

INTERNATIONAL STANDARD



Electric components – Reliability – Reference conditions for failure rates and stress models for conversion



THIS PUBLICATION IS COPYRIGHT PROTECTED

Copyright © 2017 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

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

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

IEC Catalogue - webstore.iec.ch/catalogue

The stand-alone application for consulting the entire bibliographical information on IEC International Standards, Technical Specifications, Technical Reports and other documents. Available for PC, Mac OS, Android Tablets and iPad.

IEC publications search - www.iec.ch/searchpub

The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee,...). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished

Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and also once a month by email.

Electropedia - www.electropedia.org

The world's leading online dictionary of electronic and electrical terms containing 20 000 terms and definitions in English and French, with equivalent terms in 16 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

IEC Glossary - std.iec.ch/glossary

65 000 electrotechnical terminology entries in English and French extracted from the Terms and Definitions clause of IEC publications issued since 2002. Some entries have been collected from earlier publications of IEC TC 37, 77, 86 and CISPR.

IEC Customer Service Centre - webstore.iec.ch/csc

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: csc@iec.ch.



IEC 61709

Edition 3.0 2017-02
REDLINE VERSION

INTERNATIONAL STANDARD



Electric components – Reliability – Reference conditions for failure rates and stress models for conversion

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 31.020

ISBN 978-2-8322-3989-6

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

FOREWORD.....	9
INTRODUCTION.....	11
1 Scope.....	12
2 Normative references	12
3 Terms, definitions and symbols	13
3.1 Terms and definitions.....	13
3.2 Symbols.....	16
4 Context and conditions	18
4.1 Failure modes and mechanisms.....	18
4.2 Thermal modelling	19
4.3 ~~Operating~~ Mission profile considerations.....	19
4.3.1 General	19
4.3.2 Operating and non-operating conditions	19
4.3.3 Dormancy.....	20
4.3.4 Storage ~~conditions~~	20
4.4 Environmental conditions	20
4.5 Components choice	22
4.6 Reliability growth during the deployment phase of new equipment	23
4.7 How to use this document.....	24
5 Generic reference conditions and stress models.....	25
5.1 Recommended generic reference conditions.....	25
5.2 Generic stress models	26
5.2.1 General	26
5.2.2 Stress factor for voltage dependence, π_U	27
5.2.3 Stress factor for current dependence, π_I	27
5.2.4 Stress factor for temperature dependence, π_T	27
5.2.5 Environmental application factor, π_E	29
5.2.6 Dependence on switching rate, π_S	30
5.2.7 Dependence on electrical stress, π_{ES}	30
5.2.8 Other factors of influence	30
6 Integrated semiconductor circuits	30
6.1 Specific reference conditions	30
6.2 ~~Specific stress factors~~ models.....	33
6.2.1 ~~Models~~ General	33
6.2.2 Voltage dependence, factor π_U	33
6.2.3 Temperature dependence, factor π_T	33
7 Discrete semiconductors	36
7.1 ~~Specific~~ reference conditions	36
7.2 ~~Specific stress factors~~ models.....	37
7.2.1 General	37
7.2.2 Voltage dependence for transistors, factor π_U	38
7.2.3 Temperature dependence, factor π_T	38
8 Optoelectronic components	40

8.1	Specific reference conditions	40
8.2	Specific stress ~~factors~~ models.....	42
8.2.1	General	42
8.2.2	Voltage dependence, factor π_U	42
8.2.3	Current dependence, factor π_I	42
8.2.4	Temperature dependence, factor π_T	43
9	Capacitors	45
9.1	Specific reference conditions	45
9.2	Specific stress ~~factors~~ models.....	45
9.2.1	~~Models~~ General	45
9.2.2	Voltage dependence, factor π_U	45
9.2.3	Temperature dependence, factor π_T	47
10	Resistors and resistor networks	48
10.1	Specific reference conditions	48
10.2	Specific stress ~~factors~~ models.....	49
10.2.1	~~Models~~ General	49
10.2.2	Temperature dependence, factor π_T	49
11	Inductors, transformers and coils	50
11.1	Reference conditions	50
11.2	Specific stress ~~factors~~ models.....	50
11.2.1	~~Models~~ General	50
11.2.2	Temperature dependence, factor π_T	50
12	Microwave devices	51
12.1	Specific reference conditions	51
12.2	Specific stress ~~factors~~ models.....	52
13	Other passive components	52
13.1	Specific reference conditions	52
13.2	Specific stress ~~factors~~ models.....	52
14	Electrical connections.....	52
14.1	Specific reference conditions	52
14.2	Specific stress ~~factors~~ models.....	53
15	Connectors and sockets	53
15.1	Reference conditions	53
15.2	Specific stress ~~factors~~ models.....	53
16	Relays	53
16.1	Reference conditions	53
16.2	Specific stress ~~factors~~ models.....	54
16.2.1	~~Models~~ General	54
16.2.2	Dependence on switching rate, factor π_S	54
16.2.3	Dependence on electrical stress, factor π_{ES}	55
16.2.4	Temperature dependence, factor π_T	56
17	Switches and push-buttons.....	56
17.1	Specific reference conditions	56
17.2	Specific stress ~~factors~~ models.....	57
17.2.1	~~Models~~ General	57

17.2.2	Dependence on electrical stress, factor π_{ES}	57
18	Signal and pilot lamps	58
18.1	Specific reference conditions	58
18.2	Specific stress ~~factors~~ models	58
18.2.1	~~Models~~ General	58
18.2.2	Voltage dependence, factor π_U	59
19	Printed circuit boards (PCB)	59
20	Hybrid circuits	59
Annex A (normative) Failure modes of components		60
Annex B (informative) Thermal model for semiconductors		63
B.1	Thermal model	63
B.2	Junction temperature calculation	64
B.3	Thermal resistance evaluation	65
B.4	Power dissipation of an integrated circuit P	66
Annex C (informative) Failure rate prediction		69
C.1	General	69
C.2	Failure rate prediction for assemblies	69
C.2.1	General	69
C.2.2	Assumptions and limitations	70
C.2.3	Process for failure rate prediction	70
C.2.4	Prediction models	71
~~C.2.5~~	~~Consideration of operating profiles~~	~~71~~
C.2.5	Other methods of reliability prediction	75
C.2.6	Validity considerations of reliability models and predictions	76
C.3	Component considerations	76
C.3.1	Component model	76
C.3.2	Components classification	76
C.4	General consideration about failure rate	77
C.4.1	General	77
C.4.2	General behaviour of the failure rate of components	77
C.4.3	Expected values of failure rate	78
C.4.4	Sources of variation in failure rates	79
Annex D (informative) Considerations on mission profile		80
D.1	General	80
D.2	Dormancy	80
D.3	Mission profile	81
D.4	Example of mission profile	82
Annex E (informative) Useful life models		83
E.1	General	83
E.2	Power transistors	83
E.3	Optocouplers	83
E.3.1	Useful life L	83
E.3.2	Factor L_0	84
E.3.3	Factor κ_0	84
E.3.4	Factor κ_1	85
E.3.5	Factor κ_2	85
E.3.6	Factor κ_3	85

E.4	LED and LED modules	86
E.4.1	Useful life L	86
E.4.2	Factor L_0	86
E.4.3	Factor κ_0	87
E.4.4	Factor κ_1	87
E.4.5	Factor κ_2	88
E.4.6	Factor κ_3	88
E.5	Aluminium, non-solid electrolyte capacitors	88
E.6	Relays	89
E.7	Switches and keyboards	89
E.8	Connectors	89
Annex F (informative)	Physics of failure	90
F.1	General	90
F.2	Failure mechanisms of integrated circuits	91
Annex G (informative)	Considerations for the design of a data base on failure rates	92
G.1	General	92
G.2	Data collection acquisition – collection process	92
G.3	Which data to collect and how to collect it	92
G.4	Calculation and decision making	93
G.5	Data descriptions	93
G.6	Identification of components	94
G.6.1	General	94
G.6.2	Component identification	94
G.6.3	Component technology	94
G.7	Specification of components	94
G.7.1	General	94
G.7.2	Electrical specification of components	94
G.7.3	Environmental specification of components	95
G.8	Field related issues data	95
G.8.1	General	95
G.8.2	Actual field conditions	95
G.8.3	Data on field failures	95
G.9	Test related issues data	96
G.9.1	General	96
G.9.2	Actual test conditions	96
G.9.3	Data on test failures	96
G.10	Failure rate database attributes	97
Annex H (informative)	Potential sources of failure rate data and methods of selection	99
H.1	General	99
H.2	Data source selection	99
H.3	User data	100
H.4	Manufacturer's data	100
H.5	Handbook reliability data	101
H.5.1	General	101
H.5.2	Using handbook data with this document	101
H.5.3	List of available handbooks	102
Annex I (informative)	Overview of component classification	105
I.1	General	105

I.2	The IEC 61360 system.....	105
I.3	Other systems.....	113
I.3.1	General	113
I.3.2	NATO stock numbers.....	113
I.3.3	UNSPSC codes	113
I.3.4	STEP/EXPRESS.....	113
I.3.5	IECQ	113
I.3.6	ECALS	114
I.3.7	ISO 13584	114
I.3.8	MIL specifications	114
	Annex J (informative) Presentation of component reliability data.....	115
J.1	General.....	115
J.2	Identification of components	115
J.2.1	General	115
J.2.2	Component identification	116
J.2.3	Component technology	116
J.3	Specification of components	116
J.3.1	General	116
J.3.2	Electrical specification of components	116
J.3.3	Environmental specification of components	116
J.4	Test related issues data.....	116
J.4.1	General	116
J.4.2	Actual test conditions	117
J.5	Data on test failures.....	117
	Annex K (informative) Examples	119
K.1	Integrated circuit.....	119
K.2	Transistor	119
K.3	Capacitor	119
K.4	Relay	120
	Bibliography.....	121
	Figure 1 – Comparison of the temperature dependence of π_T for CMOS IC.....	25
	Figure 2 – Selection of stress regions in accordance with current and voltage-operating conditions	55
	Figure 3 – Selection of stress regions in accordance with current and voltage-operating conditions	57
	~~Figure B.1 – Stress profile~~	~~64~~
	Figure B.1 – Temperatures inside equipment	64
	~~Figure B.2 – Averaging failure rates~~	~~65~~
	Figure B.2 – Thermal resistance model.....	65
	Figure D.1 – Mission profile	82
	Table 1 – Basic environments	21
	Table 2 – Values of environmental parameters for basic environments	22
	Table 3 – Recommended reference conditions for environmental and mechanical stresses	26
	Table 4 – Environmental application factor, π_E	29

Table 5 – Memory	31
Table 6 – Microprocessors and peripherals, microcontrollers and signal processors	31
Table 7 – Digital logic families and bus interfaces, bus driver and receiver circuits	31
Table 8 – Analog ICs	32
Table 9 – Application-specific ICs (ASICs)	32
Table 10 – Constants for voltage dependence	33
Table 11 – Factor π_U for digital CMOS-family ICs	33
Table 12 – Factor π_U for bipolar analog ICs	33
Table 13 – Constants for temperature dependence	33
Table 14 – Factor π_T for ICs (without EPROM; FLASH-EPROM; OTPROM; EEPROM; EARM)	35
Table 15 – Factor π_T for EPROM; FLASH-EPROM; OTPROM; EEPROM; EARM	35
Table 16 – Transistors common, low frequency	36
Table 17 – Transistors, microwave, (e.g. RF > 800 MHz)	36
Table 18 – Diodes	37
Table 19 – Power semiconductors	37
Table 20 – Constants for voltage dependence of transistors	38
Table 21 – Factor π_U for transistors	38
Table 22 – Constants for temperature dependence of discrete semiconductors	38
Table 23 – Factor π_T for transistors, reference and microwave diodes	39
Table 24 – Factor π_T for diodes (without reference and microwave diodes) and power semiconductors	39
Table 25 – Optoelectronic semiconductor signal receivers	40
Table 26 – LEDs, IREDs, laser diodes and transmitter components	40
Table 27 – Optocouplers and light barriers	41
Table 28 – Passive optical components	41
Table 29 – Transceiver, transponder and optical sub-equipment	41
Table 30 – Constants for voltage dependence of phototransistors	42
Table 31 – Factor π_U for phototransistors	42
Table 32 – Constants for current dependence of LEDs and IREDs	43
Table 33 – Factor π_I for LEDs and IREDs	43
Table 34 – Constants for temperature dependence of optoelectronic components	43
Table 35 – Factor π_T for optical components	44
Table 36 – Capacitors	45
Table 37 – Constants for voltage dependence of capacitors	46
Table 38 – Factor π_U for capacitors	46
Table 39 – Constants for temperature dependence of capacitors	47
Table 40 – Factor π_T for capacitors	48
Table 41 – Resistors and resistor networks	49
Table 42 – Constants for temperature dependence of resistors	49
Table 43 – Factor π_T for resistors	

Table 44 – Inductors, transformers and coils.....	50
Table 45 – Constants for temperature dependence of inductors, transformers and coils	50
Table 46 – Factor π_T for inductors, transformers and coils	51
Table 47 – Microwave devices	51
Table 48 – Other passive components	52
Table 49 – Electrical connections.....	53
Table 50 – Connectors and sockets	53
Table 51 – Relays.....	54
Table 52 – Factor π_{ES} for low current relays.....	55
Table 53 – Factor π_{ES} for general purpose relays.....	55
Table 54 – Factor π_{ES} for automotive relays.....	56
Table 55 – Constants for temperature dependence of relays.....	56
Table 56 – Factor π_T for relays	56
Table 57 – Switches and push-buttons.....	57
Table 58 – Factor π_{ES} for switches and push-buttons for low electrical stress	58
Table 59 – Factor π_{ES} for switches and push-buttons for higher electrical stress	58
Table 60 – Signal and pilot lamps	58
Table 61 – Factor π_U for signal and pilot lamps.....	59
Table A.1 – Failure modes: ICs (digital)	60
Table A.2 – Failure modes: transistors, diodes, optocouplers.....	61
Table A.3 – Failure modes: LEDs.....	61
Table A.4 – Failure modes: laser diodes and modules	61
Table A.5 – Failure modes: photodiodes and receiver modules	61
Table A.6 – Failure modes: capacitors	62
Table A.7 – Failure modes: Resistors, inductive devices, relays	62
Table B.1 – Thermal resistance as a function of package type, pin number and airflow factor	66
Table B.2 – Typical values of ν are K	66
Table B.3 – Values of P_{DC} and P_f	67
Table E.1 – Useful life limitations for switches and keyboards.....	89
Table F.1 – Failure mechanism for Integrated circuits	91
Table G.1 – Reliability prediction database attributes.....	98
Table H.1 – Result of calculation for transistors common, low frequency.....	102
Table H.2 – Sources of reliability data (in alphabetical order).....	102
Table I.1 – Classification tree (IEC 61360-4).....	106

INTERNATIONAL ELECTROTECHNICAL COMMISSION

**ELECTRIC COMPONENTS –
RELIABILITY –
REFERENCE CONDITIONS FOR FAILURE RATES
AND STRESS MODELS FOR CONVERSION****FOREWORD**

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

International Standard IEC 61709 has been prepared by IEC technical committee 56: Dependability.

This third edition cancels and replaces the second edition, published in 2011. This edition constitutes a technical revision. This third edition is a merger of IEC 61709:2011 and IEC TR 62380:2004.

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

- a) addition of 4.5 Components choice, 4.6 Reliability growth during the deployment phase of new equipment, 4.7 How to use this document, and of Clause 19 Printed circuit boards (PCB) and Clause 20 Hybrid circuits with respect to IEC TR 62380;
- b) addition of failure modes of components in Annex A;
- c) modification of Annex B, Thermal model for semiconductors, adopted and revised from IEC TR 62380;
- d) modification of Annex D, Considerations on mission profile;
- e) modification of Annex E, Useful life models, adopted and revised from IEC TR 62380;
- f) revision of Annex F (former B.2.6.4), Physics of failure;
- g) addition of Annex G (former Annex C), Considerations for the design of a data base on failure rates, complemented with parts of IEC 60319;
- h) addition of Annex H, Potential sources of failure rate data and methods of selection;
- i) addition of Annex J, Presentation of component reliability data, based on IEC 60319.

The text of this standard is based on the following documents:

FDIS	Report on voting
56/1714/FDIS	56/1721/RVD

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

The contents of the corrigendum of October 2019 have been included in this copy.

INTRODUCTION

This document is intended for the reliability prediction of **electric** components as used in equipment and is aimed at organizations that have their own data and describes how to state and use that data in order to perform reliability predictions.

It can also be used to allow an organization to set up a failure rate database and describes the reference conditions for which field failure rates should be stated. The reference conditions adopted in this document are typical of the majority of applications of components in equipment however when components operate under other conditions the users may consider stating these conditions as their reference conditions.

Using the presented stress models allows extrapolation of failure rates **from reference conditions** to other operating conditions which in turn permits the prediction of failure rates at assembly level. This allows estimation of the effect of design changes or changes in the environmental conditions on component reliability. Reliability prediction is most useful in the early design phase of ~~electrical~~ equipment. It can be used, for example, to identify potential reliability problems, the planning of logistic support strategies and the evaluation of designs.

The stress models contained herein are generic and are as simple as possible while still being comparable with more complex equations contained in other models. **The predictions generated using this document have a wide range of prediction accuracy.**

This document does not contain failure rates, but it describes how they can be stated and used. This approach allows a user to select the most relevant and up to date failure rates for the prediction from a source that they select. This document also contains information on how to select the data that can be used in the presented models.

The failure rates considered in this document are assumed to be constant, either for an unlimited period of operation (general case) or for limited periods. The limitation of life is called useful life and applies only for some few component families, reaching the wear-out failure period (during which the failure rate is increasing) within the normal period of use. It is hence assumed that during useful life, the failure rate can be considered constant for any practical use.

For the purposes of this document the term electric component includes the commonly used terms “electronic component”, “electrical component” and “electro-mechanical component”.

ELECTRIC COMPONENTS – RELIABILITY – REFERENCE CONDITIONS FOR FAILURE RATES AND STRESS MODELS FOR CONVERSION

1 Scope

This document gives guidance on ~~how the use of~~ failure rate data ~~can be employed~~ for reliability prediction of electric components ~~used~~ in equipment.

The method presented in this document uses the concept of reference conditions which are ~~numerical~~ the typical values of stresses that are observed by components in the majority of applications.

Reference conditions are useful since they ~~are the basis of the calculation of failure rate under any conditions by the application of stress models that take into account the actual operating~~ provide a known standard basis from which failure rates can be modified to account for differences in environment from the environments taken as reference conditions. Each user can use the reference conditions defined in this document or use their own. When failure rates stated at reference conditions ~~are used~~ it allows realistic reliability predictions to be made in the early design phase.

The stress models described herein are generic and can be used as a basis for conversion of failure rate data ~~given~~ at these reference conditions to actual operating conditions when needed and this simplifies the prediction approach. Conversion of failure rate data is only ~~permissible~~ possible within the specified functional limits of the components.

This document also gives guidance on how a database of component failure data can be constructed to provide failure rates that can be used with the included stress models. Reference conditions for failure rate data are specified, so that data from different sources can be compared on a uniform basis. If failure rate data are given in accordance with this document then ~~no~~ additional information on the specified conditions ~~is required~~ can be dispensed with.

This document does not provide base failure rates for components – rather it provides models that allow failure rates obtained by other means to be converted from one operating condition to another operating condition.

The prediction methodology described in this document assumes that the parts are being used within its useful life. The methods in this document have a general application but are specifically applied to a selection of component types as defined in Clauses 6 to 20 and I.2.

2 Normative references

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

~~IEC 60050-191, International electrotechnical vocabulary – Part 191: Dependability and quality of service~~

IEC 60050-192:2015, *International electrotechnical vocabulary – Part 192: Dependability*

~~IEC 60605-6, Equipment reliability testing — Part 6: Tests for the validity and estimation of the constant failure rate and constant failure intensity~~

~~IEC 60721-3-3, Classification of environmental conditions — Part 3: Classification of groups of environmental parameters and their severities — Section 3: Stationary use at weather protected locations~~

~~IEC 60721-3-4, Classification of environmental conditions — Part 3: Classification of groups of environmental parameters and their severities — Section 4: Stationary use at non-weatherprotected locations~~

~~IEC 60721-3-5, Classification of environmental conditions — Part 3: Classification of groups of environmental parameters and their severities — Section 4: Ground vehicle installations~~

~~IEC 60721-3-7, Classification of environmental conditions — Part 3: Classification of groups of environmental parameters and their severities — Section 7: Portable and non-stationary use~~

3 Terms, definitions and symbols

3.1 Terms and definitions

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

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

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

3.1.1

electric component

component with conductive terminals through which voltages or currents may be applied or delivered

Note 1 to entry: The term electric component includes the commonly used terms “electronic component”, “electrical component” and “electro-mechanical component”.

[SOURCE: IEC 61360-1:2009, 2.18, modified — Existing note deleted and Note 1 to entry added]

3.1.2

failure <of an item>

loss of ability to perform as required

~~Note 1 — When the loss of ability is caused by a pre-existing latent fault, the failure occurs when a particular set of circumstances is encountered.~~

Note 1 to entry: A failure of an item is an event that results in a fault of that item, ~~which is a state~~: see fault (IEC 60050-192:2015, 192-04-01).

Note 2 to entry: Qualifiers, such as catastrophic, critical, major, minor, marginal and insignificant, may be used to categorize failures according to the severity of consequences, the choice and definitions of severity criteria depending upon the field of application.

Note 3 to entry: Qualifiers, such as misuse, mishandling and weakness, may be used to categorize failures according to the cause of failure.

[SOURCE: IEC 60050-192:2015, 192-03-01]

3.1.3

failure mode

manner in which failure occurs

Note 1 to entry: A failure mode may be defined by the function lost or the state transition that occurred.

[SOURCE: IEC 60050-192:2015, 192-03-17]

3.1.4

instantaneous failure rate

failure rate

limit, if it exists, of the ~~ratio~~ **quotient** of the conditional probability that the ~~instant of a~~ failure of a non-repairable item occurs within time interval $(t, t + \Delta t)$, ~~to~~ **by** Δt , when Δt tends to zero, given that ~~it~~ **failure** has not ~~failed~~ **occurred** within time interval $(0, t)$

NOTE 1—The instantaneous failure rate, $\lambda(t)$, is expressed by the formula:

$$\lambda(t) = \lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} \frac{F(t + \Delta t) - F(t)}{R(t)} = \frac{f(t)}{R(t)}$$

where $F(t)$ and $f(t)$ are, respectively, the distribution function and the probability density at the failure instant, and where $R(t)$ is the reliability function, related to the reliability $R(t_1, t_2)$ by $R(t) = R(0, t)$.

Note 1 to entry: See IEC 61703, *Mathematical expressions for reliability, availability, maintainability and maintenance support terms*, for more detail.

Note 2 to entry: Other terms used for instantaneous failure rate are: “hazard function”; “hazard rate”; and “force of mortality” (abbreviation FOM).

Note 3 to entry: $\lambda(t)$ in this document is assumed to be constant over time **unless explicitly stated otherwise**.

[SOURCE: IEC 60050-192:2015, 192-05-06, modified — Note 3 to entry added]

3.1.5

reference conditions

stresses selected so as to correspond to the majority of applications and usage of components in equipment

Note 1 to entry: Stresses include electrical stress, temperature and environmental conditions.

3.1.6

reference failure rate

failure rate stated under reference conditions given in IEC 61709

Note 1 to entry: The reference failure rate is specific to the component, i.e. it includes the effect of complexity, technology of the casing, dependence on manufacturers and the manufacturing process, etc.

3.1.7

duty cycle

specified sequence of operating conditions

Note 1 to entry: The duty cycle states whether components are continuously or intermittently stressed during their operation. Continuous duty means operation for a long duration with constant or changing loads (e.g. process controls, telephone switch). Intermittent duty means operation with constant or changing loads during up state (e.g. numerical controls for machinery, road traffic signals).

[SOURCE: IEC 60050-151:2001, 151-16-02, modified — Note 1 to entry added]

3.1.8**operating state** <of an item>

state of performing as required

Note 1 to entry: For a component it means that it is energized and/or connected to a load.

[SOURCE: IEC 60050-192:2015, 192-02-04, modified — Notes 1 and 2 to entry replaced with a new Note 1 to entry]

3.1.9**non-operating state** <of an item>

state of not performing any required function

Note 1 to entry: The adjective “non-operating” designates an item in a non-operating state.

Note 2 to entry: A component may be in a non-operating state because of a failure or because it is in an idle state (IEC 60050-192:2015, 192-02-14), if it is not required to be in an up state, in a standby state (IEC 60050-192:2015, 192-02-10), during the required time or in an externally disabled time (IEC 60050-192:2015, 192-02-24), when the non operation is due to absence of external resources.

[SOURCE: IEC 60050-192:2015, 192-02-06, modified — Note 2 to entry added]

3.1.10**dormant state**

state of being inactive, but capable of becoming active

Note 1 to entry: For a component it means that it is ready to be energized and/or connected to a load.

3.1.11**standby state** <of an item>

non-operating up state during required time

[SOURCE: IEC 60050-192:2015, 192-02-10]

3.1.12**storage state**

state of being placed at a specific facility, and under stated conditions, without being energized and/or connected to a load

Note 1 to entry: For example the storage state of a component is not assembled to a piece of equipment.

3.1.13**prediction**

computation process used to obtain the predicted value of a quantity

~~NOTE The term “prediction” may also be used to denote the predicted value of a quantity.~~

[SOURCE: IEC 60050-192:2015, 192-11-01]

3.1.14**component**

constituent part of a device which cannot be physically divided into smaller parts without losing its particular function

[SOURCE: IEC 60050-151:2001, 151-11-21]

3.1.15**equipment**

single apparatus or set of devices or apparatuses, or the set of main devices of an installation, or all devices necessary to perform a specific task

Note 1 to entry: Examples of equipment are a power transformer, the equipment of a substation measuring equipment.

[SOURCE: IEC 60050-151:2001, 151-11-25]

3.1.16

useful life <of an item>

time interval, from first use until user requirements are no longer met, due to economics of operation and maintenance, or obsolescence

Note 1 to entry: In this context, "first use" excludes testing activities prior to hand-over of the item to the end-user.

[SOURCE: IEC 60050-192:2015, 192-02-27]

3.1.17

drift

difference between the final value of a characteristic at the end of a specified period and the initial value, all other operating conditions being held constant

Note 1 to entry: The use of the term "drift" to refer to the immediate change of a characteristic in direct response to changed operating conditions (for example, temperature) is deprecated.

[SOURCE: IEC 60747-1:2006, 3.6.1, ~~modified~~]

3.1.18

virtual temperature <of a semiconductor device>

internal equivalent temperature

theoretical temperature which is based on a simplified representation of the thermal and electrical behaviour of the semiconductor device

Note 1 to entry: The virtual temperature is not necessarily the highest temperature in the device.

[SOURCE: IEC 60050-521:2002, 521-05-14, modified — Note 2 to entry deleted]

3.1.19

virtual (equivalent) junction temperature

virtual temperature of the junction of a semiconductor device

[SOURCE: IEC 60050-521:2002, 521-05-15]

3.1.20

ambient air temperature

the temperature, determined under prescribed conditions, of the air surrounding the complete device

Note 1 to entry: For devices installed inside an enclosure, it is the temperature of the air outside the enclosure.

[SOURCE: IEC TR 60943:1998, 1.3.1]

3.2 Symbols

In the normative part of this document, the following symbols are used. Other symbols are used and defined in the annexes.

~~E_a~~ E_{a1}, E_{a2} activation energies of a failure process

A, C_i, k_0 constants

λ failure rate under operating conditions

~~λ_f~~ ~~failure rate at full stress for an assembly~~

λ_{ref} failure rate under reference conditions

$\lambda_{\text{component}}$	failure rate of a component
~~λ_i~~	~~failure rate during time spent idle for an assembly;~~
λ_{mode}	failure rate of a component's failure mode
~~λ_p~~	~~failure rate at part stress for an assembly;~~
~~λ_s~~	~~failure rate of a system;~~
π_I	current dependence factor
π_E	environmental application factor
π_{ES}	electrical stress dependence factor
~~π_{OP}~~	~~stress factor for operating profile;~~
π_S	switching rate dependence factor
π_T	temperature dependence factor
π_U	voltage dependence factor
I_{op}	operating current
I_{rat}	rated current
I_{ref}	reference current
P_{op}	operating power dissipation
P_{ref}	reference power dissipation
P_{rat}	rated power dissipation
R_{th}	thermal resistance
$R_{\text{th, amb}}$	thermal resistance (to the environment)
S	number of operating cycles per hour
S_{ref}	reference number of operating cycle per hour
U_{op}	operating voltage
U_{rat}	rated voltage
U_{ref}	reference voltage
ΔT	actual self-heating in degrees Celsius
ΔT_{ref}	reference self-heating in ~~degrees Celsius~~ Kelvin
θ_0	reference ambient temperature in degrees Celsius
θ_{amb}	ambient temperature in degrees Celsius ~~— for capacitors the actual capacitor temperature;~~ ~~— for discrete semiconductors and optoelectronic components the actual junction temperature;~~ ~~— for inductors the actual winding temperature;~~ ~~— for integrated circuits (ICs) the actual virtual (equivalent) junction temperature;~~ ~~— for other electric components the actual ambient temperature;~~ ~~— for resistors the actual resistor element temperature;~~
T_0	reference ambient temperature in Kelvin
T_{amb}	ambient temperature in Kelvin
T_{op}	operating temperature in Kelvin
T_{ref}	reference temperature in Kelvin
θ_{op}	operating temperature in degrees Celsius — for integrated circuits (ICs) the actual virtual (equivalent) junction temperature;

- for discrete semiconductors and optoelectronic components the actual junction temperature;
- for capacitors the actual capacitor temperature;
- for resistors the actual resistor element temperature;
- for inductors the actual winding temperature;
- for other electric components the actual ambient temperature;

θ_{ref} reference temperature in degrees Celsius

- for ICs the reference virtual (equivalent) junction temperature;
- for discrete semiconductors and optoelectronic components the reference junction temperature;
- for capacitors the reference temperature of the capacitor;
- for resistors the reference temperature of the resistor element.
- for inductors the reference temperature of the winding;
- for other electric components the reference temperature of the component;

~~$R(t_1, t_2)$ reliability between two times t_1 and t_2~~

~~t_p fraction of time with part stress for an assembly~~

~~t_i fraction of time spent idle for an assembly~~

~~t_f fraction of time with full stress for an assembly~~

~~β shape parameter of the Weibull distribution~~

4 Context and conditions

4.1 Failure modes and mechanisms

The characteristic preferred for reliability data of electric components is the (instantaneous) failure rate. It is to be noted that, although it is often generically defined as failure, the exact observed event that is measured is a failure mode.

In equipment a failure ~~(mode)~~ or functional loss is caused by a component failure ~~mode~~ where component failure mode is relevant to the application being carried out by the equipment.

It should be noted that a component has many features and only some may be used in the specific application. A function loss at the equipment level occurs only when there is a loss of the component feature that is used to support that function.

Furthermore a circuit requires the presence of component features according to what was defined by the designer; this may not encompass the total feature set of the component and may not use a particular feature to its full capacity as defined by the data sheet in terms of functional characteristics and ratings.

Handbooks usually define failure rate as an overall value, which includes all failure modes. This implies that component failure rate can be considered as the sum of the failure rates of all the modes, as follows:

$$\lambda_{\text{component}} = \sum_{i=1}^n (\lambda_{\text{mode}})_i \quad (1)$$

where $(\lambda_{\text{mode}})_i$ is the component failure rate in which the failure mode i occurs and n is the number of failure modes.

Failure modes are listed in Annex A ~~and more details about failures are contained in Annex B.~~

A failure is related to a failure mechanism, which is the basic material behaviour that results in the failure. For integrated circuits more detailed description is presented in Annex F.

4.2 Thermal modelling

Temperature is a relevant factor affecting failure rate. It is in fact known that temperature and temperature change has an effect on component reliability. For temperature change see 4.4. The temperature effect is more significant for some families (active components and aluminium capacitors with non-solid electrolyte). The models adopted are those which give the effect of temperature on the predominating failure mechanisms (which are not normally the “wear-out” mechanisms).

Thermal modelling of components should then be as accurate as possible, in particular thermal resistance for semiconductors should be measured in order to allow accurate evaluation of the internal temperature.

When thermal resistance cannot be measured, thermal resistance models provided in Annex B can be used.

4.3 ~~Operating~~ Mission profile considerations

4.3.1 General

During their life, components experience different conditions of use that represent the major factors affecting component reliability: the complex of these conditions is defined as mission profile.

~~One of the major factors affecting component reliability is operating profile.~~

The mission profile defines the required function and the environmental condition as a function of time. This will vary according to the type of operation that is undertaken. This operation may be continuous over time at a fixed level, continuous over time at a variable level or sporadic over time at either a fixed level or a variable level. In some cases switch on and switch off could be significant and of more importance than the steady state operational conditions. Careful consideration of the ~~operating~~ mission profile is needed in order to fully understand how it affects the component reliability.

The ~~operating~~ mission profile can be considered to be based on calendar time or on the time of actual operation or it can be cycle based (e.g. how many times an item is used).

More considerations on mission profile are detailed in Annex D.

4.3.2 Operating and non-operating conditions

A mission profile can be decomposed in several phases, on the basis of the typical use. The main classification of these phases is between operating and non-operating conditions. Although this document deals with components, the conditions of use usually refer to the assembly (equipment or system), and can be defined as follows when they refer to components.

- Operating: the component is assembled, powered or connected to a load and functioning at nominal conditions. See 3.1.8.
- Stand-by: the component is assembled, powered or connected to a load, but not functioning or functioning at conditions lower than nominal. See 3.1.11.
- Dormant: the component is assembled, but not powered or connected to a load. See 4.3.3.
- Storage: the component is not assembled, hence not powered or connected to a load. During storage components are packed stored in a warehouse. See 4.3.4

4.3.3 Dormancy

A component is considered dormant (i.e. in a dormant state) when it is inactive (it does not provide any of the required functions), but it is capable of becoming active and properly operating on demand (energized and/or connected to a load). To be considered dormant it is assumed that the component is assembled to a piece of equipment, but no power is applied.

Components that are dormant may fail, but usually the dormant failure rate is considerably lower than the operating failure rate, assuming that the piece of equipment is maintained within its specified conditions, when non-operating.

4.3.4 Storage conditions

Components that are under storage conditions are not immune from failure, particularly when the storing conditions are different from those specified. However the stress models for environmental application factors in this document may not apply since they only deal with operating conditions. Different failure mechanisms may exist under storage conditions that have not been considered in the models. Furthermore the case where storage conditions change the failure rate when the item is active are not dealt with in this document.

Storage conditions should be treated separately from operating conditions. They may affect the components' failure behaviour in later life.

More information on storage can be found in IEC PAS 62435. Storage conditions should be defined and controlled, in order to ensure the reliability of the components stored.

4.4 Environmental conditions

The environment contributes to failure that occurs in the life of the equipment. As a consequence the duration and intensity of environmental stresses should be included in the operational model of the equipment.

A more severe environment may cause the failures to occur more frequently than one that is less severe. There will usually be several aspects of the environment that will be pertinent to a specific failure and all may need to be understood. The locality of the environment is also important, for example on an aircraft the in-cabin and on-engine environments are very different.

The environment may be described in terms of several types of parameters and their associated interactions.

IEC 60721-3-3 describes the environment in terms of:

- climatic conditions;
- special climatic conditions;
- biological conditions;
- chemically active substances;
- mechanically active substances;
- mechanical conditions (both static and dynamic).

All the above listed conditions are in general relevant to the equipment's reliability (e.g. failure rate) and it is reasonable to consider that the reliability of components, and therefore of the equipment, decreases as the environmental stress increases (see IEC 60721 (all parts) for a detailed quantitative description of the environmental parameters for each environment).

In this document it is assumed that the climatic and mechanical conditions are the most significant and this is also valid for many standard applications of components, but there may be situations where, for example, chemical conditions could result in a higher failure rate.

Other factors influencing the failure rate can be nuclear, ultraviolet, infrared and electromagnetic radiation, acoustics, altitude, software security, six degrees of freedom vibration, explosive atmosphere environments, item induced conditions, and hostile weapons effects for military items.

Estimated failure rates generated using the models in this document are valid only if the coldest part temperature of the considered component is over the dew point temperature.

In this document only the climatic and mechanical parameters are used to describe the effect of the reference environments on failure rates. However, temperature is treated separately in this document. For simplicity it has been chosen to address three basic environments, conventionally named E1, E2 and E3. These environments refer to general field usage situations, considering the specific values of the environmental parameters. These are defined in Table 1.

Table 1 – Basic environments

E1	Stationary use at weather-protected locations	The environment is highly insensitive to the weather outdoors and humidity is controlled within defined limits. This is typical of telecommunications and computer equipment placed in buildings. This includes office situations.
E2	Stationary use at partially weather-protected or non-weather-protected locations	The environment offers thermal and mechanical stresses directly influenced by natural environmental conditions. It is typical of equipment installed outdoors.
E3	Portable and non-stationary use, ground vehicle installation	The environment offers mechanical stresses and severe thermal gradients. It is typical of equipment mounted on vehicles or that are hand portable.

~~Other environments can be defined, see 5.2.5 for details.~~

Table 2 shows the values of environmental parameters and their relationship to the classes indicated in the relevant IEC standards.

The effect of environment can be described as a change of failure rate, by applying an environmental application factor π_E (see Table 4). Note that π_E is a discrete factor since it is based on non-continuous data and summarizes a large number of different lower level factors.

It has to be noted, anyway, that most of the systems and equipment operate under controlled temperature and the effect of external environment is shielded by proper design decisions.

This document considers temperature cycle (operating times at different temperatures) in the mission profile, while rapid temperature changes are included in the environmental application factor, π_E (see 5.2.5).

The environmental application factors include all environmental parameters (excluding temperature, which has a specific model) such as rapid temperature changes, mechanical vibration, where no empirical models are available. The environmental application factors are used at equipment level.

Table 2 – Values of environmental parameters for basic environments

Basic environment Environmental parameters	E1	E2	E3
	Stationary use at weather-protected locations	Stationary use at partially weather-protected or non-weather-protected locations	Portable and non-stationary use, ground vehicle installation
Temperature rate of change	≤ 0,5° C/min	> 0,5° C/min	> 0,5° C/min
Stationary vibration, sinusoidal	2 Hz to 9 Hz <1,5 mm 9 Hz to 200 Hz ≤ 5 m/s ²	2 Hz to 9 Hz ≤3 mm 9 Hz to 200 Hz ≤ 10 m/s ²	2 Hz to 9 Hz >3 mm 9 Hz to 200 Hz ≥ 10 m/s ² 200 Hz to 500 Hz ≥15 m/s ²
Non-stationary vibration including shock	≤ 70 m/s ²	≤ 250 m/s ²	> 250 m/s ²
IEC 60721-3-3 Classes	3K1 3K2 3K3 3K4 3K5 3K6 3M1 3M2 3M3	3K7 3K7L 3K8 3K8H 3K8L 3K9 3K10 3M4 3M5 3M6 3M7	-
IEC 60721-3-4 Classes	-	-	4K1 4K2 4K3 4K4 4K4H 4K4L
IEC 60721-3-5 Classes	-	-	5K1 5K2 5K3 5K4 5K4H 5K4L 5K5 5K6 5M1 5M2 5M3
IEC 60721-3-7 Classes	-	-	7K1 7K2 7K3 7K4 7K5
ETS 300 019-1-3 Classes	3.1-3.2-3.3	3.4-3.5	-
ETS 300 019-1-4 Classes	-	4.1-4.1E	-
ETS 300 019-1-8 Classes	8.1 and Note	-	-
ETS 300 019-1-5 Classes	-	-	5.1-5.2
ETS 300 019-1-7 Classes	-	-	7.1 – 7.2 – 7.3 – 7.3E

This document ~~is written to contain~~ covers only the three environments for ~~the sake of~~ simplicity. The user can describe any environment using the same methodology and assess the proper environmental application effect π_E as described in 5.2.5.

4.5 Components choice

It is the responsibility of the manufacturer to ensure the life duration specified by the final user and that components used in equipment are compatible with the environment. Therefore, premature wear-out is assumed not to occur during the useful life period of the equipment in normal operating conditions, as prescribed by the final user.

However, some components may have a limited life duration, and so preventive maintenance has to be indicated to the final user. It is the responsibility of the component manufacturer to provide qualification and evaluation results of degradation mechanisms to the system manufacturer and to ensure that the appearance of wear-out mechanisms will be postponed beyond the useful life period of the equipment in normal operating conditions.

Good component and equipment reliability is not achieved without effort. Equipment reliability is built-in, starting from the initial design phases, by applying a rigorous quality assurance system, oriented toward improvement. This means that inadequate application of the rules for excellence in quality and reliability, taking into account the product type and its use and maintenance criticality, will affect reaching the objective.

Component failures, even those conventionally considered random, excluding wear-out and external causes, are due to manufacturing defects or misuse. These show their effects during operation.

Thus manufacturers and users have to adopt adequate preventive actions:

- qualification and control of the component manufacturing process;
- characterization and qualification of the components;
- acceptance tests;
- use of good design rules (thermal, electrical, mechanical).

This document does not describe quality levels since it does not consider quality levels lower than the best achievable set as design standards. Experience of poor quality cannot be considered in order to establish models, and waivers to the application of quality rules cannot be justified based on economic considerations when the total component/equipment cost, either of the manufacturer or of the user, is considered.

There are special applications such as space, avionics and submarine cables, where the impossibility – or at least the great difficulty – of performing maintenance, as well as for safety reasons, urge adoption of even more severe rules. These cases cannot be generalized and should be studied using specific experience with the equipment and the measures adopted (such as screening, burn-in, special quality assurance programmes).

Consequently, the equipment manufacturer has to choose component manufacturers who have the best "commercial practice" concerning quality, for example, those who comply with internationally recognized quality management systems, practise statistical process control and are approved under qualified manufacturing line approval (or able to be).

In these conditions, there are no longer any reasons to take into consideration quality factors, and the infant mortality period related to new component technology is neglected since only qualified production lines and stabilized ones are considered here.

When an equipment manufacturer uses a new component technology, and when such a manufacturer has not been able to justify the life duration in normal use conditions of its device, the equipment manufacturer has to undertake tests allowing justification of the life duration of this component to the final user.

4.6 Reliability growth during the deployment phase of new equipment

The models expounded in this document allow for calculating the failure rate of an electric item that is already in a mature production phase. However, prior to that, a newly developed item may have undergone some form of reliability growth process that is reflected by a decreasing failure rate during a more or less long period.

For instance, reliability growth is achieved by the correction of manufacturing issues such as the return of a process into control or the modification of a process to improve it. With respect to reliability growth in the field, it is the modifications to the item, its design, manufacturing or operation that lead to a more reliable item. For a comprehensive description of reliability processes and activities integrated into the product life cycle which contribute or provide for the product reliability growth, refer to IEC 61014.

A manufacturer should calibrate the reliability growth period according to its own experience. It was demonstrated experimentally on many electric items and with several manufacturers that the ratio between the failure rate during the starting period of deployment and the failure rate in the mature phase can be very different. Consequently, as soon as the observed failure rate during the beginning of the deployment of an electric item significantly exceeds the estimated value, a corrective action may have to be taken.

4.7 How to use this document

This document provides a method to convert failure rates from one set of operating conditions to another. To do this it uses the concept of failure rates at reference conditions and provides equations to convert them to other conditions.

Reference conditions are defined as the most common set of environmental and operating conditions for the user. For example if an organization has most of its equipment operating at 30°C then it should state failure rates at this operating temperature and define it as the reference conditions. The reason the organization should choose the typical operating conditions as the reference conditions is so that when they collect field reliability data they do not have to make any adjustments to it to account for environmental differences before using it.

If an organization does not have a typical operating environment then they should decide to set the reference conditions at a level that is most appropriate for them, or they can use the reference conditions that are defined in this document in Clauses 6 to 20. In this case when they collect field data they may have to make adjustments to the data to bring it all to a set of reference conditions so that it can be combined and compared.

Many organizations will not have their own reliability data and so will need to use other sources of data. This document can then be used to convert the failure rates from operating conditions to reference conditions or vice versa.

NOTE For example if an organization wants to perform a prediction for an equipment at an operating temperature of 34 °C and the component being used are not covered by a single data source with some data coming from other multiple data handbooks then the base failure rates, which are stated at a particular and different level of environmental stress in each source, can be converted and combined using the equations in this document.

The equations in this document have been derived from empirical model fitting to field data and in some cases to the equations used in other standards and handbooks. This means that the equations here will give a generic fit to the data as is suitable in an international standard.

Figure 1 shows, for CMOS IC, a comparison of the temperature dependence of factors π_T stated in a number of prediction handbooks with the factor π_T stated in this document.

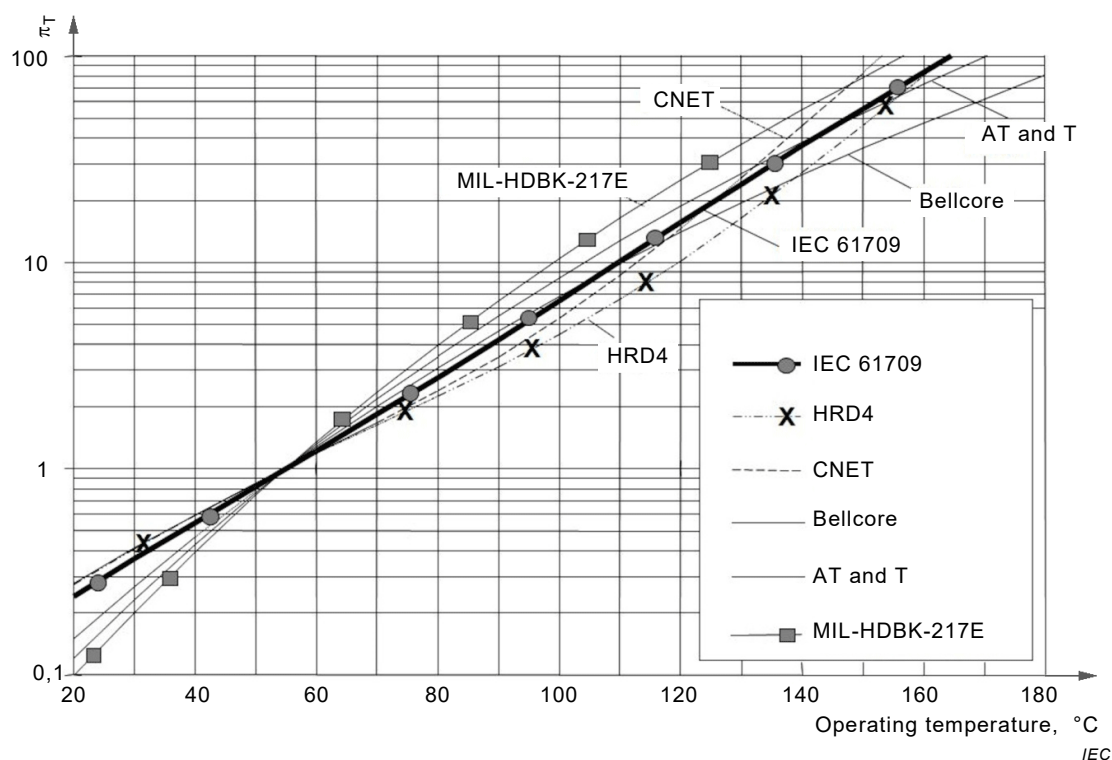


Figure 1 – Comparison of the temperature dependence of π_T for CMOS IC

Figure 1 demonstrates that the acceleration factors provided in this document are compatible with many acceleration factors given in prediction handbooks. The figure shows a fit to generic versions of the data from the prediction handbooks. The latest versions of the handbooks are detailed in H.5.3.

In order to use the equations given in this document then certain data will be required; this differs slightly by component type, but the most important data is a base failure rate stated at reference conditions. This can be obtained from field data (see IEC 60300-3-3, IEC 60300-3-5) or from manufacturer's data or from other handbooks (see Annex H). If this data is not stated at reference conditions it can be converted to a reference condition by using the equations in this document. Knowledge of the operating environment at which the failure rate is stated is necessary in order to do this. When the failure rate is at reference conditions then it can be converted to other operating conditions using the equations contained in this document.

5 Generic reference conditions and stress models

5.1 Recommended generic reference conditions

Generic reference conditions are those ~~that apply to all component types~~ values of environmental factors that are defined by an organization as being typical of the sorts of environment the organization's equipment is subjected to during normal operations. ~~In this standard, these include electrical stress, temperature and environmental conditions. If it is appropriate and if models are available, these can be considered at the specific component level.~~ The factor could be any environmental factor the organization feels is relevant and apply to all component types.

This document, necessarily, takes a more limited view and defines the environmental factors of interest as being electrical stress, temperature and environmental conditions. Extensions to this set are not supported by this document.

Table 3 contains some recommendations that ~~should~~ **can** be used by an organization unless they are not appropriate to the normal working conditions of that organization's equipment. ~~The organization is then free to choose its own appropriate reference conditions.~~ Any organization should choose conditions closest to their actual experience if they differ from those given in Table 3.

The values chosen represent the majority of component operating conditions.

~~Generic models are not available.~~

Table 3 – Recommended reference conditions for environmental and mechanical stresses

Type of stress	Reference condition ^a
Ambient temperature ^b	$\theta_0 = 40\text{ °C}$
Environmental condition	Environment E1 (see Table 1)
Special stresses	Not addressed in this document ^c
^a The failure rates stated under these conditions apply only to components not damaged during transport and storage. ^b The ambient temperature for the purposes of this document is the temperature of the medium next to the component during equipment operation, not taking into account any possible self-heating of the component. The surroundings of the component should be defined. ^c Special stresses include wind, rain and snow, icing, drips, sprays or jets of water, dust (chemically active or not), effects of animal pests, corrosive gases, radioactive radiation, etc. These stresses may be significant contributors to failure however, as a general good practice; they should be addressed by design practices. There may be cases where their effect can be treated by applicable models. These stresses have such wide ranges of effects it would be inappropriate to address them in this document.	

5.2 Generic stress models

5.2.1 General

Components may not always operate under the reference conditions. In such cases, ~~operational~~ **operating** conditions will result in failure rates different from those given for reference conditions. Therefore, models for stress factors, by which failure rates under reference conditions can be converted to values applying for operating conditions (actual ambient temperature and actual electrical stress on the components), and vice versa, may be required. In Clauses 6 to 20 specific stress models and values of π -factors for component categories are given and should be used for converting reference failure rates to field operational failure rates. π -factors are failure rate modifiers which are related to a specific stress or condition. They are a measure of the change of failure rate due to changes in that stress or condition. However, if more specific models are applicable for particular component types then these models should be used and their usage justified and reported.

The conversion of failure rates is only possible within the specified functional limits of the components.

The component failure rate under operating conditions is calculated as follows:

$$\lambda = \lambda_{\text{ref}} \times \pi_U \times \pi_I \times \pi_T \times \pi_E \times \pi_S \times \pi_{\text{ES}} \quad (2)$$

where

λ_{ref} is the failure rate under reference conditions;

π_U is the voltage dependence factor;

π_I is the current dependence factor;

π_T is the temperature dependence factor;

- π_E is the environmental application factor;
- π_S is the switching rate dependence factor;
- π_{ES} is the electrical stress dependence factor.

5.2.2 Stress factor for voltage dependence, π_U

$$\pi_U = \exp \left\{ C_3 \left[\left(\frac{U_{op}}{U_{rat}} \right)^{C_2} - \left(\frac{U_{ref}}{U_{rat}} \right)^{C_2} \right] \right\} \quad (3)$$

where

- U_{op} is the operating voltage in V;
- U_{ref} is the reference voltage in V;
- U_{rat} is the rated voltage in V;
- C_2, C_3 are constants.

Equation (3) represents an empirical model to describe the voltage dependence of failure rates and is based on existing component reliability handbooks, existing component reliability data, and publicly available publications.

NOTE When dealing with absolute values of voltage as might be necessary for some component types then Equation 3 can be modified to $\pi_U = \exp \left\{ C_1 (U_{op}^{C_2} - U_{ref}^{C_2}) \right\}$ where $C_1 = C_3 / U_{rat}^{C_2}$.

5.2.3 Stress factor for current dependence, π_I

$$\pi_I = \exp \left\{ C_4 \left[\left(\frac{I_{op}}{I_{rat}} \right)^{C_5} - \left(\frac{I_{ref}}{I_{rat}} \right)^{C_5} \right] \right\} \quad (4)$$

where

- I_{op} is the operating current in A;
- I_{ref} is the reference current in A;
- I_{rat} is the rated current in A;
- C_4, C_5 are constants.

Equation (4) represents an empirical model to describe the current dependence of failure rates and is based on existing component reliability handbooks, existing component reliability data, and publicly available publications.

5.2.4 Stress factor for temperature dependence, π_T

$$\pi_T = \exp \left[\frac{Ea_1}{k_0} \left(\frac{1}{T_{ref}} - \frac{1}{T_{op}} \right) \right] \quad (5)$$

Equation (5) is an empirical model based on the Arrhenius equation and it describes the temperature dependence of the failure rates. Ideally this computation should be made for each failure mode, however it is common practice to perform this calculation using an average of all activation energies for all failure modes or for the dominant failure mode only. It should be noted that in this latter case, the activation energy may also be a function of temperature.

since it is related to the different activation energies of the underlying failure modes. However this effect is commonly ignored.

In certain cases a more complex model using two activation energies is appropriate to fit the temperature dependence of failure rates. In such a case the following ~~model, represented by~~ Equation (6) can be used. Use of the model with two activation energies (Ea_1, Ea_2) is considered sufficient to adequately model the temperature-failure rate relation. (This is sometimes known as competing risks; see JESD-85 for details.)

This extended Arrhenius equation is standardized to avoid temperature-dependent activation energies when changing the reference temperature, T_{ref} .

$$\pi_T = \frac{A \times \exp(Ea_1 \times z) + (1 - A) \times \exp(Ea_2 \times z)}{A \times \exp(Ea_1 \times z_{\text{ref}}) + (1 - A) \times \exp(Ea_2 \times z_{\text{ref}})} \quad (6)$$

with the auxiliary variables

$$z = \frac{1}{k_0} \left(\frac{1}{T_0} - \frac{1}{T_{\text{op}}} \right) \quad \text{and} \quad z_{\text{ref}} = \frac{1}{k_0} \left(\frac{1}{T_0} - \frac{1}{T_{\text{ref}}} \right) \quad \text{in (eV)}^{-1}$$

where in Equations (5) and (6):

- A is a constant;
- Ea_1, Ea_2 are activation energies in eV;
- $k_0 = 8,616 \times 10^{-5}$ eV/K;
- $T_0 = 313$ K;
- $T_{\text{ref}} = (\theta_{\text{ref}} + 273)$ in K;
- $T_{\text{op}} = (\theta_{\text{op}} + 273)$ in K.

The temperatures θ_{ref} and θ_{op} in degrees Celsius above are as follows;

- for ICs:
 - θ_{ref} : reference virtual (equivalent) junction temperature;
 - θ_{op} : actual virtual (equivalent) junction temperature;
- for discrete semiconductors and optoelectronic components:
 - θ_{ref} : reference junction temperature;
 - θ_{op} : actual junction temperature;
- for capacitors:
 - θ_{ref} : average (*) reference capacitor temperature;
 - θ_{op} : average (*) actual capacitor temperature;
- for resistors:
 - θ_{ref} : average (*) reference temperature of the resistor element (for example, film);
 - θ_{op} : average (*) actual temperature of the resistor element;
- for inductors:

θ_{ref} : average (*) reference temperature of the winding;

θ_{op} : average (*) actual temperature of the winding;

– for other electric components:

θ_{ref} : average (*) reference ambient temperature;

θ_{op} : average (*) actual ambient temperature;

NOTE (*) In this case average means “over the entire body of the component”.

5.2.5 Environmental application factor, π_E

5.2.5.1 ~~General~~

Some data handbooks contain guidance on transferring a failure rate estimate from one general environmental condition to another. The concept ~~seems~~ is logical, but it ~~bears~~ carries some risk. For that reason, this document focuses more on situations where base failure rates are gathered from environment conditions which are similar to those applied to the component in practice. ~~For more information see B.4.4.~~

The influence of environmental application conditions on the component depends essentially on the design of equipment; for example by using the equipment on ships or in the automotive field instead of in protected rooms (laboratory conditions), ~~no~~ the influence on the environmental application conditions ~~will exist~~ can be minimized, and in some cases can be removed entirely if the component is protected in some way within the equipment. Of course this will require some extra design effort and so may not be worth doing in all cases. Whether an environmental application influence occurs depends therefore essentially on the equipment manufacturer and it is the duty of an organization to design for a specific environment or if the impact of these stresses cannot be avoided, then specific studies are necessary for these pieces of equipment.

If the only failure rate data books available came from a source with very different environmental conditions, the need for an environmental application factor arises. To use such an environmental application factor means to assume that a more severe environment causes the activation of internal failure mechanisms in a predictable, more or less linear manner. There are situations where this assumption is wrong. When a component designed for ground equipment is used under severe shock and vibration conditions – these can destroy all components in a few hours – a π_E -factor could be calculated, but is not meaningful. The ~~only~~ best practical solution ~~is~~ should be to not use the component in that environment, but that is not always possible.

The environmental application factor, π_E , should therefore be handled with care.

Table 4 – Environmental application factor, π_E

Stationary use at weather-protected locations	Stationary use at partially weather-protected or non-weather-protected locations	Portable and non-stationary use, ground vehicle installation
E1	E2	E3
1	2	4

NOTE Failure rate data books from a component supplier will often give guidance on how to transfer the failure rate to other operating and environmental conditions.

5.2.6 Dependence on switching rate, π_S

The factor π_S considers the number of operating cycles per hour, S , and only applies for relays in this document.

Factor π_S is not defined for $S < 0,01$.

$$a) \quad \pi_S = 1 \quad \text{for } \cancel{0,01} < S < S_{\text{ref}} \quad 0,01 \leq S \leq S_{\text{ref}} \quad (7)$$

$$b) \quad \pi_S = S/S_{\text{ref}} \quad \text{for } S > S_{\text{ref}} \quad (8)$$

where

S is the number of operating cycles per hour;

S_{ref} is the reference number of operating cycles per hour.

NOTE ~~For low operating cycles per hour ($S < 0,01$),~~ The factor π_S can be as much as 100 for hermetically sealed contacts, normally closed, or non-sealed contacts, normally open under small loads.

5.2.7 Dependence on electrical stress, π_{ES}

This π -factor is only applicable to certain devices and is explained in detail in the related clauses.

5.2.8 Other factors of influence

Other stress factors are given for individual types of components in Clauses 6 to 20 where the dependence is known.

At present, no generally applicable conversion methods can be given for the dependence of the failure rate on humidity, air pressure, mechanical stress, etc.

Stress factors will have to be based on vendor/user history in similar applications or appropriate testing.

If the failure rate dependence of these types of stress is known, it should be considered.

If the dependence of the failure rate under these types of stress is unknown but is expected to be a function of these types of stress, appropriate studies may be necessary.

~~6 Specific reference conditions and stress models~~

6 Integrated semiconductor circuits

6.1 Specific reference conditions

The following recommendations for reference temperatures given in Table 5 to Table 9 are based on a component ambient temperature of 40 °C and correspond to the majority of applications of components in equipment.

The reference self-heating, $\Delta T_{\text{ref}} = P_{\text{ref}} \times R_{\text{th, amb}}$, ~~shall~~ should be given when using reference temperatures other than those stated in the tables.

For any integrated circuit there are two thermal resistances generally considered: one between the junction and the case, and the other between the case and the environment. The

thermal resistance, $R_{th,amb}$, above, should be the one that is most significant in the application under consideration.

When stating a failure rate for an ambient temperature of 40 °C, the reference power dissipation, P_{ref} , and the thermal resistance, $R_{th,amb}$, to the environment for which this value holds, ~~shall~~ **should** also be given.

Table 5 – Memory

Component			θ_{ref} °C	Note
Bipolar	RAM, FIFO	static	75	---
	PROM		75	
MOS, CMOS, BICMOS	RAM	dynamic	55	
	RAM, FIFO	static slow (≥ 30 ns) static fast (< 30 ns)	55	
	ROM mask		55	
	EPROM, OTPROM	UV erasable	55	
	FLASH		55	
	EEPROM, EAROM		55	

Table 6 – Microprocessors and peripherals, microcontrollers and signal processors

Component		θ_{ref} °C	Note
Bipolar		70	---
NMOS	No. of transistors $\leq 50\,000$	70	
	No. of transistors $> 50\,000$	90	
CMOS	No. of transistors $\leq 5\,000$	50	
	No. of transistors $> 5\,000$ to $50\,000$	60	
	No. of transistors $> 50\,000$ to $500\,000$	80	
	No. of transistors $> 500\,000$	90	
BICMOS		75	

Table 7 – Digital logic families and bus interfaces, bus driver and receiver circuits

Component			θ_{ref} °C	Note Reference voltage
Bipolar	TTL, -LS, -A(L)S, -F	Logic	45	---
	Bus interface		55	
	TTL S	Logic + bus interface	80	
	ECL	10 000	65	
		100 000	75	
CMOS	10(LV)E(L) / 100(LV)E(I)(P)		60	$U_{ref} = 5V$
	HCMOS, CMOS B, ACMOS (FCT, HC, A(U), C, LVX), (LVC, LCX, LV) (VCX, ALVC, AVC, AHC, VHC)		45	
	Logic Analog switches, Bus interface			
	Bus interface	GTL(p)	50	
BICMOS	Bus driver / receiver RS422, RS423, RS485, CAN, etc. RS232, RS644/899, CML, etc.		55	
	Logic		45	

Bus interface	ABT, BCT	50	---
	LVT, ALVT	50	
	GTL(p)	50	
	BTL, ETL	95	
Bus driver / receiver		55	

Table 8 – Analog ICs

Component		θ_{ref} °C	Note Reference voltage ratio
Operational amplifiers, comparators and voltage monitors	Bipolar, BIFET	55	$U_{\text{ref}}/U_{\text{rat}} = 0,7$ ---
	CMOS	45	
Reference elements	all technologies	45	
Switch regulators	all technologies	55	
Power amplifiers and regulators (all technologies)	$\leq 1 \text{ W}$	70	
	$> 1 \text{ W}$	90	
High frequency IC (> 100 MHz)			
HF modulator, demodulator PLL, VCO	bipolar	65	
	CMOS, BICMOS	45	
Transmitter, receiver	bipolar	70	
	CMOS, BICMOS	45	
Power amplifier / receiver	GaAs	80	

Table 9 – Application-specific ICs (ASICs)

Component		θ_{ref} °C	Note
ASICs, Full custom, Gate arrays, Telecom ICs, A/D-Converters			---
Bipolar	TTL	55	
	ECL	70	
	HV (> 50 V)	80	
NMOS		55	
CMOS, BICMOS	digital, analog / mixed	No. of transistors $\leq 50\,000$	
		No. of transistors $>50\,000$ to 50×10^6	
		No. of transistors $>50 \times 10^6$	
	HV (> 50 V)	75	
Programmable ASICs (PLD) non erasable			
Bipolar	TTL	80	
	ECL	85	
CMOS	(anti-fuses)	80	
Programmable ASICs (PLD) erasable			
NMOS, CMOS	RAM basis		80
	EPROM basis	No. of transistors $\leq 5\,000$	70
		No. of transistors $> 5\,000$	80
		Flash-EPROM	80

6.2 Specific stress factors models

6.2.1 Models General

The specific stress models are given for converting the failure rates between different conditions. These stress models contain constants, which are average values for the individual component types, from various manufacturers, determined from field experience and laboratory tests.

~~The failure rate under operating conditions, from Equation (1), is:~~

$$\lambda = \lambda_{\text{ref}} \times \pi_U \times \pi_T \quad \text{for digital CMOS and bipolar analog ICs} \quad (9)$$

$$\lambda = \lambda_{\text{ref}} \times \pi_T \quad \text{for all other ICs} \quad (10)$$

The stress factors for voltage and temperature dependence are specified in 6.2.2 and 6.2.3 respectively.

6.2.2 Voltage dependence, factor π_U

The voltage dependence is only taken into account for digital CMOS and bipolar analog ICs, according to Equation (3). The constants C_1 , C_2 and C_3 given in Table 10 are used, unless other values are stated. The results are shown in Table 11 and Table 12.

Table 10 – Constants for voltage dependence

Integrated circuit	$U_{\text{ref}}/U_{\text{rat}}$	U_{ref}	C_1	C_2	C_3
Digital CMOS-family	–	5 V	0,1 V ⁻¹	1	–
Analog	0,7	–	–	4,4	1,4

Table 11 – Factor π_U for digital CMOS-family ICs

U_{op} (V)	≤3	4	5	6	7	8	9	10	11	12	13	14	15
Factor π_U	0,8	0,9	1	1,1	1,2	1,3	1,5	1,6	1,8	2,0	2,2	2,5	2,7

Table 12 – Factor π_U for bipolar analog ICs

$U_{\text{op}}/U_{\text{rat}}$	≤0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0
Factor π_U	0,75	0,77	0,80	0,87	1,0	1,3	1,8	3,0

6.2.3 Temperature dependence, factor π_T

The relationship given in Equation (6) applies only up to the rated junction temperature. The constants A , Ea_1 and Ea_2 given in Table 13 are used, unless other values have been stated. The results are shown in Table 14 and Table 15.

Table 13 – Constants for temperature dependence

	A	Ea_1 (eV)	Ea_2 (eV)
ICs (except EPROM, OTPROM, EEPROM, EAROM)	0,9	0,3	0,7
EPROM, OTPROM, EEPROM, EAROM	0,3	0,3	0,7

The factor π_T is obtained from Table 14 and Table 15:

- as a function of the actual virtual (equivalent) junction temperature;

$$\theta_{\text{op}} = \theta_{\text{amb}} + P_{\text{op}} \times R_{\text{th,amb}} \text{ in degrees Celsius,} \quad (11)$$

- and as a function of the virtual (equivalent) junction temperature under reference conditions (see 6.1);

$$\theta_{\text{ref}} = 40 + \Delta T_{\text{ref}} \text{ in degrees Celsius,} \quad (12)$$

where ΔT_{ref} is measured or calculated as $\Delta T_{\text{ref}} = P_{\text{ref}} \times R_{\text{th,amb}}$.

Table 14 – Factor π_T for ICs (without EPROM; FLASH-EPROM; OTPROM; EEPROM; EAROM)

θ_{ref} °C (see 6.1)	Factor π_{T} for θ_{op} °C																					
	≤25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	110	120	130	140	150	175
40	0,54	0,67	0,82	1	1,2	1,5	1,8	2,2	2,7	3,3	4,1	5,1	6,3	7,7	9,6	12	18	28	44	67	102	275
45	0,44	0,54	0,67	0,82	1	1,2	1,5	1,8	2,2	2,7	3,4	4,1	5,1	6,3	7,8	9,7	15	23	36	55	83	225
50	0,36	0,45	0,55	0,67	0,82	1	1,2	1,5	1,8	2,2	2,8	3,4	4,2	5,2	6,4	8	12	19	29	45	68	184
55	0,3	0,37	0,45	0,55	0,67	0,82	1	1,2	1,5	1,8	2,3	2,8	3,4	4,2	5,3	6,5	10	16	24	37	56	150
60	0,24	0,3	0,37	0,45	0,55	0,67	0,82	1	1,2	1,5	1,8	2,3	2,8	3,5	4,3	5,3	8,2	13	20	30	46	123
65	0,2	0,24	0,3	0,37	0,45	0,55	0,67	0,82	1	1,2	1,5	1,9	2,3	2,8	3,5	4,4	6,7	10	16	24	37	100
70	0,16	0,2	0,24	0,3	0,37	0,45	0,54	0,67	0,82	1	1,2	1,5	1,9	2,3	2,9	3,6	5,5	8,5	13	20	30	82
75	0,13	0,16	0,2	0,24	0,3	0,36	0,44	0,54	0,66	0,81	1	1,2	1,5	1,9	2,3	2,9	4,5	6,9	11	16	25	67
80	0,11	0,13	0,16	0,2	0,24	0,29	0,36	0,44	0,54	0,66	0,81	1	1,2	1,5	1,9	2,3	3,6	5,69	8,6	13	20	54
85	0,087	0,11	0,13	0,16	0,2	0,24	0,29	0,36	0,44	0,54	0,66	0,81	1	1,2	1,5	1,9	2,9	4,5	7	11	16	44
90	0,07	0,086	0,11	0,13	0,16	0,19	0,24	0,29	0,35	0,43	0,53	0,66	0,81	1	1,2	1,5	2,4	3,7	5,6	8,7	13	36
95	0,057	0,07	0,085	0,1	0,13	0,16	0,19	0,23	0,29	0,35	0,43	0,53	0,65	0,81	1	1,2	1,9	3	4,6	7	11	29
100	0,046	0,056	0,069	0,084	0,1	0,13	0,15	0,19	0,23	0,28	0,35	0,43	0,53	0,65	0,81	1	1,5	2,4	3,7	5,6	8,5	23

Table 15 – Factor π_T for EPROM; FLASH-EPROM; OTPROM; EEPROM; EAROM

θ_{ref} °C (see 6.1)	Factor π_T for θ_{op} °C																					
	≤25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	110	120	130	140	150	175
55	0,16	0,22	0,3	0,41	0,55	0,75	1	1,3	1,8	2,3	3,1	4,0	5,2	6,7	8,6	11	18	28	43	65	96	238

7 Discrete semiconductors

7.1 Specific reference conditions

The following recommendations for reference temperatures given in Table 16 to Table 19 are based on a component ambient temperature of 40 °C and correspond to the majority of applications of components in equipment.

The reference self-heating, $\Delta T_{\text{ref}} = P_{\text{ref}} \times R_{\text{th,amb}}$, ~~shall~~ **should** be given when using other reference temperatures than those stated in the tables. When stating a failure rate for an ambient temperature of 40 °C, the reference power dissipation, P_{ref} , and the thermal resistance, $R_{\text{th,amb}}$, to the environment for which this value holds, ~~shall~~ **should** also be given.

For discrete semiconductors there are two thermal resistances generally considered; one between the junction and the case, the other between the case and the environment. The thermal resistance, $R_{\text{th,amb}}$, above, should be the one that is most significant in the application under consideration.

Table 16 – Transistors common, low frequency

Component		θ_{ref} °C	Note Reference voltage ratio
Bipolar, universal	e.g. TO18, TO92, SOT(D)(3)23 or similar	55	$U_{\text{ref}}/U_{\text{rat}} = 0,5$
Transistor arrays		55	
Bipolar, low power	e.g. TO5, TO39, SOT223, SO8, SMA-SMC	85	
Bipolar, power	e.g. TO3, TO220, D(D)-Pack	100	
FET	junction	55	
	MOS	55	
MOS power (SIPMOS)	e.g. TO3, TO220, D(D)-Pack	100	

Table 17 – Transistors, microwave, (e.g. RF > 800 MHz)

Component		θ_{ref} °C	Note Reference voltage ratio
Bipolar	wide band, small signal	55	$U_{\text{ref}}/U_{\text{rat}} = 0,5$
	power	125	
GaAs FET	small signal low noise	95	
	medium power	110	
	high power	145	
MOSFET	wide band, small signal	55	
	power	125	

Table 18 – Diodes

Component	θ_{ref} °C	Note	
Universal diode (also with avalanche characteristics)	55	---	
Schottky diode	55		
Limiting diode (suppressor diode)	40		
Zener diode ($P_{\text{tot}} < 1 \text{ W}$) voltage protection ^a	40		
Zener diode, power stabilization ^b	100		
Reference diode	45		
Microwave diode, small signal	detector diode		45
	capacitance diode		45
	mixer diode		70
	pin diode		55
Microwave diode, power	storage varactor		100
	gun diode		160
	impatt diode		180
	pin diode		100
High-voltage rectifier diode	85		

^a If applied for voltage protection the calculation can be made without accounting for self-heating ($\theta_{\text{ref}} = 40^{\circ}\text{C}$).

^b If used for stabilization then the calculation ~~shall~~ should take self-heating into account.

Table 19 – Power semiconductors

Component	θ_{ref} °C	Note
Rectifier diodes (also with avalanche characteristics)	70	----
Rectifier bridges	85	
Schottky diodes	85	
Thyristors	85	
Triacs, diacs	85	
Specialized and custom-made power semiconductors	consult manufacturer	

7.2 Specific stress ~~factors~~ models

7.2.1 General

The specific stress models are given for converting the failure rates between different conditions. These stress models contain constants which are average values for the individual component types from various manufacturers (determined from field experience and laboratory tests).

~~6.2.2.2~~ Models

The failure rate under operating conditions, from Equation (2), is as follows:

$$\lambda = \lambda_{\text{ref}} \times \pi_{\text{U}} \times \pi_{\text{T}} \quad \text{for transistors} \quad (13)$$

$$\lambda = \lambda_{\text{ref}} \times \pi_{\text{T}} \quad \text{for diodes and power semiconductors} \quad (14)$$

NOTE 1 Diodes refer to general purpose diodes, Schottky diodes, voltage regulators and Zener diodes.

NOTE 2 Power semiconductors refer to rectifier diodes, bridge diodes, thyristors, triacs and diacs.

The stress factors for voltage and temperature dependence are given in 7.2.2 and 7.2.3 respectively. Current may also be a significant factor.

7.2.2 Voltage dependence for transistors, factor π_U

The voltage dependence is only taken into account for transistors according to Equation (3). The constants C_2 and C_3 given in Table 20 are used, unless other values are stated. The results are shown in Table 21.

Table 20 – Constants for voltage dependence of transistors

$U_{\text{ref}}/U_{\text{rat}}$	C_2	C_3
0,5	8,0	1,4

Table 21 – Factor π_U for transistors

$U_{\text{op}}/U_{\text{rat}}$	$\leq 0,6$	0,65	0,7	0,75	0,8	0,85	0,9	0,95	1
Factor π_U	1	1,04	1,08	1,14	1,26	1,46	1,82	2,52	4

7.2.3 Temperature dependence, factor π_T

The relationship given in Equation (6) applies only up to the maximum permissible junction temperature. The constants A , Ea_1 and Ea_2 given in Table 22 are used, unless other values have been stated. The results are shown in Table 23 and Table 24.

Table 22 – Constants for temperature dependence of discrete semiconductors

Component	A	Ea_1 (eV)	Ea_2 (eV)
Transistors, reference and microwave diodes	0,9	0,3	0,7
Diodes (without reference and microwave diodes)	1,0	0,4	–
Power semiconductors ^a			
^a Rectifier diodes, bridge rectifiers, Schottky diodes, thyristors, triacs and diacs			

The factor π_T is obtained from Table 23 and Table 24:

- as a function of the actual junction temperature;

$$\theta_{\text{op}} = \theta_{\text{amb}} + P_{\text{op}} \times R_{\text{th,amb}} \quad \text{in degrees Celsius,} \quad (15)$$

- and as a function of the junction temperature under reference conditions (see 7.1);

$$\theta_{\text{ref}} = 40 + \Delta T_{\text{ref}} \quad \text{in degrees Celsius,} \quad (16)$$

where ΔT_{ref} is measured or calculated as $\Delta T_{\text{ref}} = P_{\text{ref}} \times R_{\text{th,amb}}$.

θ_{ref} °C (see 7.1)	Factor π_T for θ_{op} °C																										
	≤ 25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	110	120	125	130	140	145	150	160	175	180	200
40	0,54	0,67	0,82	1	1,2	1,5	1,8	2,2	2,7	3,3	4,1	5,1	6,3	7,7	9,6	12	18	28	35	44	67	83	102	153	275	332	689
45	0,44	0,54	0,67	0,82	1	1,2	1,5	1,8	2,2	2,7	3,4	4,1	5,1	6,3	7,8	9,7	15	23	29	36	55	68	83	125	225	272	563
55	0,3	0,37	0,45	0,55	0,67	0,82	1	1,2	1,5	1,8	2,3	2,8	3,4	4,2	5,3	6,5	10	16	19	24	37	45	56	84	150	182	377
70	0,16	0,2	0,24	0,3	0,37	0,45	0,54	0,67	0,82	1	1,2	1,5	1,9	2,3	2,9	3,6	5,5	8,5	11	13	20	25	30	46	82	99	206
85	0,087	0,11	0,13	0,16	0,2	0,24	0,29	0,36	0,44	0,54	0,66	0,81	1	1,2	1,5	1,9	2,9	4,5	5,6	7	11	13	16	24	44	53	110
95	0,057	0,07	0,085	0,10	0,13	0,16	0,19	0,23	0,29	0,35	0,43	0,53	0,65	0,81	1	1,2	1,9	3	3,7	4,6	7	8,6	11	16	29	35	72
100	0,046	0,056	0,069	0,084	0,1	0,13	0,15	0,19	0,23	0,28	0,35	0,43	0,53	0,65	0,81	1	1,5	2,4	3,0	3,7	5,6	6,9	8,5	13	23	28	58
110	0,03	0,036	0,045	0,055	0,067	0,081	0,099	0,12	0,15	0,18	0,22	0,28	0,34	0,42	0,52	0,65	1	1,5	1,9	2,4	3,6	4,5	5,6	8,3	15	18	38
125	0,015	0,019	0,023	0,028	0,035	0,043	0,052	0,063	0,078	0,095	0,12	0,14	0,18	0,22	0,27	0,34	0,52	0,81	1	1,2	1,9	2,3	2,9	4,3	7,8	9,4	20
145	0,006 6	0,008 1	0,009 9	0,012	0,015	0,018	0,022	0,027	0,033	0,041	0,05	0,061	0,076	0,094	0,12	0,14	0,22	0,34	0,43	0,53	0,81	1	1,2	1,85	3,3	4,0	8,3
160	0,003 5	0,005 4	0,004 4	0,006 6	0,008 0	0,009 8	0,012	0,015	0,018	0,022	0,027	0,033	0,041	0,051	0,063	0,074	0,12	0,19	0,24	0,3	0,44	0,54	0,67	1	1,87	2,2	4,6
180	0,001 6	0,002 0	0,002 5	0,003 0	0,003 7	0,004 5	0,005 5	0,006 7	0,008 2	0,01	0,012	0,015	0,019	0,023	0,029	0,036	0,055	0,085	0,11	0,13	0,2	0,25	0,31	0,46	0,83	1	2,1

θ_{ref} °C (see 7.1)	Factor π_T for θ_{op} °C																										
	≤25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	110	120	125	130	140	145	150	160	175	180	200
40	0,47	0,61	0,79	1	1,3	1,6	2	2,4	3	3,7	4,4	5,4	6,5	7,7	9,2	11	15	20	24	27	36	41	47	61	87	98	151
55	0,24	0,31	0,4	0,51	0,64	0,80	1	1,2	1,5	1,9	2,3	2,7	3,3	3,9	4,7	5,5	7,6	10	12	14	18	21	24	31	44	50	77
70	0,13	0,17	0,21	0,27	0,35	0,43	0,54	0,67	0,82	1	1,2	1,5	1,8	2,1	2,5	3,0	4,1	5,6	6,5	7,5	9,9	11,3	13	17	24	27	41
85	0,07 4	0,09 5	0,12	0,16	0,2	0,25	0,31	0,38	0,46	0,57	0,69	0,83	1	1,2	1,4	1,7	2,3	3,2	3,7	4,3	5,6	6,4	7,3	9,5	14	15	23
100	0,04 4	0,05 6	0,07 2	0,09 2	0,12	0,15	0,18	0,22	0,28	0,34	0,41	0,49	0,59	0,71	0,84	1	1,4	1,9	2,2	2,5	3,3	3,8	4,4	5,6	8,0	9,0	14

8 Optoelectronic components

8.1 Specific reference conditions

The following recommendations for reference temperatures given in Table 25 to Table 29 are based on a component ambient temperature of 40 °C and correspond to the majority of applications of components in equipment.

The reference self-heating, $\Delta T_{\text{ref}} = P_{\text{ref}} \times R_{\text{th,amb}}$, ~~shall~~ **should** be given when using reference temperatures other than those stated in the tables.

When stating a failure rate for an ambient temperature of 40 °C, the reference power dissipation, P_{ref} , and the thermal resistance, $R_{\text{th,amb}}$, to the environment for which this value holds, ~~shall~~ **should** also be given.

For optoelectronic components there are two thermal resistances generally considered: one between the junction and the case, the other between the case and the environment. The thermal resistance, $R_{\text{th,amb}}$, above, should be the one that is most significant in the application under consideration.

Table 25 – Optoelectronic semiconductor signal receivers

Component	Reference junction temperature θ_{ref} °C	Note Reference voltage ratio
Phototransistor plastic and hermetically enclosed	45	$U_{\text{ref}}/U_{\text{rat}} = 0,5$
Photodiode (Si and Si PIN, InP, InP APD, Ge, Ge APD)	45	---
Photo element	45	
Detector module	40	
Solar component	40	

Table 26 – LEDs, IREDs, laser diodes and transmitter components

Component	Reference junction temperature θ_{ref} °C	Note Reference current ratio
LED visible light (radial and SMT, large power packages (> 100 mA DC))	45	$I_{\text{ref}}/I_{\text{rat}} = 0,5$
LED IRED ((Al)GaAs, InP)	75	
Laser diode (GaAs 880 nm, InP 1 300 nm, InP 1 500 nm)	75	---
Laser array, pump laser / pump laser cooled (GaAs 980 nm, InP 1 480 nm)	45	
Laser-transmitter modules	consult manufacturer	
Displays (LED)	55	
Displays (LCD, vacuum fluorescence)	consult manufacturer	
Semiconductor optical amplifier (SOA)	45	
Fibre (EDFA)	consult manufacturer	
Modulators (InP, LiNbO ₃)	40	

Table 27 – Optocouplers and light barriers

Component		Reference junction temperature θ_{ref} °C	Note
Optocoupler	with bipolar output	55	---
	with FET output	65	
	with subsequent electronics	55	
	with subsequent power electronics	65	
Light barrier	with diode output / transistor output	55	
	with subsequent electronics	55	

Table 28 – Passive optical components

Component		Reference junction temperature θ_{ref} °C	Note
Optical waveguide connector (n-fold)		40	---
Optical fibre pigtail (one driver and one connector)		40	
Fibre		40	No temperature dependence to consider
Dispersion compensating fibre (DCF)		40	
Isolators		40	
Circulators		40	
Optical multiplexer, demultiplexer (thin film, arrayed-waveguide grating (AWG))		40	
Optical attenuators (fixed value, electromechanical)		40	
Switch (electromagnetical, MEMs)		40	
Coupler, splitter, filter (thin film, Bragg)		40	

Table 29 – Transceiver, transponder and optical sub-equipment

Component		Reference junction temperature θ_{ref} °C	Note
Transceiver, Transponder	SFF, SFP	40	---
	Xponder / Long haul tuneable	Consult manufacturer	
Optical spectrum analyzer (OPA, complex / OSA, complex)			
Active dispersion compensator			
Wavelength selective switch			
Wavelength blocker			
Ground trip current (GTC) interrupter (electro-mechanical)		40	No temperature dependence to consider

8.2 Specific stress factors models

8.2.1 General

The specific stress models are given for converting the failure rates between different conditions. These stress models contain constants. They are average values for the individual component types from various manufacturers (determined from field experience and laboratory tests).

6.3.2.2 Models

The failure rate under operating conditions according to Equation (2) is:

$$\lambda = \lambda_{\text{ref}} \times \pi_U \times \pi_T \quad \text{for phototransistors} \quad (17)$$

$$\lambda = \lambda_{\text{ref}} \times \pi_T \quad \text{for other optical semiconductor signal receivers,} \quad (18)$$

optocouplers and light barriers,
optical waveguide connectors, optical fibre pigtails,
transceivers, transponders

$$\lambda = \lambda_{\text{ref}} \times \pi_I \times \pi_T \quad \text{for light-emitting diodes (LEDs) and infrared-emitting} \quad (19)$$

diodes (IREDs)

$$\lambda = \lambda_{\text{ref}} \quad \text{for other optical components} \quad (20)$$

The stress factors for voltage, current, and temperature dependence are given in 8.2.2 to 8.2.4.

8.2.2 Voltage dependence, factor π_U

The voltage dependence is only taken into account for phototransistors according to Equation (3). The constants C_2 and C_3 given in Table 30 are used, unless other values are stated. The results are shown in Table 31.

Table 30 – Constants for voltage dependence of phototransistors

$\frac{U_{\text{ref}}}{U_{\text{rat}}}$	C_2	C_3
0,5	8,0	1,4

Table 31 – Factor π_U for phototransistors

$\frac{U_{\text{op}}}{U_{\text{rat}}}$	$\leq 0,6$	0,65	0,7	0,75	0,8	0,85	0,9	0,95	1
Factor π_U	1	1,04	1,08	1,14	1,26	1,46	1,82	2,52	4

8.2.3 Current dependence, factor π_I

The current dependence is only taken into account for LEDs and IREDs, according to Equation (4). The constants C_4 and C_5 given in Table 32 are used, unless other values are stated. The results are shown in Table 33.

Table 32 – Constants for current dependence of LEDs and IREDs

$\frac{I_{\text{ref}}}{I_{\text{rat}}}$	C_4	C_5
0,5	1,4	8,0

Table 33 – Factor π_I for LEDs and IREDs

$\frac{I_{\text{op}}}{I_{\text{rat}}}$	$\leq 0,6$	0,65	0,7	0,75	0,8	0,85	0,9	0,95	1
Factor π_I	1	1,04	1,08	1,14	1,26	1,46	1,82	2,52	4

8.2.4 Temperature dependence, factor π_T

The relationship given in Equation (5) applies only up to the maximum permissible junction temperature. The values for the constant Ea_1 given in Table 34 are used, unless other values have been stated. The results are shown in Table 35.

Table 34 – Constants for temperature dependence of optoelectronic components

Component		Ea_1 (eV)
Optical semiconductor signal receiver	Si	0,3
	InP	0,7
	Ge	0,6
Light-emitting diodes (LED)		0,65
Infrared-emitting diodes (IRED)	(Al)GaAs	0,65
	InP	1,0
Semiconductor laser	GaAs	0,6
	InP	0,8
Optocoupler and light barriers		0,5
Optical waveguide connector; optical fibre pigtail		0,3
Transceiver, transponder		0,4

The factor π_T is obtained from Table 35:

- as a function of the actual junction temperature;

$$\theta_{\text{op}} = \theta_{\text{amb}} + P_{\text{op}} \times R_{\text{th,amb}} \quad \text{in degrees Celsius,} \quad (21)$$

- and as a function of the junction temperature under reference conditions (see 8.1);

$$\theta_{\text{ref}} = 40 + \Delta T_{\text{ref}} \quad \text{in degrees Celsius,} \quad (22)$$

where ΔT_{ref} is measured or calculated as $\Delta T_{\text{ref}} = P_{\text{ref}} \times R_{\text{th,amb}}$.

Table 35 – Factor π_T for optical components

Optical semiconductor signal receiver																	
	θ_{ref} °C	Factor π_T for θ_{op} °C															
		≤ 25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Si	40	0,57	0,69	0,83	1	1,2	1,4	1,7	2	2,3	2,6	3,1	3,5	4	4,6	5,3	6
	45	0,48	0,58	0,7	0,84	1	1,2	1,4	1,6	1,9	2,2	2,6	3	3,4	3,9	4,4	5
InP	40	0,27	0,42	0,66	1	1,5	2,2	3,3	4,8	6,8	9,7	14	19	26	36	48	65
	45	0,18	0,28	0,44	0,66	1	1,5	2,2	3,2	4,5	6,4	9	13	17	24	32	43
Ge	40	0,33	0,48	0,7	1	1,4	2	2,8	3,8	5,2	7	9,4	12	16	21	28	36
	45	0,23	0,34	0,49	0,7	1	1,4	1,9	2,7	3,7	4,9	6,6	8,8	12	15	20	25
LED (visible light and IRED)																	
	θ_{ref} °C	Factor π_T for θ_{op} °C															
		≤ 25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
(Al)GaAs	45	0,20	0,31	0,46	0,68	1	1,4	2,1	2,9	4,1	5,6	7,7	11	14	19	25	33
	55	0,099	0,15	0,22	0,33	0,49	0,7	1	1,4	2	2,7	3,7	5,1	6,9	9,2	12	16
	75	0,026	0,04	0,06	0,088	0,13	0,19	0,27	0,38	0,53	0,73	1	1,4	1,8	2,4	3,2	4,3
InP	75	0,004	0,007	0,013	0,024	0,043	0,076	0,13	0,22	0,37	0,62	1	1,6	2,5	4	6,1	9,3
Semiconductor laser																	
	θ_{ref} °C	Factor π_T for θ_{op} °C															
		≤ 25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
GaAs	75	0,035	0,051	0,074	0,11	0,15	0,21	0,3	0,41	0,55	0,75	1	1,3	1,7	2,3	3	3,8
InP	75	0,035	0,051	0,074	0,11	0,15	0,21	0,3	0,41	0,55	0,75	1	1,3	1,7	2,3	3	3,8
Optocoupler and light barrier																	
	θ_{ref} °C	Factor π_T for θ_{op} °C															
		≤ 25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
	55	0,17	0,23	0,32	0,43	0,57	0,76	1	1,3	1,7	2,2	2,8	3,5	4,4	5,5	6,8	8,5
	65	0,1	0,14	0,19	0,25	0,34	0,45	0,59	0,77	1	1,3	1,6	2,07	2,6	3,3	4,05	5,01
Optical waveguide connector; optical fibre pigtail; modulator; wavelength selective switch; wavelength blocker																	
	θ_{ref} °C	Factor π_T for θ_{op} °C															
		≤ 25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
	40	0,57	0,69	0,83	1	1,2	1,4	1,7	2	2,3	2,6	3,1	3,5	4	4,6	5,3	6
Transceiver, transponder																	
	θ_{ref} °C	Factor π_T for θ_{op} °C															
		≤ 25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
	40	0,47	0,61	0,79	1	1,3	1,6	2	2,4	3	3,7	4,4	5,4	6,5	7,7	9,2	11

9 Capacitors

9.1 Specific reference conditions

The recommendations for reference temperatures given in Table 36 are based on a component ambient temperature of 40 °C and correspond to the majority of applications of components in equipment.

Table 36 – Capacitors

Type of capacitor	Reference capacitor temperature θ_{ref} °C	Note Reference voltage ratio
Metal foil Polystyrol, polypropylene, polycarbonate, polyethylene terephthalate	40	50 % of rated voltage at 40 °C $U_{\text{ref}}/U_{\text{rat}} = 0,5$
Metallized film Polypropylene, polycarbonate, polyethylene terephthalate, acetyl cellulose		
Metallized paper (film)		
Mica		
Glass		
Acetyl cellulose		
Ceramic		
Deposited capacitors for hybrid circuits		
Tantalum electrolytic – non-solid electrolyte – solid electrolyte		
Aluminium electrolytic – non-solid electrolyte – solid and polymer electrolyte	40	80 % of rated voltage at 40 °C $U_{\text{ref}}/U_{\text{rat}} = 0,8$
Variable	40	----

9.2 Specific stress factors model

9.2.1 Model General

The failure rate under operating conditions according to Equation (2) is:

$$\lambda = \lambda_{\text{ref}} \times \pi_U \times \pi_T \quad (23)$$

NOTE Aluminium electrolytic components with non-solid electrolyte are electrochemical components with an especially wide technology range. Therefore the given constants and factors are just estimates of the values. More specific values may can be given in the relevant component specifications or may can be agreed upon between user and manufacturer.

The stress factors for voltage and temperature dependence are given in 9.2.2 and 9.2.3.

9.2.2 Voltage dependence, factor π_U

The voltage dependence is only taken into account for fixed capacitors, according to Equation (3).

For variable capacitors, $\pi_U = 1$.

The constants c_2 and c_3 given in Table 37 are used, unless other values are stated. The results are shown in Table 38.

Table 37 – Constants for voltage dependence of capacitors

Type of capacitor	$\frac{U_{ref}}{U_{rat}}$	c_2	c_3
Paper, metallized paper Metallized polypropylene film Metallized polyethylene terephthalate film Metallized cellulose acetate film	0,5	1,07	3,45
Polycarbonate film metal foil Metallized polycarbonate film	0,5	1,50	4,56
Polystyrene film Polyethylene terephthalate film metal foil Polypropylene film metal foil	0,5	1,29	4,0
Glass	0,5	1,11	4,33
Mica	0,5	1,12	2,98
Ceramic	0,5	1,0	4,0
Deposited capacitors for hybrid circuits	0,5	1,0	4,0
Aluminium electrolytic, non-solid electrolyte	0,8	1,0	1,36
Aluminium electrolytic, solid electrolyte	0,8	1,9	3,0
Tantalum electrolytic, non-solid electrolyte	0,5	1,0	1,05
Tantalum electrolytic, solid electrolyte	0,5	1,04	9,8

Table 38 – Factor π_U for capacitors

Type of capacitor	Factor π_U for U_{op}/U_{rat}									
	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
Paper, metallized paper Metallized polypropylene film Metallized polyethylene terephthalate film Metallized cellulose acetate film	0,26	0,36	0,50	0,71	1,0	1,40	2,0	2,9	4,2	6,1
Polycarbonate film metal foil Metallized polycarbonate film	0,23	0,30	0,42	0,63	1,0	1,7	2,9	5,2	9,8	19
Polystyrene film Polyethylene terephthalate film metal foil Polypropylene film metal foil	0,24	0,32	0,45	0,66	1,0	1,5	2,4	3,9	6,4	11
Glass	0,19	0,28	0,42	0,64	1,0	1,6	2,5	4,0	6,3	10
Mica	0,32	0,42	0,55	0,74	1,0	1,4	1,9	2,6	3,6	5
Ceramic	0,20	0,30	0,45	0,67	1,0	1,5	2,2	3,3	5,0	7,4
Deposited capacitors for hybrid circuits	0,20	0,30	0,45	0,67	1,0	1,5	2,2	3,3	5,0	7,4
Aluminium electrolytic, non-solid electrolyte	0,39	0,44	0,51	0,58	0,67	0,76	0,87	1,0	1,2	1,3
Aluminium electrolytic, solid electrolyte	0,15	0,16	0,19	0,24	0,31	0,44	0,64	1,0	1,6	2,8
Tantalum electrolytic, non-solid electrolyte	0,66	0,73	0,81	0,90	1,0	1,1	1,2	1,4	1,5	1,7
Tantalum electrolytic, solid electrolyte	0,021	0,054	0,14	0,37	1,0	2,7	7,4	20	56	154

9.2.3 Temperature dependence, factor π_T

The relationship given in Equation (6) applies only up to the maximum permissible component temperature. The constants A , Ea_1 and Ea_2 given in Table 39 are used, unless other values have been stated. The results are shown in Table 40.

Table 39 – Constants for temperature dependence of capacitors

Type of capacitor	A	Ea_1 eV	Ea_2 eV
Paper Metallized paper Metallized polypropylene film Metallized polyethylene terephthalate film Metallized acetyl cellulose film Polyethylene terephthalate film metal foil Polypropylene film metal foil Polystyrene film metal foil Metallized paper film	0,999	0,5	1,59
Polycarbonate film metal foil, Metallized polycarbonate film	0,998	0,57	1,63
Glass, mica	0,86	0,27	0,84
Ceramic	1,0	0,35	–
Deposited capacitors for hybrid circuits	1,0	0,15	–
Aluminium electrolytic, non-solid electrolyte	0,87	0,5	0,95
Aluminium electrolytic, solid electrolyte	0,40	0,14	0
Tantalum electrolytic, non-solid electrolyte	0,35	0,54	0
Tantalum electrolytic, solid electrolyte	0,961	0,27	1,1
Variable	1,0	0,15	–

The factor π_T is obtained from Table 40:

- as a function of the actual capacitor temperature;

$$\theta_{\text{op}} = \theta_{\text{amb}} + \Delta T \quad \text{in degrees Celsius,} \quad (24)$$

where ΔT is the temperature change due to operating conditions;

- and as a function of the capacitor temperature under reference conditions (see Table 36);

$$\theta_{\text{ref}} = 40^\circ\text{C} \quad (25)$$

Table 40 – Factor π_T for capacitors

Type of capacitor	Capacitor temperature under reference conditions θ_{ref} °C	Factor π_T for θ_{op} °C ^a													
		≤ 20	30	40	50	60	70	80	85	90	100	105	110	120	125
Paper, Metallized paper, Metallized polypropylene film, Metallized polyethylene terephthalate film, Metallized acetyl cellulose film, Polyethylene terephthalate film metal foil, Polypropylene film metal foil, Polystyrene film metal foil, Metallized paper film	40	0,28	0,54	1,0	1,8	3,1	5,2	9	12	16	33	49	77	210	350
Polycarbonate film metal foil, Metallized polycarbonate film	40	0,24	0,50	1,0	1,9	3,6	6,7	13	18	27	63	100	170	510	900
Glass, mica	40	0,45	0,67	1,0	1,5	2,5	4,2	7,5	10	-	-	-	-	-	-
Ceramic	40	0,41	0,65	1,0	1,5	2,2	3,1	4,4	5,1	6	8,1	9,3	11	14	16
Aluminium electrolytic, non-solid electrolyte	40	0,26	0,51	1,0	1,9	3,7	7,2	14	20	28	55	77	110	210	290
Deposited capacitors for hybrid circuits	40	0,68	0,83	1,0	1,2	1,4	1,6	1,9	2	2,2	2,5	2,6	2,8	3,1	3,3
Aluminium electrolytic, solid electrolyte	40	0,88	0,94	1,0	1,1	1,2	1,2	1,3	1,4	1,4	1,5	1,6	1,6	1,8	1,8
Tantalum electrolytic, non-solid electrolyte	40	0,74	0,83	1,0	1,3	1,8	2,7	4	5	-	-	-	-	-	-
Tantalum electrolytic, solid electrolyte	40	0,49	0,7	1,0	1,45	2,2	3,7	7	10	15	32	49	73	170	250
Variable	40	0,68	0,83	1,0	1,2	1,4	1,6	1,9	2	2,2	2,5	2,6	2,8	3,1	3,3
^a The relationships given apply up to the rated capacitor temperature only.															

10 Resistors and resistor networks

10.1 Specific reference conditions

The recommendations for reference resistor element temperatures given in Table 41 are based on a component ambient temperature of 40 °C and correspond to the majority of applications of components in equipment. The reference self-heating, ΔT_{ref} , ~~shall~~ **should** be given when using other reference temperatures.