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Standard

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Space systems — Methods to decide thermal vacuum test cycles of recurring production according to precipitation efficiency and reliability

Systèmes spatiaux — Méthodes pour déterminer les cycles d'essais sous vide thermique de la production récurrente en fonction de l'efficacité et de la fiabilité des précipitations

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Foreword

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Introduction

The thermal vacuum test is one of the most important and expensive environment tests of space systems. The thermal vacuum test is required in general to demonstrate the ability of the test item to meet the design, function and performance requirements under the combination of vacuum conditions and temperature extremes experienced during spaceflight, and to screen out initial failure, known as infant mortality, such as workmanship error, integration error and latent material defect (ISO 15864). The number of thermal cycles, to be referred hence forth as simply cycles, is one of the test conditions in thermal vacuum test, is an essential parameter used to determine the screening effectiveness of initial failure. The number of cycles should be determined, generally based on technical aspects and with careful consideration of various factors such as test item complexity, heritage, and maturity of design and manufacturing, as well as reliability required of the test article. However as experienced in mass production industry, it is a natural expectation that as the design and manufacturing process of an item matures through continuous improvement of the manufacturing process, workmanship defects and initial failure will be reduced.

This document provides two technical methods specified to calculate the precipitation efficiency and reliability by the failure data to measure the quantity of screening effectiveness used to determine number of cycles of thermal vacuum test. These methods can be applied to reduce the number of cycles performed during a thermal vacuum test specified for recurring production of flight hardware, such as higher volume unit production runs and hardware produced for large constellation programs. This document supplements ISO 15864 used as either an option to reduce or a tailoring method to the baseline of thermal vacuum and thermal cycle acceptance tests specific for the recurring production hardware.

Space systems — Methods to decide thermal vacuum test cycles of recurring production according to precipitation efficiency and reliability

1 Scope

This document provides technical methods to calculate the precipitation efficiency and liability of a flight model by measuring the screening effectiveness of thermal cycles. This document is applicable to the recurring production unit and other hardware assembly levels, as either an option to reduce or a method to tailor the baseline number of cycles for thermal vacuum and thermal cycle acceptance tests.

2 Normative references

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

ISO 15864, *Space systems — General test methods for spacecraft, subsystems and units*

3 Terms, definitions, and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 15864 and the following apply.

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

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1.1
failure
termination of the ability of an *item* (3.1.5) to perform a required function

[SOURCE: ISO 10795:2019, 3.98]

3.1.2
flight model
model dedicated to being launched and operated in orbit and subjected to acceptance testing

3.1.3
hardware
items (3.1.5) of identifiable equipment including piece parts, components, assemblies, subsystems and systems

[SOURCE: ISO 10795:2019, 3.119, modified — The abbreviated term "H/W" has been removed.]

3.1.4
initial failure
probability of *failure* (3.1.1) or defect under an environmental test

3.1.5
item

node of a product breakdown structure

Note 1 to entry: An item can be any functional unit, subsystem, or system in ISO 15864 that can be individually considered.

Note 2 to entry: An item can be considered either as a “product” or a “component” on a “product breakdown structure” of more than two levels of decomposition. Items are designated “products” when described as being decomposed and designated “components” when described as decompositions.

[SOURCE: ISO 10795:2019, 3.134, modified — The domain "<space system>" has been removed; in note 1 to entry, a reference has been made to ISO 15864.]

3.1.6
latent defect

defect caused by workmanship error, integration error or latent material, which is not detectable in a stress-free environment, but is either screened under environmental test conditions or flight environment

3.1.7
precipitation efficiency

PE

probability of screening out *latent defects* (3.1.6) in a specific environmental test

3.1.8
reliability

ability of an *item* (3.1.5) to perform as required under given conditions for a given time interval

Note 1 to entry: In this document, reliability is equivalent to the probability that the *hardware* (3.1.3) is failure-free.

[SOURCE: ISO 10795:2019, 3.198, modified — "a required function" has been replaced by "as required"; the original two notes to entry have been replaced by a new one.]

3.1.9
tailoring

process by which individual requirements of specifications, standards, and related documents are evaluated and made applicable to a specific project by selection and, in some exceptional cases, modification of existing or addition of new requirements

[SOURCE: ISO 10795:2019, 3.237]

3.1.10
test temperature range

difference between the maximum and minimum temperatures in a thermal vacuum test

Note 1 to entry: The thermal vacuum test is specified in ISO 15864:2021, 7.18.

3.2 Abbreviated terms

AT	acceptance test
MPE	maximum predicted environment
PE	precipitation efficiency
TCT	thermal cycle test
TESS	thermal environmental stress screening
TTC	telemetry, tracking and command
TVT	thermal vacuum test

4 Methods of TVT cycles determination

4.1 General

Thermal cycle and thermal vacuum tests (TVT) are required for system and certain types of subsystem/unit acceptance test (AT), as specified in ISO 15864:2021, Table 1 and Table 3. The number of cycles is determined in general by consideration of the overall development and test history of the hardware under test, for example, the complexity and heritage of design and tests of lower-level assemblies before integrated assemblies, TVT conditions such as temperature range and duration. Initial screening for latent defects of flight hardware, also called infant mortality, which is caused by manufacturing, material and workmanship defects, shall be demonstrated by the acceptance test. The determination of TVT cycles depends on the essential parameter used to measure the screening effectiveness for initial latent defects by the precipitation efficiency and reliability of the test. Although in ISO 15864 there is no statement for the value of number of cycles, the expected number of cycles for thermal environmental stress screening (TESS) is determined by the required precipitation efficiency (PE) and temperature range in TVT[1],[2].

The number of TVT cycles for the relevant kinds of hardware (system, subsystem and unit) of recurring production can be tailored to reduce the number of cycles specified in baseline requirement by prior experience and studies of the failure database. This document provides the technical methods to support tailoring thermal vacuum test cycles of the relevant hardware. Methods used to calculate the precipitation efficiency and reliability are used to measure the quantity of the TESS effectiveness, by the priorly revealed failure database collected from the objective hardware. The failure database used in these methods shall support the justification of number of cycles determination.

The term of recurring production stated herein shall be replaced by spacecraft, subsystem or unit defined in ISO 15864 in case of tailoring the baseline of thermal vacuum and thermal cycle acceptance tests. Recurring production can be hardware used for constellation programs, or more generally, the hardware made with a constant block of design and manufacture, such as mass production hardware, replicating manufactured hardware.

The failure database may be extended to the hardware that has similarity in design, manufacture and part grade integrated in the production, but the technical rationale of supporting the similarity claim shall be justified. An example to support similarity can be when the hardware is designed and manufactured by relative standards, reliability and quality control by same management standards, high class parts (e.g. class I) are used in the hardware[3].

4.2 Failure data collection and analysis

The failure distribution function is used for estimating TESS effectiveness by the fatigue induced stress. Failure data collected shall be revealed that failures are relevant to initial defects due to foreign substance contamination in manufacturing and workmanship of the relevant hardware. Failure data collection at acceptance TVT shall provide the following basic information.

a) The cycle numbers and test parameters, including minimum and maximum temperatures, in the TVT when the failure occurred. The minimum temperature of failure data collected should be 55 °C.

b) The results from function tests performed. A function test shall be performed during and after exposure to the TVT environment to ensure the perceptiveness of potential failures. In cases that failures are discovered after exposing to TVT environment and the cycles when the failure occurred are difficult to be identified, an increased number of cycles should be assigned. This assignment of increased cycles is to obtain a conservative estimation.

c) Failure data from previous and/or follow-on environmental tests. If the hardware is exposed to a number of environments sequential, for example, a vibration environment could be exposed on the hardware before or after TVT, the failure data collected shall be carefully analysed. Failures escaping from a previous exposure environment or into a follow-on exposed environment shall be carefully analysed to confirm if there are TVT environment related failures. If the failure related environment is indistinct, this kind of failure data shall not be included.

d) Failure data from different lot tests. If the failure data are collected from different lots or replicating manufactured hardware, the failure data should be carefully analysed to determine if there are different number of failure cycles between lots or replicating hardware. Test parameters to influence the TESS, such as temperature range, temperature transition rate, hardware operation, failure modes, should be carefully examined.

e) Failure data from thermal cycle tests (TCT). Thermo-mechanical fatigue failures in TCT may be included in the failure database.

Typical failure data and initial defects of electronic units are shown in Table B.1.

The collected failure data shall be sorted in ascending order by the cycle number x when the failure is discovered and their corresponding test temperature range ΔT. If there are k failures, the failure data shall be sorted to,

$$x = (x_1, x_2, \cdots, x_k) \tag{1}$$

$$\Delta T = (\Delta T_1, \Delta T_2, \cdots, \Delta T_k) \tag{2}$$

where

x_i is the cycle number when the failure is discovered; i is the index of i^{th} failure;

ΔT_i is the TVT temperature range corresponding to the i^{th} failure.

If there are different TVT temperature ranges, temperature effect shall be considered by normalizing equivalent fatigue with the low-cycle fatigue equivalence.[4] The equivalent temperature normalized cycle number x' shall be decided by Formula (3).

$$x' = (x'_1, x'_2, \cdots, x'_k) = \left(x_1 (\Delta T_1 / \Delta T')^b, x_2 (\Delta T_2 / \Delta T')^b, \cdots, x_k (\Delta T_k / \Delta T')^b\right) \tag{3}$$

where

b is the low-cycle fatigue equivalent exponent value;

$\Delta T'$ is the reference test temperature range in the TVT for equivalent temperature normalization; the minimum reference temperature for normalization shall be 55 °C.

Fatigue equivalent exponent b shall be determined by the material and failure mode of the test hardware. $b = 2$ is recommended for solder joint, which is widely used for electric unit.[5] Empirically equivalent value comprising multiple failure modes, and materials should be calculated following the method in 4.4.

NOTE Examples of electric unit failure data related to manufacturing, material and workmanship defects, and cycle number that the failure occurred, normalized cycles number at reference temperature 85 °C using $b = 2$, are shown in Table B.2.

4.3 Method 1 – Precipitation efficiency method

4.3.1 General

The PE method is used to calculate probability of screening latent defects versus the number of cycles with the collected TVT failure database specified in 4.2. PE value calculated by this method shall be used to demonstrate the compliance with the relevant precipitation requirement designated by the customer and support the justification for execution of the option to reduce or a tailoring method to the baseline of thermal vacuum. PE value should be set to 0,95 for the acceptance thermal test[6].

4.3.2 Precipitation efficiency estimation

PE is calculated by Weibull distribution.[7] Weibull parameter shall be estimated by the failure data in 4.2. PE is calculated by the Formula (4).

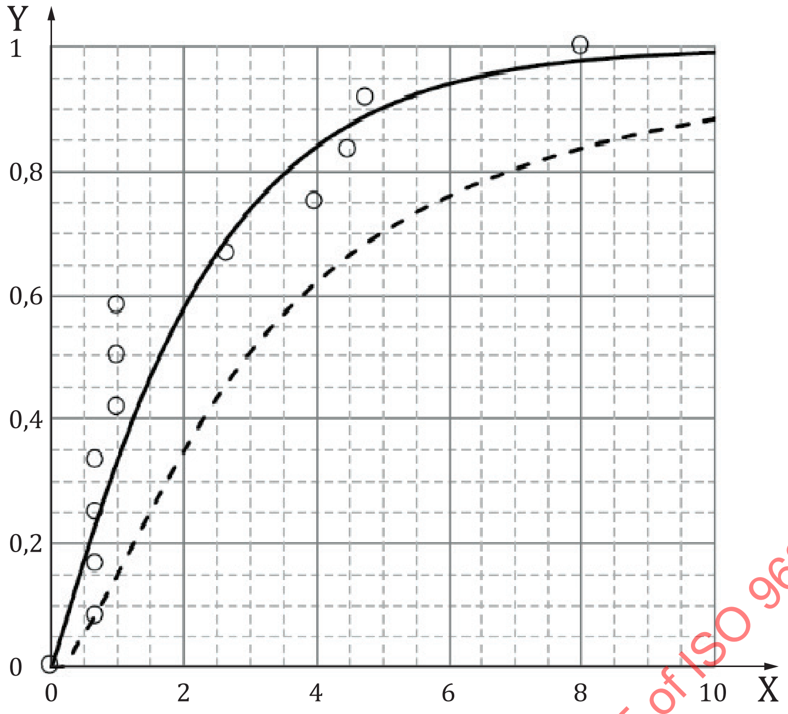
$$\varepsilon_{\mathrm{PE}}(x') = F(x'|\theta) = 1 - \exp\left\{-\left(\frac{x'}{\eta}\right)^{m}\right\} \tag{4}$$

Where

$\varepsilon_{\mathrm{PE}}$	is the precipitation efficiency (PE);
$\hat{\theta}(\hat{m},\hat{\eta})$	is the estimation of Weibull parameter (m,η) by the failure data stated in 4.2;
m	is the shape parameter;
η	is the scale parameter of Weibull distribution.

Statistical confidence interval of estimated Weibull parameter with a smaller number of failure data k shall be considered. Statistical confidence P95/50, that is a value of 95 % probability limit band with 50 % confidence,[8] is recommended for acceptance test level in most test standards, named MPE (maximum predicted environment). Other "normal tolerance factor" larger than P95/50 may be applied if there is reason for more conservative purpose. Typical normal tolerance factor is calculated in Annex A.

NOTE The detailed process to decide the cycle number by using the method 1 (the PE method) by the failure data is demonstrated in Annex B. An example of precipitation efficiency versus normalized cycle number calculated by failure data in B.1 is shown in Figure 1.[9] If the required value of PE is 0,80, the cycle number is determined as 4 (using mean value) or 7 (using P95/90 lower limit).



Key

X	normalized cycle number
Y	precipitation efficiency
○	sample data
———	mean
– – –	P95/90 lower limit

Figure 1 — Example of precipitation efficiency and normalized cycle number calculated by example of failure data in Table B.1

4.4 Method 2 – Reliability method

4.4.1 General

The Reliability method is used to calculate reliability value versus the number of cycles. Reliability value calculated by this method shall be used to demonstrate the compliance to the relevant reliability requirement designated by the customer and support the justification for implementing the option to reduce or tailoring method to the baseline number of TVT cycles. The reliability requirement of electronic equipment may be selected according to MIL-HDBK-217, 1991[10].

4.4.2 Reliability method

Reliability $R(x')$, a function of cycles x' is the probability that the hardware is failure-free from TVT. Reliability method is the method to calculate reliability of the hardware by PE that is calculated by the collected failure data stated in 4.2.

$$R(x')=1-p_0\{1-\varepsilon_{\mathrm{PE}}(x')\} \tag{5}$$

Where, p_0 is the initial value of failure rate of the objective hardware which can be estimated by the percentage of hardware with failure detected (k) among total number of TVT tested hardware N, $p_0=k/N$.

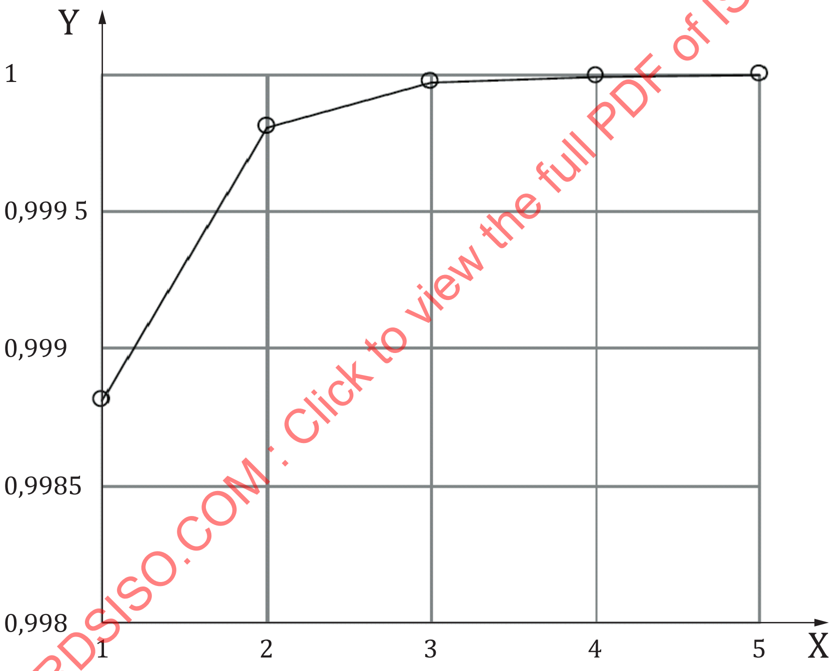
Reliability for the recurring hardware can be updated while subsequential hardware has successfully passed failure-free at baseline required number of TVT cycles. The updated reliability value of subsequential n^{th} hardware R_n, can be calculated by the previous reliability value of $(n–1)^{\mathrm{th}}$ hardware R_{n-1} and $\varepsilon_{\mathrm{PE}n}$.

$$R_n = 1 - \frac{(1-\varepsilon_{\mathrm{PE}n})(1-R_{n-1})}{1-\varepsilon_{\mathrm{PE}n}(1-R_{n-1})} \qquad (6)$$

In case of constant precipitation efficiency, that is $\varepsilon_{\mathrm{PE1}} = \varepsilon_{\mathrm{PE2}} = \cdots = \varepsilon_{\mathrm{PE}n} = \varepsilon_{\mathrm{PE}}$, the updated reliability value of nth hardware is simplified by:

$$R_n = 1 - \frac{(1-\varepsilon_{\mathrm{PE}})^n p_0}{1-p_0+(1-\varepsilon_{\mathrm{PE}})^n p_0} \qquad (7)$$

NOTE An example of collected failure data, calculation process of reliability by the failure data, and determination of number of cycles by method 2 (the reliability method) is described in Clauses B.2 and B.3. Figure 2 is an example of updating reliability versus sequential items (from 1 to 5) passing failure-free for a TVT with a baseline requirement of eight (8) cycles.[11] This example shows that the reliability increases most greatly from the first to third sequential failure-free tests than any subsequential test thereafter. Therefore by example, if 99,95 % is a required reliability, the number of 4 cycles can be determined appropriate after 2 sequential failure-free tested items, a 50 % reduction from baseline required 8 cycles; and henceforth, a 4 cycle TVT can be applied to the third item as a tailored baseline.



Key

X number of subsequential item passed failure-free TVT

Y reliability

Figure 2 — Example of reliability versus number of subsequential item passed failure-free at baseline 8 TVT cycles

4.5 Empirical equivalent fatigue exponent by failure data

Fatigue induced failure may be a combination of failure modes and is dependent on variable material that contributes the fatigue modes; an equivalent fatigue acceleration exponent $\bar{b}$ which comprises material that contributes the fatigue types should be applied to collected failure data normalization to determine the empirically by a weighted summation failure type m numbers of material n collected from history of TVT data as follows [12],[13].

$$\bar{b} = \sum_{i=1}^{m} a_i \sum_{j=1}^{n_i} q_{ij} b_{ji} \tag{10}$$

Where, q_{ij} is the contribution coefficient and b_{ji} is the acceleration exponent for the j^{th} materials that contributes the i^{th} thermal fatigue failure type.

NOTE The empirical estimation of equivalent acceleration exponent is expected to be a more specialized and effective approach for thermal test requirement analysis especially when a complex testing object is employed or where the failure characteristics and fatigue mechanisms of the tested object are needed to be customized more reasonably to the concurring production if it has this kind of information. The integrated fatigue acceleration exponent $\bar{b}$ can be selected from 1,4 to 2,6 according to experience for the conventional spacecraft with high technology maturity. An example of the method to estimate fatigue exponent b for solder fatigue failure is described in Clause B.4.

Annex A
(informative)

Theory of estimating PE and its lower band limit

Maximum likelihood estimation of Weibull parameter $\theta=(m,\eta)$ is a maximum solution of Logarithm expression likelihood function (A.1) by $\frac{\partial}{\partial\theta}\ln L(\theta|x')=0$. k is the number of failure data and x' is the corresponding cycles of failure.

$$\ln L(\theta|x')=\sum_{i=1}^{k}\ln f(x_i'|\theta) \tag{A.1}$$

The lower confidence limit of precipitation efficiency ε_{PE} is calculated by assuming that the deviation of $g(\theta)$, which is transformed from $F(\theta)$ by Formula (A.2), follows normal distribution statistically.

$$g(\theta)=\ln\left\{\ln\frac{1}{1-F(\theta)}\right\}=m(\ln x-\ln\eta) \tag{A.2}$$

The variance of $g(\theta)$ is obtained by using the variance and covariance of Weibull parameter [7].

$$\mathrm{Var}\{g(\theta)\}=\left\{\frac{\partial g(\theta)}{\partial\eta}\right\}^2\mathrm{Var}(\eta)+\left\{\frac{\partial g(\theta)}{\partial m}\right\}^2\mathrm{Var}(m)+\frac{\partial g(\theta)}{\partial\eta}\frac{\partial g(\theta)}{\partial m}\mathrm{Cov}(\eta,m) \tag{A.3}$$

where,

$\mathrm{Var}(\eta)$	is variance of η;
$\mathrm{Var}(m)$	is variance of m;
$\mathrm{Cov}(\eta,m)$	is covariance of η and m;

The variance and covariance of each parameter in Formula (A.3) is obtained as the elements in the inverse of Fisher information matrix [8].

$$\begin{aligned}\Sigma_{\hat\theta}&=\begin{bmatrix}\mathrm{Var}(\eta) & \mathrm{Cov}(\eta,m)\\ \mathrm{Cov}(\eta,m) & \mathrm{Var}(m)\end{bmatrix}\\ &=I_\theta^{-1}\\ &=\begin{bmatrix}-\frac{\partial^2}{\partial\eta^2}\ln L(\theta|x) & -\frac{\partial^2}{\partial\eta\partial m}\ln L(\theta|x)\\ -\frac{\partial^2}{\partial\eta\partial m}\ln L(\theta|x) & -\frac{\partial^2}{\partial m^2}\ln L(\theta|x)\end{bmatrix}^{-1}\end{aligned} \tag{A.4}$$

$$=\begin{bmatrix} \frac{k}{m^2}+\sum_{i=1}^{k}\left(\frac{x_i}{\eta}\right)^m \left\{\ln\left(\frac{x_i}{\eta}\right)\right\}^2 & \frac{k}{\eta}-\frac{1}{\eta}\sum_{i=1}^{k}\left(\frac{x_i}{\eta}\right)^m-\frac{m}{\eta}\sum_{i=1}^{k}\left(\frac{x_i}{\eta}\right)^m \ln\left(\frac{x_i}{\eta}\right) \\ \frac{k}{\eta}-\frac{1}{\eta}\sum_{i=1}^{k}\left(\frac{x_i}{\eta}\right)^m-\frac{m}{\eta}\sum_{i=1}^{k}\left(\frac{x_i}{\eta}\right)^m \ln\left(\frac{x_i}{\eta}\right) & -\frac{km}{\eta^2}+\frac{m}{\eta^2}(1+m)\sum_{i=1}^{k}\left(\frac{x_i}{\eta}\right)^m \end{bmatrix}^{-1}$$

If $P_{k\beta\gamma}$ is the percentile level that encompasses β percent of the data estimated with γ confidence, by number of samples k, the lower confidence limit $g(\theta)$ is calculated by:

$$g_{k\beta\gamma}(\theta)=g(\theta)-C_{k\beta\gamma}\sqrt{\mathrm{Var}\{g(\theta)\}} \tag{A.5}$$

where, $C_{k\beta\gamma}$ is the “normal tolerance factor” for a selected probability C %, and is a constant depending on β, γ and number of samples k can be obtained from statistics upper limit[14]; some of the calculated results are shown in Table A.1;

Returning $g_{k\beta\gamma}(\theta)$ to the original scale by Formula (A.2), the lower confidence limit of precipitation efficiency $\varepsilon_{\mathrm{PE}}$ is calculated by Formula (A.6).

$$\varepsilon_{\mathrm{PE}_{k\beta\gamma}}(\theta)=1-\exp\left[-\exp\left\{g_{k\beta\gamma}(\theta)\right\}\right] \tag{A.6}$$

P95/50 is recommended for acceptance test level mostly in space standards defined as the maximum predicted environment level.[15],[16] Other “normal tolerance factor” larger than P95/50 may be applied if there is reason for more conservative purpose.

Table A.1 — Normal tolerance factors $C_{k\beta\gamma}$

k	$\gamma=0{,}50$			$\gamma=0{,}90$		
	$\beta=0{,}50$	$\beta=0{,}95$	$\beta=0{,}99$	$\beta=0{,}50$	$\beta=0{,}95$	$\beta=0{,}99$
3	1,50	1,94	2,76	4,26	5,31	7,34
4	1,42	1,83	2,60	3,19	3,96	5,44
5	1,38	1,78	2,53	2,74	3,40	4,67
6	1,36	1,75	2,48	2,49	3,09	4,24
7	1,35	1,73	2,46	2,33	2,89	3,97
8	1,34	1,72	2,44	2,22	2,76	3,78
9	1,33	1,71	2,42	2,13	2,65	3,64
10	1,32	1,70	2,41	2,06	2,57	3,53
12	1,32	1,69	2,40	1,97	2,45	3,37
14	1,31	1,68	2,39	1,90	2,36	3,26
16	1,31	1,68	2,38	1,84	2,30	3,17
18	1,30	1,67	2,37	1,80	2,25	3,11
20	1,30	1,67	2,37	1,76	2,21	3,05
25	1,30	1,67	2,36	1,70	2,13	2,95
30	1,29	1,66	2,35	1,66	2,08	2,88
35	1,29	1,66	2,35	1,62	2,04	2,83
40	1,29	1,66	2,35	1,60	2,01	2,79
50	1,29	1,65	2,34	1,56	1,96	2,74
∞	1,28	1,64	2,33	1,28	1,64	2,33

Annex B
(informative)

Worked example

B.1 Applied example of precipitation efficiency-based method (method 1)

A calculation example of the method to decide number of cycles based on PE is shown. Table B.1 is the collected failure data that are carefully analysed under 4.2 to reveal as workmanship errors, material defect and TVT related, from more than 700 flight units.[9] These 12 modes of collected failure data have different test temperature ranges (ΔT) that vary from 60 °C to 85 °C, and cycles (x) which vary from 1 to 9. The normalized number of cycles (x') is calculated by equivalent fatigue of low-cycle fatigue law in Formula (3), where $b=2{,}0$ and $\Delta T=85$ °C.

Table B.1 — Example of collected failure data and their normalized cycles

No. of samples(*i*)	Failure mode	Cause of failure	Type of unit	Cycle No. that the failure occurred	Test temperature range °C	Normalized cycles number
1	Contact resistance fluctuation	Improper coating	EPS	1	70	0,68
2	Conduction failure in connector	Assembly error	INT	1	70	0,68
3	SRAM failure	Parts error	DM	1	70	0,68
4	Short in IC lead	Contamination	TT&C	1	70	0,68
5	FPGA lead fracture	Improper bonding	DM	1	85	1
6	MPU failure	ESD	AOCS	1	85	1
7	Short in diode	Contamination	AOCS	1	85	1
8	Short in FET lead	Improper etching	AOCS	3	80	2,66
9	HIC anomalous oscillation	Parts error	AOCS	8	60	3,99
10	PROM failure	Parts error	TT&C	9	60	4,49
11	MIC output power fluctuation	Assembly error	TT&C	7	70	4,75
12	Warpage of PCB	Assembly error	TT&C	8	85	8

NOTE The reason of 9 cycles in sample no. 10 which exceeds baseline (8 cycles) is that this hardware underwent additional re-testing.

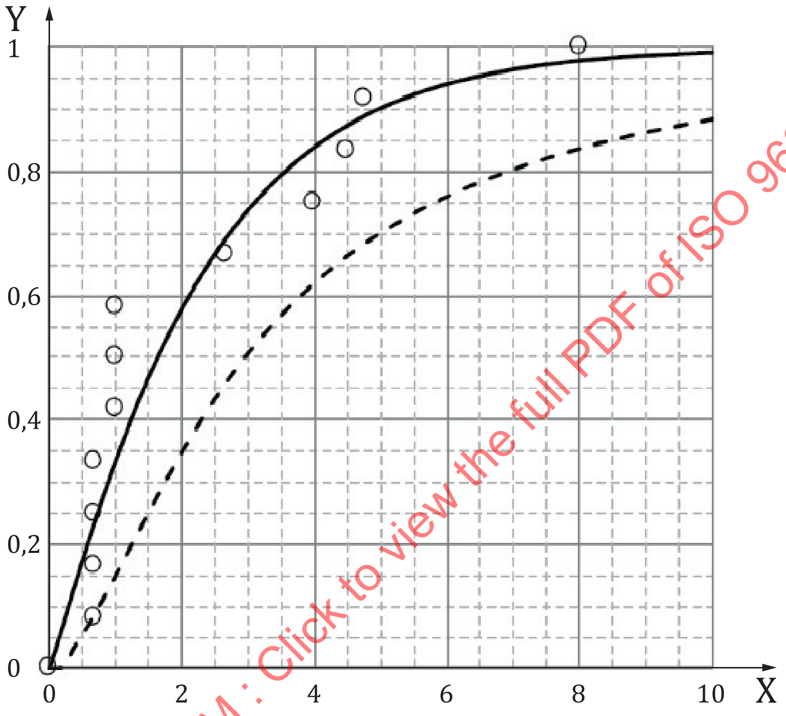
Maximum likelihood estimated value of Weibull parameter $\hat{\theta} = \left(1{,}08,\ 2{,}28\right)$ can be calculated by solving maximum likelihood solution of Formula (A.1).

The variance and covariance of Weibull parameters of the example can be calculated by the Formula (A.4).

$$\begin{bmatrix} \mathrm{Var}(\eta) & \mathrm{Cov}(\eta,m) \\ \mathrm{Cov}(\eta,m) & \mathrm{Var}(m) \end{bmatrix} = \begin{bmatrix} 0{,}36 & 0{,}044 \\ 0{,}044 & 0{,}047 \end{bmatrix} \tag{B.1}$$

P95/90 ($\beta = 0{,}95$, $\gamma = 0{,}90$) lower limit of $g(\theta)$ can be calculated by Formula (A.3). In this case that number of samples is 14, $C_{k\beta\gamma} = 2{,}36$ can be obtained from the value in Table A.1. P95/90 lower limit of PE is calculated by substitution of lower limit value of $g_{k\beta\gamma}(\theta)$ into Formula (A.6).

Figure B.1 shows the relationship between calculated mean and low limit value of PE versus normalized cycle number. If the required value of PE is 0,80, the mean value is 4 and the conservative value of number of cycles is 7 cycles or more can be decided from the Figure B.1.



Key

X normalized cycle number

Y precipitation efficiency

○ sample data

——— mean

– – – P95/90 lower limit

Figure B.1 — Relationship between precipitation efficiency and normalized cycle number.

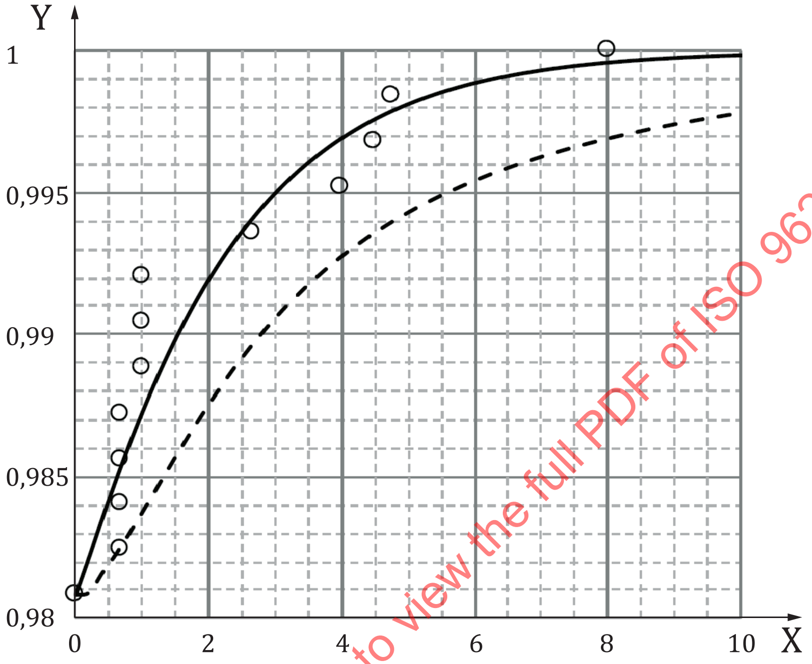
B.2 Applied example of reliability method (method 2)

This is the example by using the failure data in Table B.1 to calculate the reliability versus normalized cycles. If the initial reliability (without TVT cycle testing) p_0 is estimated from the database by the failure rate of number of test items with failure over the total number items conducted TVTs, includes those by similarity. The sample in the study is that there are 1 200 electric units conducted in TVTs, and 23 electric units had

TVT related failure that were revealed as workmanship errors and material defect, under 4.2.[9],[11] Therefore, the initial reliability may be calculated for the samples:

$$p_0 = \frac{23}{1\,200} = 1{,}71\,\% \tag{B.2}$$

Reliability corresponding to the number of cycles is calculated by Formula (7) with substituting calculated $\varepsilon_{\mathrm{PE}}\left(x'\right)$ in Clause B.1. Figure B.2 shows the calculation result of the example which shows the reliability versus normalized cycles. If the value of reliability requirement is 99,5 %, the conservative cycle number using P95/90 low limit value can be determined to be greater than 6 cycles.



Key

X	normalized cycle number
Y	reliability
○	sample data
———	mean
— — —	P95/90 lower limit

Figure B.2 — Relationship between reliability and normalized cycle number

B.3 Example of updating reliability

The example shows the updating reliability and how it works to reduce the cycles from 8 to 4. Let $\varepsilon_{\mathrm{PE}}(8)$ and $\varepsilon_{\mathrm{PE}}(4)$ represent the precipitation efficiency corresponding to 8 and 4 TVT cycles, respectively, that are calculated in Clause B.1. If there are n items that have already passed 8 TVT cycles, then the reliability of the nth item (R_n) can be calculated[9],[11].