the following result:

$$\lambda_0 = -\frac{\ln[R_0(t_0)]}{t_0} = 2{,}22 \cdot 10^{-6}$$
$$\lambda_{Test} = -\frac{\ln[R_0(t_0)]}{t_0} \cdot A = 1{,}64 \cdot 10^{-3} \quad \text{(B.24)}$$

Or using MTBF :

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

$\theta_{Test} = 608{,}7$ 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, θ_0 = 3,93 × 10^5 h, but the MTBF about 600 times lower MTBF, θ_{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.

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	ς_{Use}	°C/min
Number of thermal cycles	c_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	c	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 those 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:

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

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

$$A_{Ramp\_Rate} = \left(\frac{\zeta_{Test}}{\zeta_{Uset}} \right)^{1/3} \tag{B.26}$$

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

$$N_{TC\_Test} = \frac{N_{TC\_Use} \cdot k}{A_{TC} \cdot A_{Ramp\_Rate}} \tag{B.27}$$

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:

$$t_{TC\_x} = x \cdot A_{TC} \cdot A_{Ramp\_Rate} \cdot \frac{24}{c_T} \tag{B.28}$$

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:

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

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

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

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

$$t_{TD\_Test} = \frac{t_{TD\_Use} \cdot k}{A_{TD}} \tag{B.31}$$

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

$$t_{TD\_y} = A_{TD} \cdot \frac{t_0}{t_{TD\_Use}} \cdot y \tag{B.32}$$

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

$$t_{St} = \frac{t_{TD\_Test}}{N_{TC\_Test}} \tag{B.33}$$

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

The total duration of a thermal cycle is then:

$$t_{TC\_Test}(\text{hours}) = \frac{(T_{Test} - T_{Amb})}{\xi_{Test} \cdot 60} + t_{St} + \frac{t_{TD\_Test}}{N_{TC\_Test}} + \frac{(T_{Test} - T_{Low})}{\xi_{Test} \cdot 60} + t_{Test\_Low} + \xi \frac{(T_{Amb} - T_{Low})}{\xi_{Test} \cdot 60} \tag{B.34}$$

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:

$$t_{TD\_z} = \frac{z(\text{h})}{t_{TC\_Test}(\text{h})} \cdot \frac{t_{TD\_Test}}{N_{TC\_Test}} \cdot A_{TD} \cdot \frac{t_0}{t_{TD\_Use}} \tag{B.35}$$

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:

$$A_H = \left(\frac{RH_{Test}}{RH_{Use}}\right)^h \cdot e^{\left[\frac{E_a}{k_B}\cdot\left(\frac{1}{T_{ON}+273}-\frac{1}{T_{H\_Test}+273}\right)\right]} \quad \text{(B.36)}$$

The total duration of humidity test is then:

$$t_{H\_Test} = \frac{t_{TD\_Use}}{A_H} \quad \text{(B.37)}$$

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

$$t_{H\_w} = A_H \cdot \frac{t_0}{t_{TD\_Use}} \cdot w \quad \text{(B.38)}$$

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:

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

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

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:

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

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 o operational cycles, then the actual time to a failure in use is:

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

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

	A	B	C	D	E	F	G	H	I	J	K	L
1	t_0	t_a	T_{ON}	T_{OFF}	E_a	k_B	n	k	m	c_T	h	
2	hours	H/day	˚C	˚C	eV	eV/K						
3	87 600	2	55,00	25	0,8	8,62E-05	24	1,5		2	3,5	
4	**Thermal cycling**											
5	ΔT_{use}	ΔT_{test}	m	c_T	N_{TC_Use}	A_{TC}	N_{TC_test}	**24/c_T**				
6					=B3*(A3/24)	=(B7/A7)^D7	=(E7*H3)/F7	=24/D7				
7	45	120	2,50	2	7 300	7,11	818,16	12				
8	ς_{Use}	ς_{Test}	g	A_{Ramp_rate}								
9				=(B10/A10)^C10								
10	1,5	10	0,33	1,88								
11	**Example: failure within x = 36 test cycles**											
12	x		t_{TC_x} **h**									
13			**= A14*F7*D10*H7**									
14	**36**		**5 781,73**									
15	**Thermal dwell**		$T_{high\_chamber}$	ΔT	T_{high}	$T_{low\_chamber}$	T_{room}					
16			85,00	20	105	–40	25					
17	t_{TD_Use}					t_0/t_{TD_Use}	A_{TD}					
18	=(B3/24)*A3+((24-B3)/24)*A3*EXP(-(E3/F3)*((1/(D3+273))-(1/(C3+273))))					=A3/A19	=EXP((E3/F3)*((1/(C3+273))-(1/(E16+273))))					
19	11 951,94					7,33	42,21					
20	t_{TD_test}											
21	=A19*H3*EXP(-(E3/F3)*((1/(C3+273))-(1/(E16+273))))											
22	424,705 712											
23	**Example: failure occurs 60 h in the thermal dwell h of dwell added**											
24	y		t_{TD_y} **h**									
25			**=A26*G19*F19**									
26	**60**		**18 563,44**									
27	**When time to failure recorded as time in thermal cycling:**											
28	Temperature cycle duration (h)			t_{St}	T_{test_low}							
29			1 test cycle (h)	0,25	0,25							
30			=2*(C16-F16)/(B10*60)+((A22/G7)+E29)+(F29)									
31			1,19									
32												
33	**Example: failure occurs within 212 h of thermal cycling**											
34	z **(h)**		t_{TD_z}									
35			**=(A36/C31)*(A22/G7)*G19*(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)*A3+((24-B3)/24)*A3*EXP(-(E3/F3)*((1/(D3+273))-(1/(C3+273))))				=((B40/A40)^K3)*EXP((E3/F3)*((1/(C3+273))-(1/(D40+273))))					
40	50	95	11 951,94	70			32,59					
41												
42	**Example**											
43	**Failure in humidity at w = 16 h**											
44	w **h**		t_{H_w} **h**									
45			**=A46*G40*(A3/A19)**									
46	**16**		**3 821,33**	**Life**								
47	**Vibration**											
48	D											
49	150 000											
50	W_{Use}	W_{Test}	M	A_{Vib}	t_{Vib_test}							
51				=(B54/A54)^C54	=A51/D54							
52	14,715	29,43	4,00	16	9 375							
53												
54	**Example**											
55	**Failure in vibration at v = 3 h**											
56	v **(h)**		t_{H_v} **h**									
57			**=A58*D52*(A3*1000)/A49**									
58	**1,5**		**14 016,00**	**Hours of life**								
59	N_{oc_use}	c		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.

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 h	Cumulative time to failure n = 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.

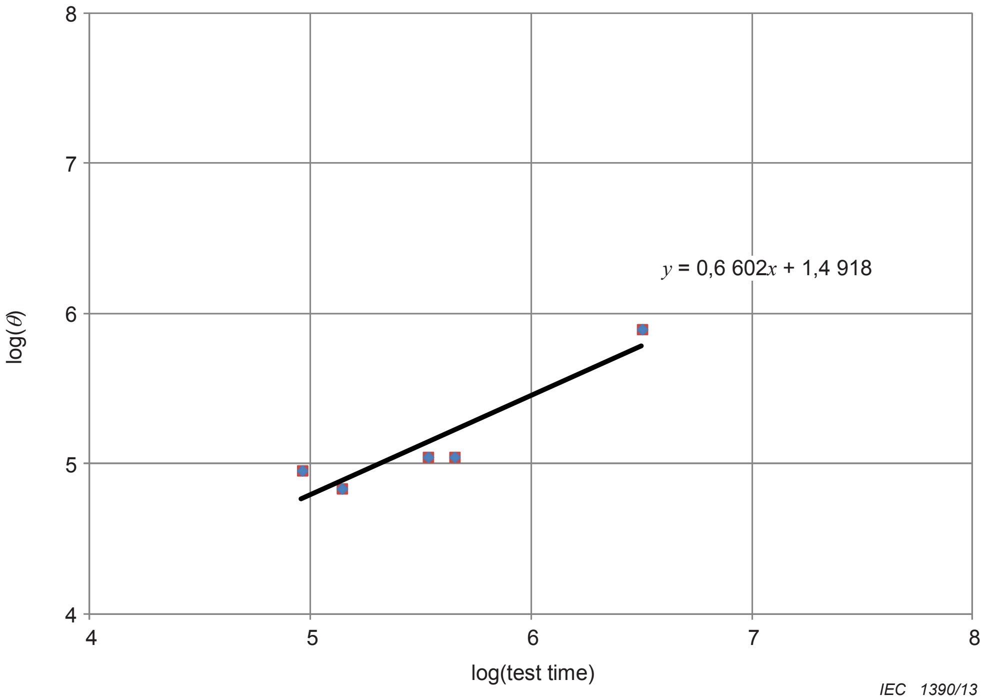


Figure B.3 – Determination of the growth rate

From the data in Table B.5, and the plot in Figure B.3, the results are as follows:

– growth rate, α = 0,66;
– final test MTBF: θ_{Final} = 1 431 964 h;
– reliability at t_0 = 87 600 h: $R(t_0)$ = 0,999 97.

Annex C
(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

Annex D
(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 failure to time (FIT) in operating condition, the supplier should, for example, test:

- 500 components for 1 year at 100 °C and observe one failure. The failure rate can be calculated as 228 FIT;
- another 300 components for 1 year at 125 °C and observe 3 failures. The failure rate can be calculated as 1 146 FIT;
- another 300 components for 1 year at 140 °C and observe 9 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 D.1 below:

$$E_a = k_B \times \frac{\ln[\lambda(T)] - \ln[\lambda(T_0)]}{\frac{1}{T_0} - \frac{1}{T}} \quad \text{(D.1)}$$

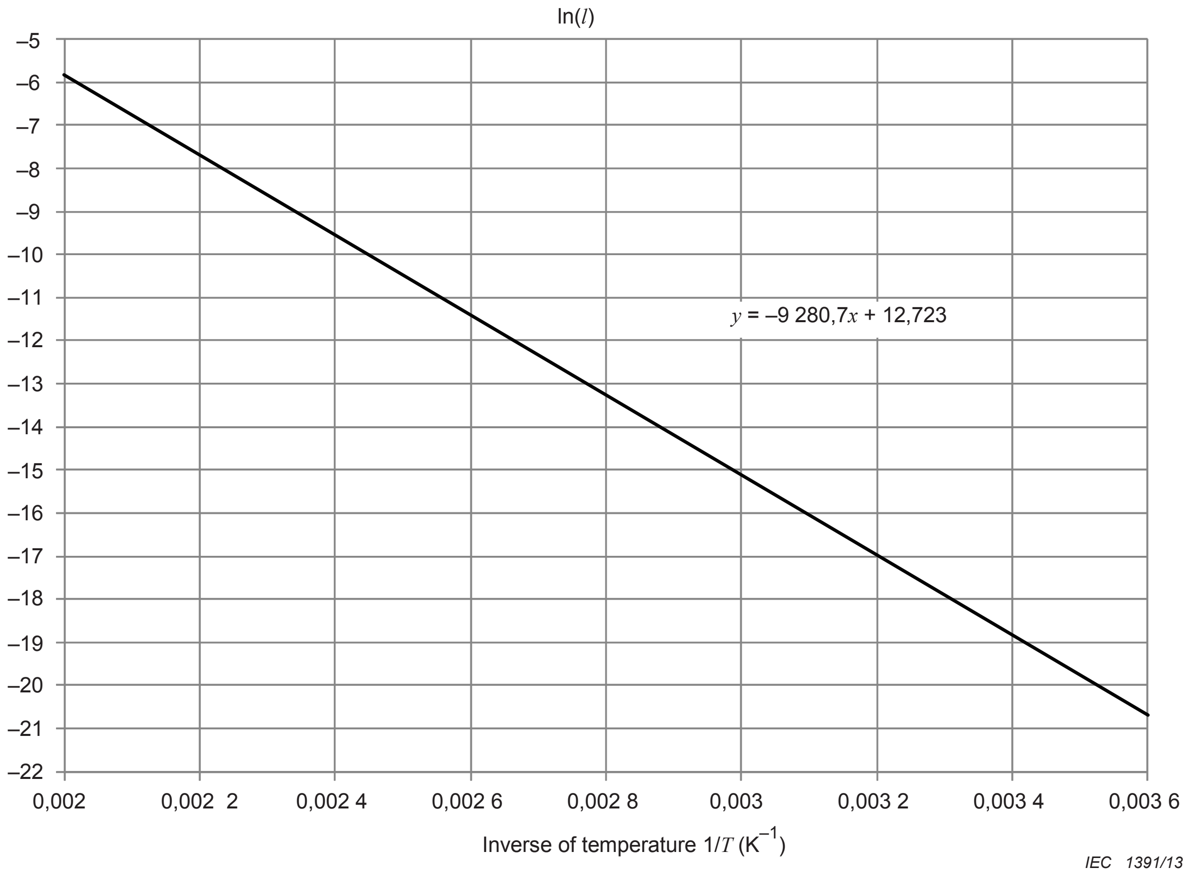


Figure D.1 – Plotting failures to estimate the activation energy E_a

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 E
(informative)

Calibrated accelerated life testing (CALT)

E.1 Purpose of test

The purpose of a calibrated accelerated life test (CALT) is to estimate the reliability or life time of a product based on 3 accelerated tests of a few samples. The procedure is adapted from GMW8758 [16]. There exists commercial software that supports the method.

E.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 e.g. 90 % of the level identified in Step 1. This is the high stress level.

Step 3 Test at least two products 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 this Step 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 e.g. 10 %. This is the medium stress level.

Step 6 Test at least two products at the stress level determined in Step 5 and record the number of cycles to failure or time to failure 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 Weibull plot 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 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 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 are as close as possible to the expected stress in the field taking in 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 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 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.

Step 18 Transpose the cycles/time to failure for the data points from Step 8 and 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/time to failure are the times/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 confidence limit to the Weibull curve plotted in Step 19 and read the relevant reliability/time to failure at the expected stress level in the field for the tested items.

Annex F
(informative)

Example on 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 °C. One in this group failed after 700 cycles and 10 after 1 000 cycles. A second test has been performed on 21 samples between –40 °C and +150 °C. In this second test group B, 4 failed after 300 cycles, 10 after 400 cycles, and additional 5 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 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:

$$F(c) = 1 - e^{-\left(\frac{c}{\eta}\right)^{\beta}} \quad \text{(F.1)}$$

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 F.1). Two Weibull curves are parallel with a shape parameter value of approximately 4. 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:

$$\begin{aligned}
1 - F(c) &= e^{-\left(\frac{c}{\eta}\right)^{\beta}} \\
\frac{1}{1 - F(c)} &= e^{\left(\frac{c}{\eta}\right)^{\beta}} \\
\ln\left[\frac{1}{1 - F(c)}\right] &= \left(\frac{c}{\eta}\right)^{\beta} \\
\ln\left\{\ln\left[\frac{1}{1 - F(c)}\right]\right\} &= \beta \times \ln(c) - \beta \times \ln(\eta)
\end{aligned} \quad \text{(F.2)}$$

$F(c)$ is determined as median rank of numbers of failure:

$$F(c) = \frac{i - 0{,}3}{n + 0{,}4}$$

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 F.1.

Table F.1 – Probability of failure of test samples A and B

c	F_A(c)	F_B(c)
300		0,200935
400		0,668224
500		0,808411
700	0,03125	
1 000	0,120536	

Data transformation for plotting is shown it 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		-1,494715295
5,991465		0,098302188
6,214608		0,502231166
6,55108	-3,449903552	
6,907755	-2,052275323	

The Weibull plot is shown in Figure F.1.

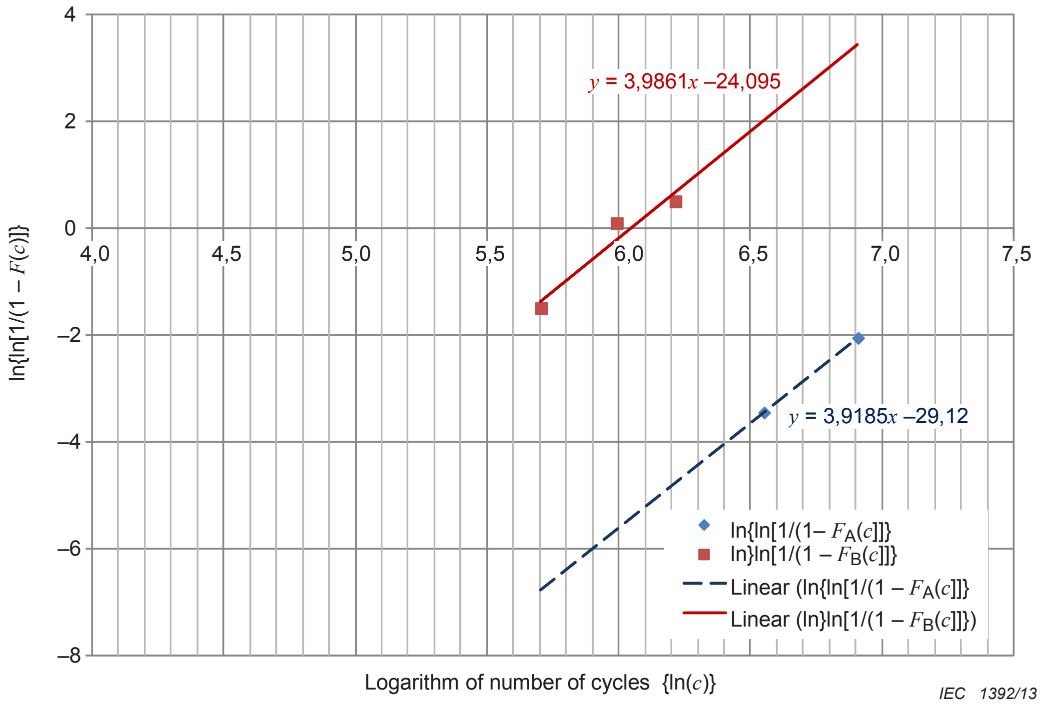


Figure F.1 – Weibull graphical data analysis

Equations of the linear data fit show values of the shape parameters as the slope, and the intercept is the negative product 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:

$$\beta \cdot \ln(\eta) = -intercept$$
$$\eta = \mathrm{e}^{-\frac{intercept}{\beta}} \qquad \text{(F.3)}$$

From Equation (F.3), the scale parameters determined for the two tests are as follows:

η_A = 8 231 cycles

η_B = 446 cycles

Thermal cycling acceleration, A_{190_125} between ΔT_{B} = 190 °C and ΔT_A = 125 °C is:

$$A_{\Delta T_B\_\Delta T_A} = \left(\frac{\Delta T_B}{\Delta T_A}\right)^m = \frac{\eta_A}{\eta_B} \qquad \text{(F.4)}$$

Solving for the exponent m, which is a characteristic of the test items:

$$A_{\Delta T_B\_\Delta T_A} = \left(\frac{\Delta T_B}{\Delta T_A}\right)^m = \frac{\eta_A}{\eta_B}$$
$$m = \frac{\ln\left(\frac{\eta_A}{\eta_B}\right)}{\ln\left(\frac{\Delta T_B}{\Delta T_A}\right)} \qquad \text{(F.5)}$$

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:

$$\eta(\Delta T) = \eta_B \times \left(\frac{\Delta T_B}{\Delta T}\right)^m \qquad \text{(F.6)}$$

Scale parameter as a function of thermal cycling temperature range is shown in Figure F.2.

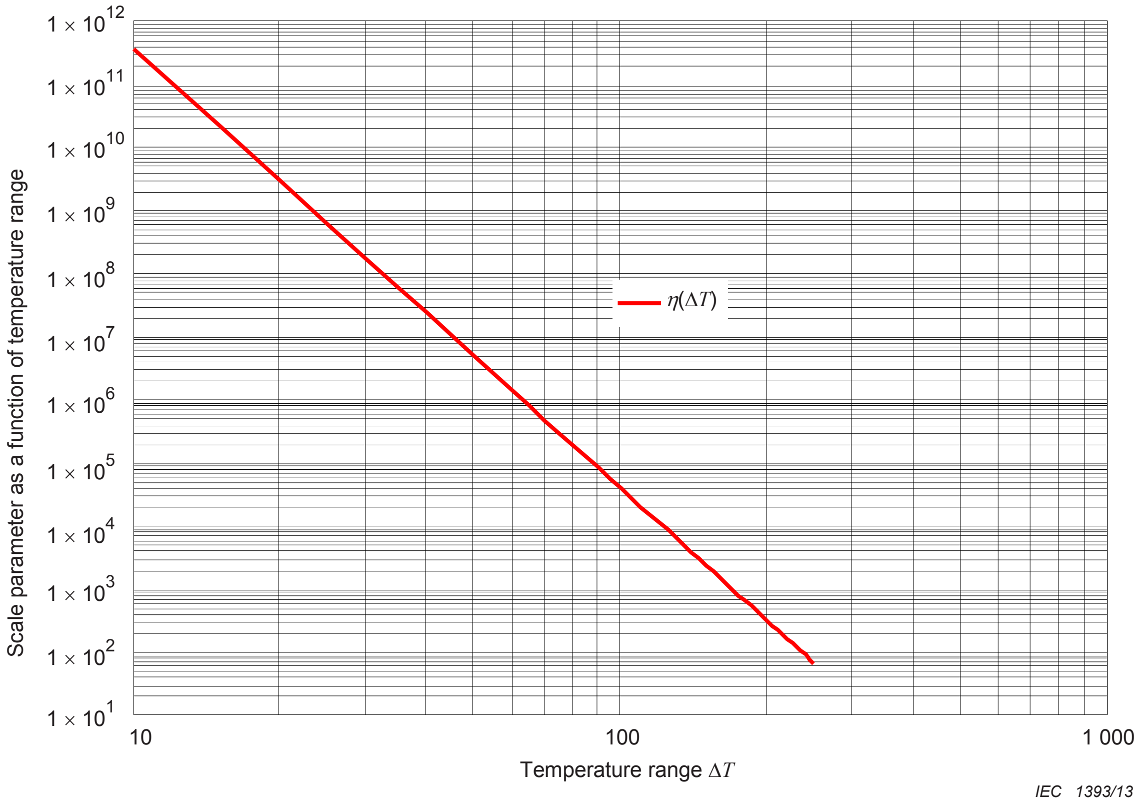


Figure F.2 – Scale parameter as a function of the temperature range

To calculate the scale parameter corresponding to the thermal cycling in use of ΔT = 50 °C:

$$\eta(50) = 446 \times \left(\frac{190}{50}\right)^{6,96} = 4,838 \times 10^6 \qquad (F.7)$$

For the temperature cycling range of 50 °C (in use) probability of failure as a function of the number of cycles is shown in Figure F.3.

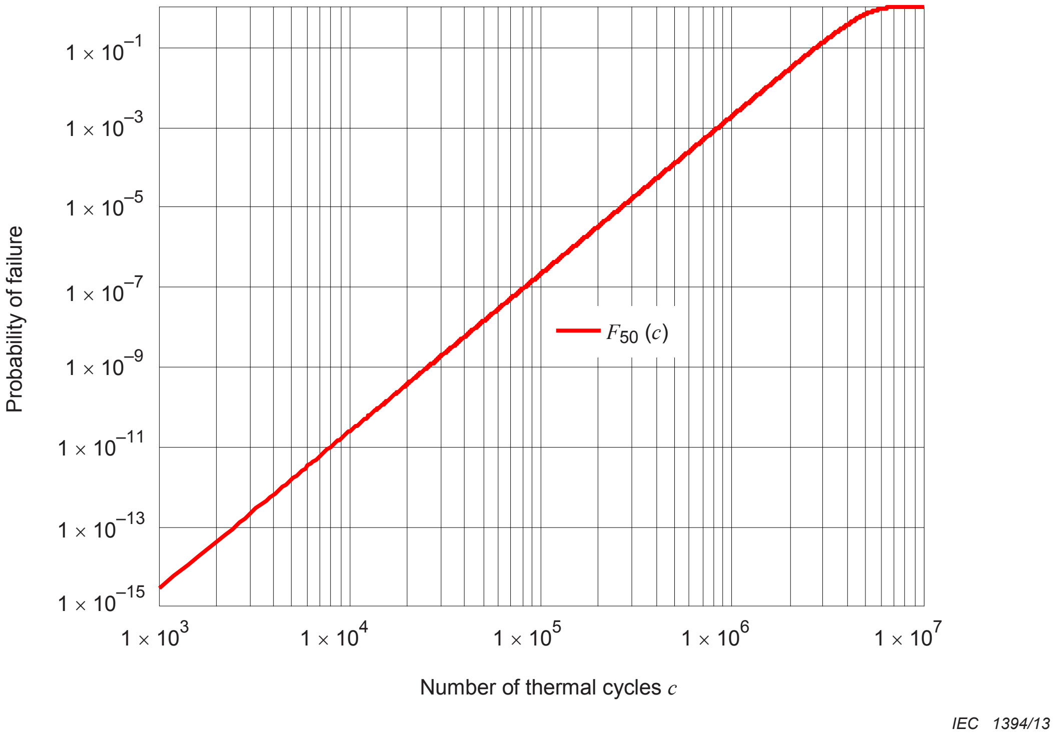


Figure F.3 – Probability of failure as a function of number of cycles ΔT = 50 °C

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.

Annex G
(informative)

Determination of acceleration factors by testing to failure

G.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 vs. the ratio of the stress levels determines the acceleration factor.

G.2 Determination of acceleration factor, example

A voltage acceleration factor was determined for a semiconductor (power transistor) by test at three voltages as shown in Table G.1.

Table G.1 – Voltage test failure data for Weibull distribution

Failure no.	Time to failure h	$F(t)$	ln(t)	ln(ln(1/(1-$F(t)$)))
1	100	0,07	4,61	-2,66
2	180	0,16	5,19	-1,72
3	240	0,26	5,48	-1,20
4	290	0,36	5,67	-0,82
5	335	0,45	5,81	-0,51
6	377	0,55	5,93	-0,23
7	420	0,64	6,04	0,03
8	450	0,74	6,11	0,30
9	470	0,84	6,15	0,59
10	485	0,93	6,18	0,99
1	600	0,07	6,40	-2,66
2	1 100	0,16	7,00	-1,72
3	1 580	0,26	7,37	-1,20
4	2 030	0,36	7,62	-0,82
5	2 430	0,45	7,80	-0,51
6	2 810	0,55	7,94	-0,23
7	3 160	0,64	8,06	0,03
8	3 460	0,74	8,15	0,30
9	3 710	0,84	8,22	0,59
10	3 910	0,93	8,27	0,99

Failure no.	Time to failure h	$F(t)$	ln(t)	ln(ln(1/(1-$F(t)$)))
1	1 800	0,07	7,50	-2,66
2	3 500	0,16	8,16	-1,72
3	5 000	0,26	8,52	-1,20
4	6300	0,36	8,75	-0,82
5	7 450	0,45	8,92	-0,51
6	8 450	0,55	9,04	-0,23
7	9 300	0,64	9,14	0,03
8	10 080	0,74	9,22	0,30
9	10 730	0,84	9,28	0,59
10	11 330	0,93	9,34	0,99

The data was plotted as Weibull distribution, shown in Figure G.1, and the trend lines were drawn. 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.

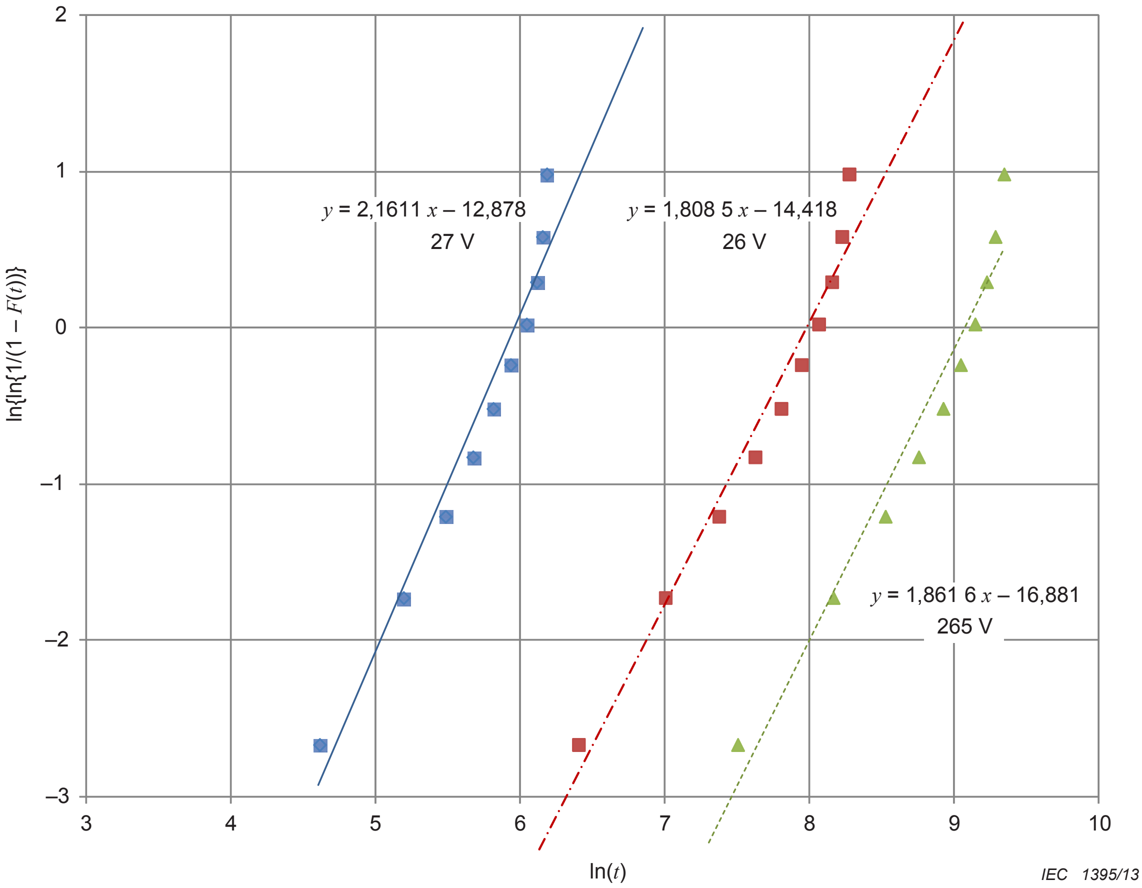
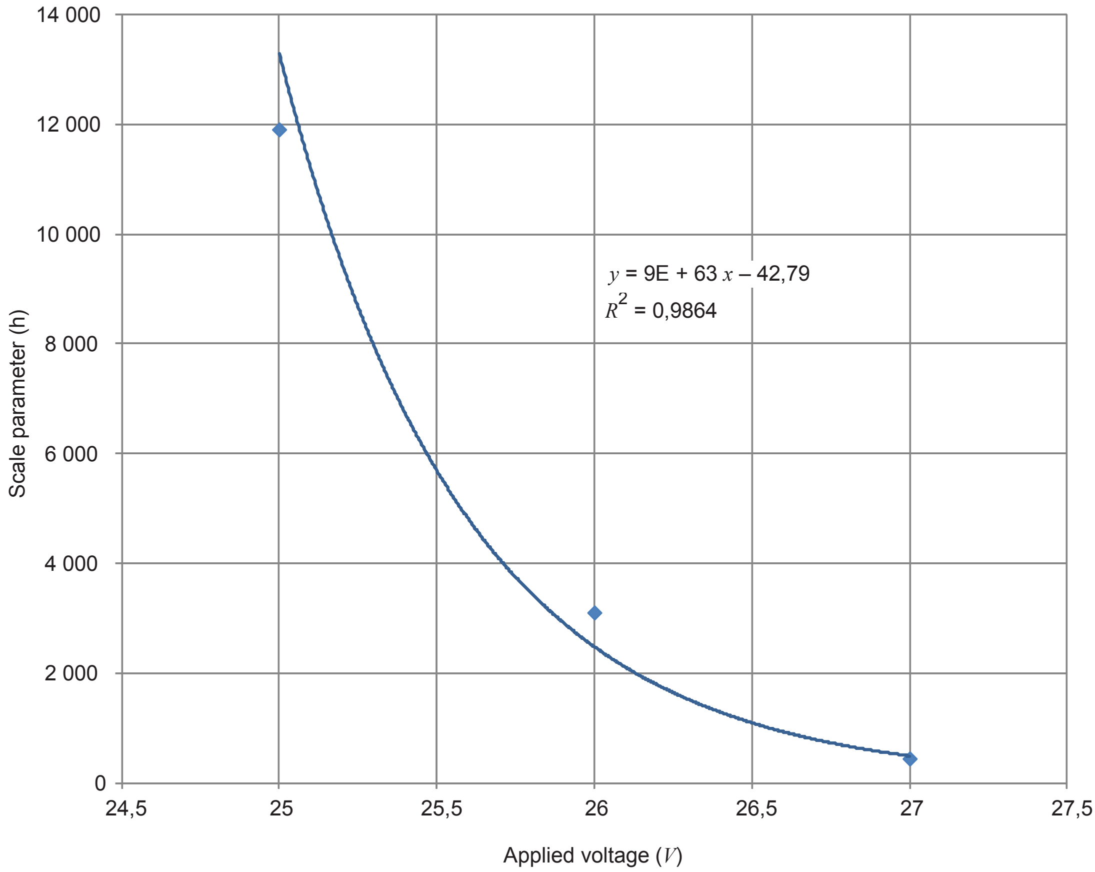


Figure G.1 – Weibull plot of the three data sets

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.



IEC 1396/13

Figure G.2 – Scale parameters' values fitted with a power line

The equation of the power line provides then values of the scale parameter as a function of voltage as:

$$\eta(V) = A \times 10^{\,B \times V^{-m}} \tag{G.1}$$

The acceleration factor here is:

$$A(V) = \frac{10^{B \times \ddot{V}_2^{\,-m}}}{10^{B \times \ddot{V}_1^{\,-m}}} \tag{G.2}$$

Bibliography

[1] IEC 60050-191:—*International Electrotechnical Vocabulary – Chapter 191: Dependability and quality of service*[3]

[2] IEC 60812, *Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA)*

[3] HU, J.M., BARKER, D., DASGUPTA, A., ARORA, A., *The Role of Failure Mechanism Identification in Accelerated Testing, Journal of the Institute of Environmental Science,* pp.39-45, July 1993

[4] NELSON*, Wayne, Accelerated Testing: Statistical Methods for Reliability Data,* John Wiley and Sons, Inc. New York, 1990, 2004

[5] GHOSH, B.K. and SEN, P.K., *Handbook of Sequential Analysis*, Marcel Dekker, Inc., New York.

[6] *Accelerated Life Testing Analysis, ALTA,* Reference, ReliaSoft Publishing, Tucson, Arizona, 2007

[7] PUNCH, J. and LOLL, V. *Graphical Analysis and Guidelines for Step-Stress Testing,* RAMS 2003.

[8] KRASICH, M. *Accelerated Testing for Demonstration of Product Lifetime Reliability,* Reliability and Maintainability Symposium 2002

[9] KRASICH, M., *Accelerated Reliability Growth Testing and Data Analysis*, Reliability and Maintainability Symposium 2008, Las Vegas, Nevada

[10] KRASICH, M., *How to design Reliability Demonstration and Assurance Tests and Analyze Test Data Using Physics of Failure Principles*, Reliability and Maintainability Symposium 2010

[11] IEC 60605-7:1978, *Equipment reliability testing – Part 7: Compliance test plans for failure rate and mean time between failures assuming constant failure rate* (withdrawn 1999)[4]

[12] KRASICH, M. 2009, *Realistic Reliability Requirements for Stresses in Use*, Journal of the IEST, 52 (2): 00-00

[13] KRASICH, M. 2007, *Accelerated Reliability Growth Testing and Data*, Journal of the IEST, 50 (2): 98-117

[14] SALMELA, Olli; ANDERSSON, Klas; PERTTULA, Altti; SÄRKKÄ, Jussi, and TAMMENMAA, Markku, *Re-calibration of Engelmaiers Model for leadless, Leadfree Solder Attachments*, QRE 2007 Vol. 23:415-429

[15] OTTO, Susanne: *HALT & HASS –when and how is it relevant?,* – SPM-169 – June 2004 www.delta.dk/spm

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3 The second edition of IEC 60050-191 is due to be published shortly.

4 Replaced by IEC 61124.

[16] GMW8758, *Calibrated Accelerated Life testing (CALT)* – General Motors Corporation October 2004

[17] CARUSO, H. and DASGUPTA, A., *A Fundamental Overview of Accelerated Testing Analytic Models,* RAMS 1998

[18] KRASICH, M. 2004, *Accelerated Testing for Demonstration of Product Lifetime Reliability*, Journal of the IEST, 47 (2): 48-58

[19] SILVERMAN, M, 2010, *How Reliable is Your Product? 50 Ways to Improve your Product Reliability*. Superstar Press, 2010.

[20] MIL-HDBK-189, *Reliability growth testing*

[21] MIL-HDBK-78, *Reliability test methods*

[22] IEC 61125:1992, *Unused hydrocarbon-based insulating liquids – Test methods for evaluating the oxidation stability*

[23] JESD22-A110, *Highly Accelerated Temperature and Humidity Stress Test (HAST*)

[24] JEDEC JESD-A113, *Preconditioning of Nonhermetic Surface Mount Devices Prior to Reliability Testing*

[25] JESD47B, *Stress-Test-Driven Qualification of Integrated Circuits*

[26] JESD74, *Early Life Failure Rate Calculation Procedure for Electronic Components*

[27] JESD85, *Methods for Calculating Failure Rates in Units of FITs*

[28] JEDEC JESD A104-B, *Temperature cycling*

Additional non-cited references

IEC 61703:2001, *Mathematical expressions for reliability, availability, maintainability and maintenance support terms*

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