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.

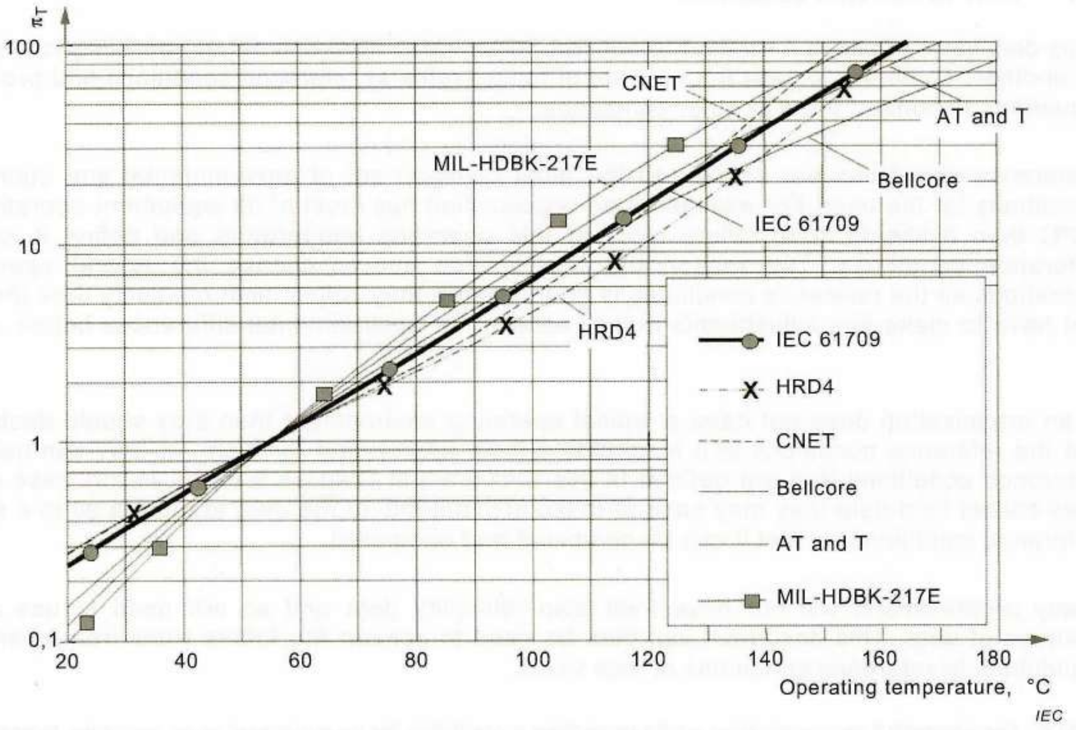

Figure 1 – Comparison of the temperature dependence of π_T for CMOS IC

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 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. 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 can be used by an organization unless they are not appropriate to the normal working conditions of that organization's equipment. Any

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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.

Table 3 – Recommended reference conditions for environmental and mechanical stresses

Type of stress	Reference condition[a]
Ambient temperature[b]	θ_0 = 40 °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, 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:

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

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

$$\pi_\text{U} = \exp\left\{ C_3 \left[\left(\frac{U_\text{op}}{U_\text{rat}} \right)^{C_2} - \left(\frac{U_\text{ref}}{U_\text{rat}} \right)^{C_2} \right] \right\} \tag{3}$$

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 $\pi_\text{U} = \exp\left\{ C_1 \left(U_\text{op}^{C_2} - U_\text{ref}^{C_2} \right) \right\}$ where $C_1 = C_3 / U_\text{rat}^{C_2}$.

5.2.3 Stress factor for current dependence, π_I

$$\pi_\text{I} = \exp\left\{ C_4 \left[\left(\frac{I_\text{op}}{I_\text{rat}} \right)^{C_5} - \left(\frac{I_\text{ref}}{I_\text{rat}} \right)^{C_5} \right] \right\} \tag{4}$$

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

$$\pi_\text{T} = \exp\left[\frac{Ea_1}{k_0} \left(\frac{1}{T_\text{ref}} - \frac{1}{T_\text{op}} \right) \right] \tag{5}$$

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 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}.

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

with the auxiliary variables

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

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_{ref}	$= \left(\theta_{\text{ref}} + 273\right)$ in K;
T_{op}	$= \left(\theta_{\text{op}} + 273\right)$ 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}

Some data handbooks contain guidance on transferring a failure rate estimate from one general environmental condition to another. The concept is logical, but it 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.

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), the influence on the environmental application conditions 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 best practical solution 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 E1	Stationary use at partially weather-protected or non-weather-protected locations E2	Portable and non-stationary use, ground vehicle installation 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) $\pi_{\text{S}} = 1$ for $0{,}01 \leq S \leq S_{\text{ref}}$ (7)

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

where

S is the number of operating cycles per hour;

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

NOTE 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 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, $\Delta T_{ref} = P_{ref} \times R_{th,amb}$, should be given when using reference temperatures other that 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, 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 ≤ 50 000	70	
	No. of transistors > 50 000	90	
CMOS	No. of transistors ≤ 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	Reference voltage
Bipolar	TTL, -LS, -A(L)S, -F	Logic	45	---
	Bus interface		55	
	TTL S	Logic + bus interface	80	
	ECL	10 000 100 000 10(LV)E(L) / 100(LV)E(I)(P)	65 75 60	
CMOS	HCMOS, CMOS B, ACMOS (FCT, HC, A(U),C, LVX), (LVC, LCX, LV) (VCX, ALVC, AVC, AHC, VHC) Logic Analog switches, Bus interface		45	$U_{\text{ref}} = 5\text{V}$
	Bus interface	GTL(p)	50	
	Bus driver / receiver RS422, RS423, RS485, CAN, etc. RS232, RS644/899, CML, etc.		55	
BICMOS	Logic		45	---
	Bus interface	ABT, BCT LVT, ALVT GTL(p) BTL, ETL	50 50 50 95	
	Bus driver / receiver		55	

Table 8 – Analog ICs

Component		θ_{ref} °C	**Reference voltage ratio**
Operational amplifiers, comparators and voltage monitors	Bipolar, BIFET CMOS	55 45	$U_{ref}/U_{rat} = 0{,}7$
Reference elements	all technologies	45	---
Switch regulators	all technologies	55	
Power amplifiers and regulators (all technologies)	≤ 1 W > 1 W	70 90	
High frequency IC (> 100 MHz)			
HF modulator, demodulator PLL, VCO	bipolar CMOS, BICMOS	65 45	
Transmitter, receiver	bipolar CMOS, BICMOS	70 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 ≤ 50 000 No. of transistors >50 000 to 50 × 10^6 No. of transistors >50 × 10^6	55 70 80	
	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 EEPROM basis Flash-EPROM	No. of transistors ≤ 5 000 No. of transistors > 5 000	70 80 80	

6.2 Specific stress models

6.2.1 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.

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

$\lambda = \lambda_{\text{ref}} \times \pi_{\text{T}}$ for all other ICs (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	0,6

The factor π_{T} is obtained from Table 14 and Table 15:

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

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

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

$\theta_{\text{ref}} = 40 + \Delta T_{\text{ref}}$ in degrees Celsius, (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, $\Delta T_{\mathrm{ref}} = P_{\mathrm{ref}} \times R_{\mathrm{th,\,amb}}$, 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, $R_{\mathrm{th,\,amb}}$, to the environment for which this value holds, 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, $R_{\mathrm{th,amb}}$, above, should be the one that is most significant in the application under consideration.

Table 16 – Transistors common, low frequency

Component		θ_{ref} °C	Reference voltage ratio
Bipolar, universal	e.g. TO18, TO92, SOT(D)(3)23 or similar	55	$U_{\mathrm{ref}}/U_{\mathrm{rat}} = 0,5$
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	Reference voltage ratio
Bipolar	wide band, small signal	55	$U_{\mathrm{ref}}/U_{\mathrm{rat}} = 0,5$
	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 ($P_{\text{tot}} < 1$ 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 ($\theta_{\text{ref}} = 40$°C).

[b] If used for stabilization then the calculation 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 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).

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

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

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

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_{ref}/U_{rat}	C_2	C_3
0,5	8,0	1,4

Table 21 – Factor π_U for transistors

U_{op}/U_{rat}	≤ 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) Power semiconductors [a]	1,0	0,4	–
[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;

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

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

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

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

Table 23 – Factor π_T for transistors, reference and microwave diodes

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	0,0066	0,0081	0,0099	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	0,0035	0,0054	0,0044	0,0066	0,0080	0,0098	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	0,0016	0,0020	0,0025	0,0030	0,0037	0,0045	0,0055	0,0067	0,0082	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

Table 24 – Factor π_T for diodes (without reference and microwave diodes) and power semiconductors

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	0,074	0,095	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	0,044	0,056	0,072	0,092	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

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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, $\Delta T_{\text{ref}} = P_{\text{ref}} \times R_{\text{th, amb}}$, 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, 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	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	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 florescence)	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 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).

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

$\lambda = \lambda_{\text{ref}} \times \pi_{\text{U}} \times \pi_{\text{T}}$ for phototransistors (17)

$\lambda = \lambda_{\text{ref}} \times \pi_{\text{T}}$ for other optical semiconductor signal receivers, optocouplers and light barriers, optical waveguide connectors, optical fibre pigtails, transceivers, transponders (18)

$\lambda = \lambda_{\text{ref}} \times \pi_{\text{I}} \times \pi_{\text{T}}$ for light-emitting diodes (LEDs) and infrared-emitting diodes (IREDs) (19)

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

$\frac{U_{\text{op}}}{U_{\text{rat}}}$	**≤ 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

$\frac{I_{\text{op}}}{I_{\text{rat}}}$	**≤ 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;

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

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

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

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	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 model

9.2.1 General

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

$$\lambda = \lambda_{\text{ref}} \times \pi_{\text{U}} \times \pi_{\text{T}} \tag{23}$$

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 can be given in the relevant component specifications or 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, $\pi_{\text{U}} = 1$.

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

	Factor π_U for U_{op}/U_{rat}									
Type of capacitor	**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;

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

where ΔT is the temperature change due to operating conditions;

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

$$\theta_{ref} = 40\,°C \tag{25}$$

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}, should be given when using other reference temperatures.

Table 41 – Resistors and resistor networks

Component	Reference resistor element temperature θ_{ref} °C	Reference power ratio
Carbon film	55	50 % of rated power at 40 °C $P_{\text{ref}}/P_{\text{rat}} = 0{,}5$
Metal film	55	
Deposited thin film resistors for hybrid circuits	55	
Deposited thick film resistors for hybrid circuits	55	
Networks (film circuits) per resistor element	55	
Metal-oxide	85	
Wire-wound	85	
Variable	55	

10.2 Specific stress models

10.2.1 General

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

$$\lambda = \lambda_{\text{ref}} \times \pi_{\text{T}} \tag{26}$$

The stress factors for temperature dependence are given in 10.2.2.

10.2.2 Temperature dependence, factor π_{T}

The relationship given in Equation (6) applies only up to the maximum permissible resistor element temperature. The constants A, Ea_1 and Ea_2 given in Table 42 are used, unless other values have been stated. The results are shown in Table 43.

Table 42 – Constants for temperature dependence of resistors

A	Ea_1 eV	Ea_2 eV
0,873	0,16	0,44

The factor π_{T} is obtained from Table 43:

- as a function of the average actual temperature of the resistor element;

$$\theta_{\text{op}} = \theta_{\text{amb}} + \Delta T \quad \text{in degrees Celsius,} \tag{27}$$

where, $\Delta T = P_{\text{op}} \times R_{\text{th,amb}} = (\theta_{\max} - 40) \times (P_{\text{op}}/P_{\text{rat}})$ in degrees Celsius, is the temperature change due to operation (with $\theta_{\max}$ as maximum resistor element temperature);

- and as a function of the average temperature of the resistor element under reference conditions (see Table 41);

$$\theta_{\text{ref}} = 40 + \Delta T_{\text{ref}} \tag{28}$$

Table 43 – Factor π_T for resistors

Component	θ_{ref} °C (see 10.1)	Factor π_T for θ_{op} °C											
		≤ 25	30	40	50	60	70	80	90	100	110	120	125
Resistors	55	0,49	0,56	0,71	0,89	1,1	1,4	1,8	2,2	2,8	3,6	4,6	5,1
	85	0,25	0,28	0,35	0,45	0,56	0,71	0,89	1,1	1,4	1,8	2,3	2,6

11 Inductors, transformers and coils

11.1 Reference conditions

The recommendations for reference temperatures given in Table 44 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}, should be given when using other reference temperatures.

Table 44 – Inductors, transformers and coils

Component		Average reference winding temperature θ_{ref} °C	Reference power ratio
Inductors for EMC applications	≤ 3A > 3A	60 85	50 % of rated power at 40 °C $P_{ref}/P_{rat} = 0,5$
Low frequency inductors and transformers	≤ 25 kHz	55	
High frequency inductors and transformers	> 25 kHz	55	
Mains transformers and transformers for switched-mode power supplies		85	

11.2 Specific stress model

11.2.1 General

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

$$\lambda = \lambda_{ref} \times \pi_T \tag{29}$$

The stress factors for temperature dependence are given in 11.2.2.

11.2.2 Temperature dependence, factor π_T

The relationship given in Equation (6) applies only up to the maximum permissible winding temperature. The constants A, Ea_1 and Ea_2 given in Table 45 are used, unless other values have been stated. The results are shown in Table 46.

Table 45 – Constants for temperature dependence of inductors, transformers and coils

A	Ea_1 eV	Ea_2 eV
0,996	0,06	1,13

The factor π_T is obtained from Table 46:

- as a function of the actual average winding temperature;

  $$\theta_{op} = \theta_{amb} + \Delta T \quad \text{in degrees Celsius} \tag{30}$$

  where ΔT is the temperature change due to operating conditions;
- and as a function of the average winding temperature under reference conditions (see Table 44);

  $$\theta_{ref} = 40 + \Delta T_{ref} \quad \text{in degrees Celsius} \tag{31}$$

  where ΔT_{ref} is measured or calculated at $0{,}5 \times P_{rat}$.

Table 46 – Factor π_T for inductors, transformers and coils

Component	θ_{ref} °C (see 11.1)	Factor π_T for θ_{op} °C												
		≤ 25	30	40	50	60	70	80	85	90	100	110	120	125
Inductors, transformers, coils	55	0,79	0,82	0,89	0,96	1,1	1,2	1,5	1,9	2,3	4,3	8,8	19	29
	60	0,75	0,78	0,84	0,91	1	1,1	1,5	1,8	2,2	4	8,4	18	27
	85	0,43	0,44	0,48	0,52	0,57	0,66	0,83	1	1,3	2,3	4,8	10	15

12 Microwave devices

12.1 Specific reference conditions

The reference conditions are given in Table 47.

Table 47 – Microwave devices

Component	Reference component temperature θ_{ref} °C	Note
Microwave elements	40	Temperature and electrical stress have no impact on the failure rates.
Coaxial and wave guides		
Load		
Attenuator fixed		
Attenuator variable		
Fixed elements		
Directional couplers		
Fixed stubs		
Cavities		
Variable elements		
Tuned stubs	40	
Tuned cavities		
Ferrite device (transmitter)		
Ferrite device (receiver)		
RF/microwave passives		
Filter		
Isolator		
Circulator		
Splitter/combiner		
Synthesizer		

12.2 Specific stress models

No models are currently known from experience in applying temperature and electrical stresses.

13 Other passive components

13.1 Specific reference conditions

The reference conditions are given in Table 48.

Table 48 – Other passive components

Component	Reference component temperature θ_{ref} °C	Note
Varistors	40	Temperature and electrical stress have no impact on the failure rates.
PTC thermistors, NTC thermistors		
Surge arresters		
Ceramic resonators		
Filters		
Surface wave filters (SAW), Surface wave oscillators (SAW-oscillators), voltage controlled oscillators (VCO)		
Piezoelectric components (transducers and sensors)		
Crystals		
Crystal oscillators: XO (clock), VCXO (voltage controlled), TCXO (temperature compensated), OCXO (oven controlled)		
Feed-through capacitors, feed-through filters		
Fuses		

13.2 Specific stress models

No models are currently known from experience in applying temperature and electrical stresses.

14 Electrical connections

14.1 Specific reference conditions

The reference conditions are given in Table 49.

Table 49 – Electrical connections

Component	Conductor cross-section mm^2	θ_{ref} °C	Reference current ratio
Solder (manual, machine)	-	40	50 % of rated current for the connected conductor $I_{\text{ref}} / I_{\text{rat}} = 0{,}5$
Wire bond for hybrid circuits (Al, Au)	-		
Wire-wrap	0,05 to 0,5		
Crimp (manual, machine)	0,05 to 300		
Termi-point	0,1 to 0,5		
Press in	0,3 to 2		
Insulation displacement	0,05 to 1		
Screw	0,5 to 16		
Clamp (elastic force)	0,5 to 16		

14.2 Specific stress models

No models are currently known from experience in applying temperature and electrical stresses.

15 Connectors and sockets

15.1 Reference conditions

The reference conditions are given in Table 50.

Table 50 – Connectors and sockets

Component		θ_{ref} °C	Note
Plug-in contacts that should be inserted without electrical load (gold or comparably corrosion-resistant, silver, tin, others) NOTE These also include connectors that can be inserted with a limited electrical load according to the data sheet.		40	Operating current within the limits stated in the data sheet
Plug-in contacts that are intended to be inserted under electrical load			
Coaxial plugs			
Time period:	Up to the time interval that 90 % of the components survive.		
Duty cycle:	For the electrical stress, the duty cycle is continuously or intermittently in operating state.		
Plugging frequency:	≤ 1 plugging cycle per 1 000 hours.		

15.2 Specific stress models

No models are currently known from experience in applying temperature and electrical stresses.

16 Relays

16.1 Reference conditions

Information contained in Clause 16 does not cover all today's relays technology.

The reference conditions are given in Table 51.

Table 51 – Relays

Component	Electrical contact stress	θ_{ref} °C	Reference number of operating cycles per hour
Low duty relays:	$(0{,}5 < U \leq U_{\text{rat}})$ V AC and $(0 < I \leq 0{,}1)$ A by resistive load	40	$\pi_{\text{S}} = 1$
General purpose relays:	$(0 < U \leq 13)$ V and $(0{,}1 < I \leq I_{\text{rat}})$ A by resistive load and AC		
Automotive relays:	$(0 < U \leq 13)$ V and $(0{,}1 < I \leq I_{\text{rat}})$ A by resistive load		
Operating current within the limits stated in the data sheet			
Electrical contact stress (See stress regions in 16.2.3, Figure 2)			
Time period:	Up to the time interval that 90 % of the relays survive.		
Duty cycle:	The duty cycle can be chosen within the limits set by the relay's specification (for coil and contact assembly).		
Operating cycles:	Up to the maximum number of operating cycles specified in the data sheet.		

16.2 Specific stress models

16.2.1 General

The failure rate under operating conditions is:

$$\lambda = \lambda_{\text{ref}} \times \pi_{\text{ES}} \times \pi_{\text{S}} \times \pi_{\text{T}} \tag{32}$$

where

π_{ES} is the electrical stress dependence factor;

π_{S} is the switching rate dependence factor;

π_{T} is the temperature dependence factor.

The values of the stress factors are given in 16.2.3 and 16.2.4.

16.2.2 Dependence on switching rate, factor π_{S}

The factor π_{S} considers the number of operating cycles per hour, S, according to Equations (7) and (8). Factor π_{S} is not defined for $S < 0{,}01$.

a) $\pi_{\text{S}} = 1$ for $0{,}01 \leq S \leq S_{\text{ref}}$ (33)

b) $\pi_{\text{S}} = S/S_{\text{ref}}$ for $S > S_{\text{ref}}$ (34)

where

S is the number of operating cycles per hour;

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

NOTE 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.

16.2.3 Dependence on electrical stress, factor π_{ES}

The factors π_{ES} given in Table 52 to Table 54 are based on the selection of the stress region in Figure 2 and the type of load.

Contacts where surge suppression is used can be treated like contacts under resistive load.

The rated current I_{rat} and the rated switching voltage U_{rat} are obtained from the relay detail specification of the individual relay type.

If different electrical stress conditions are used, a mission profile should be considered (otherwise the higher stress factor should be applied).

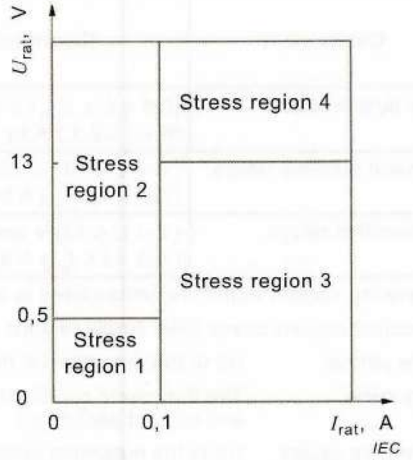

Figure 2 – Selection of stress regions in accordance with current and voltage-operating conditions

Table 52 – Factor π_{ES} for low current relays

Stress region (see Figure 2)	**Factor π_{ES} for:** Resistive load	Capacitive[a] and incandescent lamp load	Inductive load
1	2	2	–
2	1	8	8
3	2	20	40
4	8	40	–

[a] Maximum current peak (see relay detail specification) not to be exceeded.

Table 53 – Factor π_{ES} for general purpose relays

Stress region (see Figure 2)	**Factor π_{ES} for:** Resistive load DC	Resistive load AC	Capacitive[a] and incandescent lamp load DC	Capacitive[a] and incandescent lamp load AC	Inductive load DC	Inductive load AC
1 without Au-coating	50	50	2	1	–	–
1 with Au-coating	20	10	2	1	–	–
2	20	10	10	5	10	5
3	2	1	10	5	20	10
4	10	2	10	5	50	20

[a] Maximum current peak (see relay detail specification) not to be exceeded.

Table 54 – Factor π_{ES} for automotive relays

Stress region (see Figure 2)	Factor π_{ES} [a] for: Resistive load	Capacitive[b] and incandescent lamp load	Inductive load
3	1	2 (1)	2 (1)
4	1	2 (1)	5 (1)

[a] Values in parentheses are valid for tungsten pre-contact.

[b] Maximum current peak (see relay detail specification) not to be exceeded.

16.2.4 Temperature dependence, factor π_T

The relationships given in Equations (5) and (6) apply only up to the maximum permissible component temperature. The formula constants A, Ea_1 and Ea_2 given in Table 55 are used, unless other values have been stated.

Table 55 – Constants for temperature dependence of relays

Supporting construction	A	Ea_1 eV	Ea_2 eV
Plastic	1,0	0,175	–
Metal, glass, ceramic	0,006	0,646	0

The calculated factors π_T are shown in Table 56 and are dependent on the ambient temperature, θ_{amb} .

Table 56 – Factor π_T for relays

Supporting construction	Factor π_T for the average ambient temperature θ_{amb} [a] ≤ 40 °C	70 °C	100 °C	125 °C
Plastic	1	1,8	2,8	4
Metal, glass, ceramic	1	1	1,3	2

[a] Valid only up to the maximum permissible ambient temperature according to the relay detail specification.

17 Switches and push-buttons

17.1 Specific reference conditions

The reference conditions are given in Table 57.

Table 57 – Switches and push-buttons

Component	Electrical contact stress	θ_{ref} °C	Note
Dip fix and encoding switches:	within the limits of the data sheet	---	Operating current within the limits stated in the data sheet
Switches and push-buttons for light-current applications:	$(0{,}5 < U \leq U_{\text{ref}})$ V AC and $(0{,}1 < I \leq I_{\text{ref}})$ A by resistive load		Electrical contact stress (see stress regions in Figure 3)
Switches and push-buttons for higher load:	$(0{,}5 < U \leq 13)$ V and $(0{,}1 < I \leq I_{\text{ref}})$ A by resistive load		
Time period:	Up to the time interval that 90 % of the switches and push-buttons survive.		
Duty cycle:	The duty cycle can be chosen within the limits set by the specification.		

17.2 Specific stress model

17.2.1 General

The failure rate under operating conditions is:

$$\lambda = \lambda_{\text{ref}} \times \pi_{\text{ES}} \qquad (35)$$

where π_{ES} is the electrical stress dependence factor. The values of the stress factors are given in 17.2.2.

17.2.2 Dependence on electrical stress, factor π_{ES}

a) for dip fix, coding switches and foil push-buttons:

$\pi_{\text{ES}} = 1$

b) for other switches and push-buttons:

The factors π_{ES} given in Table 58 and Table 59 are based on the selection of the stress region in Figure 3 and the type of load.

The rated current I_{rat} and the rated switching voltage U_{rat} are obtained from the data sheet of the individual switches and push-button types.

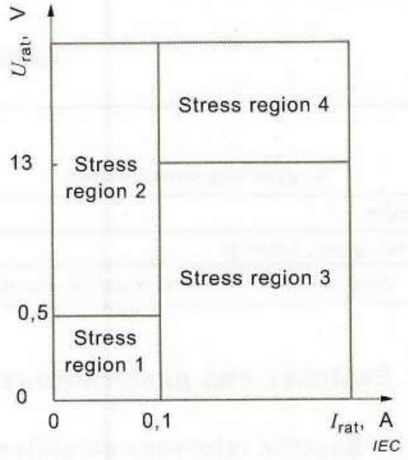

Figure 3 – Selection of stress regions in accordance with current and voltage-operating conditions

Table 58 – Factor π_{ES} for switches and push-buttons for low electrical stress

Stress region (see Figure 3)	Factor π_{ES} for:		
	Resistive load	Capacitive[a] and incandescent lamp load	Inductive load
1	2	2	–
2	1	8	8
3	2	20	40
4	8	40	–

[a] Maximum current peak (see data sheet) not to be exceeded.

Table 59 – Factor π_{ES} for switches and push-buttons for higher electrical stress

Stress region (see Figure 3)	Factor π_{ES} for:					
	Resistive load		Capacitive[a] and incandescent lamp load		Inductive load	
	DC	AC	DC	AC	DC	AC
1 Without Au-coating	50	50	2	1	–	–
1 With Au-coating	20	10	2	1	–	–
2	20	10	10	5	10	5
3	2	1	10	5	20	10
4	10	2	10	5	50	20

[a] Maximum current peak (see data sheet) not to be exceeded.

18 Signal and pilot lamps

18.1 Specific reference conditions

The reference conditions are given in Table 60.

Table 60 – Signal and pilot lamps

Component	Ambient temperature θ_{ref} °C	Note
Incandescent lamps	40	Rated voltage according to specifications
Glow lamps		

Time period: Up to the time interval that 93,5 % of the lamps survive.

Duty cycle: The duty cycle is continuously in operating state; for intermittent operation the operating time is the sum of the periods alight.

18.2 Specific stress model

18.2.1 General

The failure rate under operating conditions, as a function of the operating voltage, is calculated according to Equation (2) as follows:

$$\lambda = \lambda_{ref} \times \pi_U \qquad (36)$$

18.2.2 Voltage dependence, factor π_U

The stress factor π_U for voltage dependence is given in Table 61.

Table 61 – Factor π_U for signal and pilot lamps

Type of lamp		Factor π_U for U_{op}/U_{rat}										
		≤ 0,70	0,80	0,85	0,90	0,95	1,0	1,05	1,1	1,15	1,2	1,30
Incandescent lamps	Signal and pilot lamps; railway-signalling lamps; low voltage traffic-light lamps	0,02	0,10	0,20	0,30	0,60	1,0	1,70	3,0	4,50	7,0	17,0
	Halogen lamps	–	–	–	–	0,60	1,0	1,7	3,0	–	–	–
	High voltage traffic-light lamps	–	–	–	–	0,60	1,0	2,0	4,0	–	–	–
Glow lamps	(with necessary series resistance)	–	–	–	0,5	0,7	1	1,3	1,6	2,0	–	–

NOTE 1 The failure rate, irrespective of construction and stress, may be higher for DC operation, higher ambient temperature, stress due to mechanical impact and electrical surges, or non-standard switching profiles.

NOTE 2 Consult the manufacturer for additional information.

19 Printed circuit boards (PCB)

Failures of PCBs should be taken into account in the stated failure rate for machine-soldered connections (see 14.1).

20 Hybrid circuits

A hybrid integrated circuit, hybrid microcircuit, or simply hybrid, is a miniaturized electronic circuit manufactured of individual devices, such as semiconductor devices (transistors and diodes) and passive components (resistors, inductors, transformers, and capacitors), bonded to a substrate or printed circuit board. A hybrid circuit is a circuit where two or more technologies are combined (SMD, ASIC and flexible circuit technology). Hybrid circuits have gradually become synonymous with circuits, where one of the methods used is thick film technology, whereby tracks and resistors are printed on a ceramic substrate.

A hybrid circuit is not considered a component in this document, in agreement with what is declared in its introduction and scope. In fact a hybrid is to be considered an assembly, also if miniaturized, but not an electric component.

Deposited capacitors and thick or thin film resistors are considered in the specific component clauses.

Annex A
(normative)

Failure modes of components

The failure mode is a description of what constitutes failure for a particular component type. There are generally three types of failure – complete, partial or degraded and drift – however most data handbooks do not make this distinction, giving a total failure rate of a component that represents failure in all modes.

However information on failure modes is useful since it is the rate of occurrence of failure modes that is observed. This information is also a useful input into reliability analysis, such as diagnostics coverage, and in safety analysis in order to calculate criticality of systems.

Annex A contains details on failure modes that are useful for this purpose. These modes are higher level, usually as perceived at circuit level, than the actual physical modes that they represent and will often include within them a number of lower level modes.

The data presented herein has been derived from a number of sources such as those listed in Annex H and in IEC TR 62380. The tables give a means of allocating estimated failure rate to specific failure modes when given a specific value for total failure rate.

For prediction purposes, component failure modes can be found in Table A.1 to Table A.7.

Table A.1 – Failure modes: ICs (digital)

Environment type	Input/output fixed to 1 Stuck at U_{cc} %	Input/output fixed to 0 Stuck at ground %	Open circuit %
Stationary use at weather-protected locations E1[a]	50	50	-
Stationary use at partially weather-protected or non-weather-protected locations E2[a] Portable and non-stationary use, ground vehicle installation E3[a]	5	5	90

NOTE For digital ICs the signal pins can be defined as inputs or outputs. When a failure occurs, for each input or output pin, there are three chances:

- the (internal) failure caused the signal to be fixed at the logical level=1;
- the (internal) failure caused the signal to be fixed at logical level=0;
- the pin is no more internally connected.

The logical level=1, in terms of voltage, is usually the value of U_{cc} (positive supply voltage), while the logical level=0 is usually ground ($U = 0$).

Sometimes there are different voltages, hence it is more appropriate to speak in terms of stuck-at-1 or stuck-at-0 for the fixed signal at the failed pin.

For interface circuits, almost all defects are open circuits.

[a] See Table 1.

Table A.2 – Failure modes: transistors, diodes, optocouplers

		Short circuit %	Open circuit %	Drift %	Forward leakage current drift %
Transistors	Silicon	85	15		-
	GaAs	95	5		-
Diodes	Silicon	80	20		-
	GaAs	95	5		-
Zener diodes		70	20	10	
Thyristors		20	20		60
Optocouplers		10	50	40	-
Laser diodes		85	15	-	-

Table A.3 – Failure modes: LEDs

	Short circuit (forward degradation) %	Open circuit %	Optical coupling, or fibre %
Light emitting diode modules package type: with window	70	10	20
Light emitting diode modules package type: with fibre	40	10	50

Table A.4 – Failure modes: laser diodes and modules

	Diode failure %	Coupling failure %	Broken fibre %
Laser diodes modules 1,3 μm/1,55 μm modules	(degradation of the spectrum, current increase) 10	(high drop in output power) 90	-
Pump laser modules (0,98 μm 1,48 μm)	(high current increase) 90	(high drop in output power) 10	-
Modules (transmission) 0,85 μm modules (monomode fibre 9/125)	(no laser effect, degradation of the spectrum, current increase) 80	(high drop in output power) 10	(no output power) 10
Compact disks 0,85 μm modules (monomode fibre 9/125)	(no laser effect, degradation of the spectrum, current increase) 100	-	-

Table A.5 – Failure modes: photodiodes and receiver modules

	Short circuit (reverse degradation) %	Open circuit %	Coupling %
Photodiodes and receiver modules for telecommunications package type: with window	80	20	-
Photodiodes and receiver modules for telecommunications package type: with fibre	40	10	50

Table A.6 – Failure modes: capacitors

			Short circuit %	Open circuit %	Drift %
Ceramic	NPO-COG Fixed ceramic dielectric capacitors – Defined temperature coefficient – Class I		70	10	20
	X7R-X5R		90	10	-
	5ZU-Y5V-Y4T		90	10	-
	Feedthrough capacitors		70	30	-
Aluminium electrolytic	non-solid electrolyte	nominal voltage < 350 V	30	30	40
		nominal voltage > 350 V	50	-	50
	solid electrolyte		10	90	-
Tantalum electrolytic	non-solid electrolyte		80	20	-
	solid electrolyte		80	20	-
Metallized film			10	90	-
Mica			40	40	20
Variable ceramic capacitors, disks (dielectric ceramic)			40	10	50
Other technologies			10	90	-
Fixed plastic, paper, dielectric capacitors – Radio interference suppression capacitors (plastic, paper)			10	90	-
Thermistors with negative temperature coefficient (NTC)			70	10	20

Table A.7 – Failure modes: resistors, inductive devices, relays

		Open circuit %	Short circuit %	Drift %
Resistors	Carbon film	100	-	-
	Metal film	40	-	60
	High dissipation film resistors	100	0	
	Wire-wound	100	-	-
	Variable (non wirewound cermet potentiometer)	80	-	20
	Resistors network (surface mounting resistors and resistive array)	40		60
Inductive devices		80	20	-
Relays	General purpose	80	20	-
	Power relays	80	20	-
	Solid state relays	80	20	-
	Coaxial relays	80	20	-

Annex B
(informative)

Thermal model for semiconductors

B.1 Thermal model

This document defines the equipment ambient temperature θ_a as the average temperature around the equipment. According to IEC TR 60943 it is the air surrounding the complete device and, for devices installed inside an enclosure, it is the temperature of the air outside the enclosure.

Inside the equipment/system, there is a temperature distribution that depends on the position of the parts that dissipate power. Even if each unit in the equipment has its own temperature distribution (depending on the type of component and its position), a component ambient temperature θ_{ac} is conventionally defined, that is constant for all components in the unit, obtained by averaging the temperatures near each component. This hypothesis is generally valid for electronic units, although sometimes those that dissipate a lot of power in a single point should be excluded, in fact when a unit has areas with temperatures significantly different from θ_{ac}, for thermal modelling purposes they should be considered as two separate units.

More precisely, the component ambient temperature θ_{ac} is the temperature that would be found at the point where the component is installed supposing it could be removed (with or without heat sink). This is equivalent to supposing that there are no components that by themselves significantly influence the ambient temperature for nearby components. In other words, it is as if between each component and the others there would be a zone of separation that has a temperature equal to the component ambient temperature, that is a characteristic of the whole unit (see Figure B.1).

Situations that do not correspond to this hypothesis are handled by considering separately the parts of the unit as if they were thermally separate units, each with its own value of θ_{ac}.

Each unit inside the equipment therefore has its own thermal difference ($\Delta\theta_{a-ac}$) between the equipment ambient temperature and the component ambient temperature. This difference is assumed to be constant for each value of θ_a throughout the whole range of the latter in the range of temperatures considered normal for electric equipment, and depending on the power dissipated by the entire unit.

For all components of a unit:

$$\theta_{ac} = \theta_a + \Delta\theta_{a-ac} \tag{B.1}$$

where

θ_{ac} is the component ambient temperature (°C);

θ_a is the equipment ambient temperature (°C);

$\Delta\theta_{a-ac}$ is the difference between the equipment and component ambient temperatures (K).

In order to define or calculate the failure rate of the components, the component temperature also has to be evaluated:

$\theta_j = \theta_{ac} + \Delta\theta_{ac-j}$ junction temperature, for integrated circuits and semiconductors (B.2)

$\theta_{\mathrm{c}} = \theta_{\mathrm{ac}} + \Delta\theta_{\mathrm{ac-c}}$ body temperature, for passive components subjected to dissipation (B.3)

In conclusion, the general thermal model can be summarized as:

$$\Delta\theta_{\mathrm{ac-c}} = P \times R_{\mathrm{th,\,ac-j}} \qquad \text{(B.4)}$$

$$\Delta\theta_{\mathrm{ac-c}} = P \times R_{\mathrm{th,\,ac-c}} \qquad \text{(B.5)}$$

where

P	is the component power dissipation;
$R_{\mathrm{th,\,ac-j}}$	is the thermal resistance between component ambient temperature and junction temperature;
$R_{\mathrm{th,ac-c}}$	is the thermal resistance between component ambient temperature and body temperature.

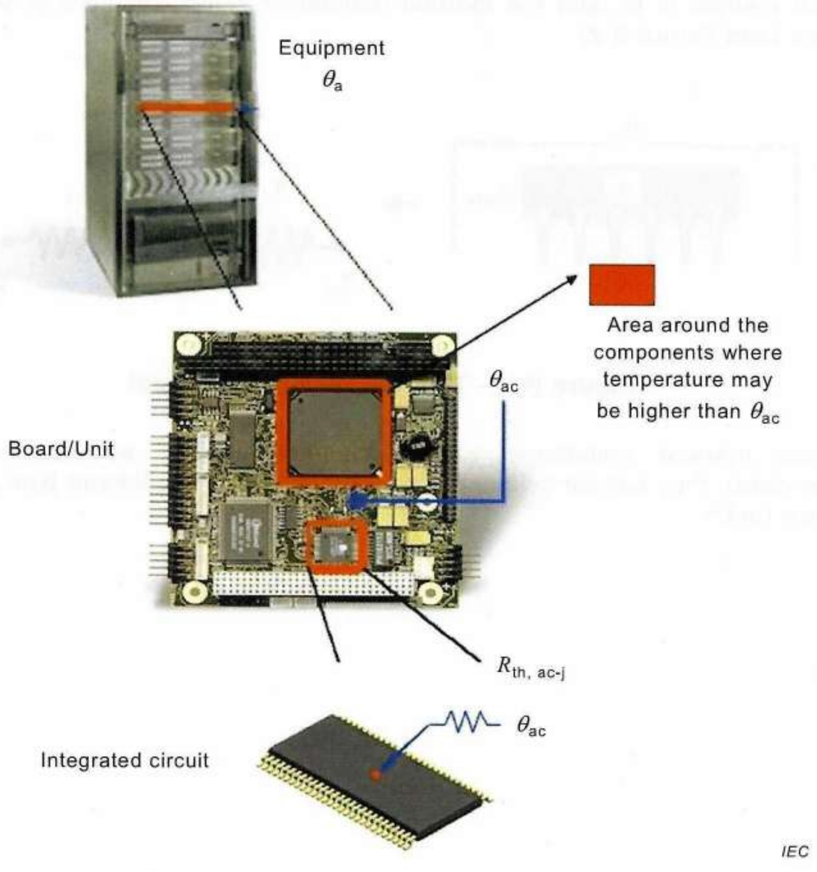

Figure B.1 – Temperatures inside equipment

B.2 Junction temperature calculation

When it is not possible to obtain the junction temperature value using the appropriate tools of the experimental thermal analysis the junction temperature value can be calculated as a function of the mean power dissipation P and of the device thermal resistance.

The simplified equation proposed here is sufficiently accurate for reliability calculations:

$$\theta_j = \theta_{\mathrm{ac}} + P \times R_{\mathrm{th,\,ac-j}} \tag{B.6}$$

$$\theta_{\mathrm{j}} = \theta_{\mathrm{case}} + P \times R_{\mathrm{th,\,c\text{-}j}} \tag{B.7}$$

where

θ_{j}	is the junction temperature (°C);
θ_{ac}	is the component ambient temperature (°C);
θ_{case}	is the case temperature (°C);
P	is the component power dissipation (W);
$R_{\mathrm{th,\,ac-j}}$	is the thermal resistance component ambient-junction (°C/W);
$R_{\mathrm{th,c-j}}$	is the junction-case thermal resistance (°C/W).

B.3 Thermal resistance evaluation

The preferred method is to take the thermal resistance value specified or published by the manufacturers (see Figure B.2).

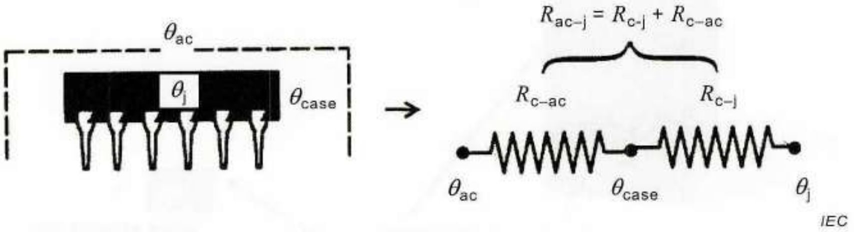

Figure B.2 – Thermal resistance model

If the device thermal resistance values are not directly available (measurements, manufacturer data), they can be calculated as a function of the package type, the pin number and the airflow factor.

Table B.1 – Thermal resistance as a function of package type, pin number and airflow factor

	$R_{\text{th, c-j}}$ °C/W	$R_{\text{th, ac-j}}$ °C/W
DIL package ceramic	$0{,}23\left(10+\frac{1520}{N+3}\right)$	$(0{,}23+0{,}66K)\left(10+\frac{1520}{N+3}\right)$
DIL package plastic	$0{,}33\left(10+\frac{1520}{N+3}\right)$	$(0{,}33+0{,}66K)\left(10+\frac{1520}{N+3}\right)$
PLCC package plastic	$0{,}28\left(15+\frac{1600}{N+3}\right)$	$(0{,}28+0{,}72K)\left(15+\frac{1600}{N+3}\right)$
SOJ and SOL package plastic	$0{,}28\left(15+\frac{1760}{N+3}\right)$	$(0{,}28+0{,}72K)\left(15+\frac{1760}{N+3}\right)$
PGA package ceramic	$0{,}33\left(10+\frac{1440}{N+3}\right)$	$(0{,}33+0{,}66K)\left(10+\frac{1440}{N+3}\right)$
QFP package plastic	$0{,}4\left(27+\frac{2260}{N+3}\right)$	$(0{,}4+0{,}6K)\left(27+\frac{2260}{N+3}\right)$
BGA package plastic	$0{,}4\left(6{,}6+\frac{1{,}1\times10^{6}}{N^{2}}\right)$	$(0{,}4+0{,}6K)\left(6{,}6+\frac{1{,}1\times10^{6}}{N^{2}}\right)$

where

N is the number of pins of the package;

K is the airflow factor given, according to the air velocity v in m/s, by the following equation

$$K=\frac{0{,}59\times v+1{,}11}{v+0{,}7} \tag{B.8}$$

where v is the air velocity in m/s. Typical values of v and K are given in Table B.2.

Table B.2 – Typical values of v are K

	v m/s	K
Natural convection	0,15	1,4
Slightly assisted cooling	0,5	1,2
Fan assisted cooling	1	1
Forced cooling	4	0,7

B.4 Power dissipation of an integrated circuit *P*

The power dissipation of an integrated circuit (where experimental values are not available) can be calculated considering its composing elements:

- a constant part from the direct current supply (P_{DC});
- a frequency dependent part (P_{f});
- duty cycle, for device with standby mode (P_{stby}).

P_{DC} and P_{f} calculation can be performed using Table B.3:

Table B.3 – Values of P_{DC} and P_{f}

Type		P_{DC} W	P_{f} W
MOS, Bipolar, ECL, GaAs		$U_{\mathrm{cc\,Nom}}\,I_{\mathrm{cc\,Max}}$	0
CMOS	ACT	$1{,}6\ 10^{-3}\ U_{\mathrm{cc\,Nom}}\,N_1$	$U_{\mathrm{cc}}{}^2 f_{\mathrm{op}} 10^{-6} (C_{\mathrm{pd}} N_2 + C_{\mathrm{L}} N_3)$
	other	$U_{\mathrm{cc\,Nom}}\,I_{\mathrm{cc\,Max}}$ [a]	$U_{\mathrm{cc}}{}^2 f_{\mathrm{op}} 10^{-6} (C_{\mathrm{pd}} N_2 + C_{\mathrm{L}} N_3)$
	memories	$U_{\mathrm{cc\,Nom}}\,I_{\mathrm{cc\,Max}}$	0
BICMOS		$U_{\mathrm{cc\,Nom}}\,I_{\mathrm{cc\,Max}}$	$U_{\mathrm{cc}}{}^2 f_{\mathrm{op}} 10^{-6} (C_{\mathrm{pd}} N_2 + C_{\mathrm{L}} N_3)$

[a] Normally $P_{\mathrm{f}} = 0$

where

$U_{\mathrm{cc\,Nom}}$ is the nominal voltage (V)
(default value $U_{\mathrm{cc\,Nom}}$ = 3 V, for BICMOS $U_{\mathrm{cc\,Nom}}$ = 1 V to 1,8 V);

$I_{\mathrm{cc\,Max}}$ is the maximum supply current (A);

f_{op} is the operation frequency (MHz);

C_{L} is the load capacitance (default value C_{L} = 50 pF);

C_{pd} is the power dissipation capacitance (pF);

N_1 is the number of inputs;

N_2 is the number of function elements;

N_3 is the number of outputs.

If a linear device has more than one current supply, P_{DC} is calculated separately for every supply and the values are summed.

The sum of P_{DC} and P_{f}, calculated in the conditions defined above, identifies the power dissipation in the worst case P_{WC} and it is a value representative of the values dispersion of different manufacturers and of different production lots.

For semi-custom integrated circuits (gate arrays and cell based), the power dissipation calculation is complex because the knowledge of the device internal composition is required, in relation to its use (registers, flip-flop and latches number).

The calculation has to be extended considering every case and it is convenient for these devices to define the maximum worst case power P_{fWC} as that one related to the maximum admitted operating frequency.

The worst case power value at the operating frequency is given by

$$P_{\mathrm{WC}} = \frac{P_{\mathrm{fWC}} f_{\mathrm{op}} + P_{\mathrm{DC}}(f_{\mathrm{max}} - f_{\mathrm{op}})}{f_{\mathrm{max}}} \qquad \text{(B.9)}$$

where

P_{fWC} is the worst case power dissipation at the maximum frequency (W);

P_{DC} is the DC power dissipation (W);

f_{op} is the operating frequency (MHz);

f_{max} is the maximum operating frequency (MHz);

f_{max} = 30 MHz (HC, HCT), f_{max} = 50 MHz (AC, ACT), f_{max} = 100 MHz (BICMOS).

A conventional value of the power dissipation P_{op} to be used in the junction temperature calculation is:

$$P_{op} = P_{WC}\frac{(P_{DC}+3{,}5)}{3\cdot P_{WC}+5} \tag{B.10}$$

For devices with a standby mode, particularly memories, the power dissipation P_{av} is calculated considering the duty cycle:

$$P_{av} = P_{op}\frac{D}{100} + P_{stby}\frac{(100-D)}{100} \tag{B.11}$$

where

P_{stby} is the standby power dissipation (W);

D is the duty cycle (%).

Annex C
(informative)

Failure rate prediction

C.1 General

Reliability predictions are conducted during the whole life cycle of equipment at various levels and degrees of detail, in order to evaluate, determine and improve the dependability of the equipment.

Successful reliability prediction of equipment generally requires a model that considers the structure of the equipment. The level of detail in that model will depend on the information available at the time (e.g. parts list, circuit diagram), and several reliability models are available depending on the problem (e.g. reliability block diagrams, fault tree analysis, state-space methods).

During the conceptual and early design phase, failure rate prediction is applicable to estimate equipment failure rate in order to check if reliability targets may be achieved and to help make decisions about the architecture for the product (e.g. use of redundancy, cooling).

Reliability prediction calculations should begin as early as possible, at the start of the equipment design phase, even if not all the applicable conditions can yet be known: in this case default values can be used provisionally, to help determine those conditions which are as yet unknown. These default values will then gradually be updated as the definitive conditions are identified.

This method is far preferable to the simplified calculation method (for which all the values are replaced by default values, including those, which are already known). The calculations should therefore be prepared in such a way as to enable values to be modified easily.

The procedures in this document can be used to carry out failure rate prediction at reference and operating conditions (prediction at reference conditions is also known as part count prediction which assumes an average stress on all components, while prediction at operating conditions, also known as part stress method takes the individual load on each component into account. The part count method is usually used in the early phase of the design, while part stress prediction is used later when the detailed design has been made. For part count prediction see C.2.4.2 and for part stress see C.2.4.3.).

C.2 Failure rate prediction for assemblies

C.2.1 General

Failure rate prediction is usually performed at assembly level. Predictions are useful for several important activities in the life cycle of equipment where they are used, in addition to many other important procedures, to ensure reliability goals.

Examples of such activities:

- assess whether reliability goals can be reached;
- identify and mitigate potential design weaknesses;
- compare alternative designs;
- evaluate designs;
- provide input data for higher level assembly dependability analysis;
- conduct cost calculations (e.g. life-cycle costs);

- establish objectives for reliability tests;
- plan logistic support strategies (e.g. spare parts and resources).

Failure rate prediction is often used in combination with other tools which can be used to improve the process of prediction by making it more representative of reality by allowing assembly structure and measures of importance to be introduced.

Failure rates to be used for spare parts provisioning and life-cycle costs calculation require particular attention. For these activities, failure rates should include all causes, even design errors, equipment and dependent (pattern) failures, to provide a realistic figure of what is happening or will happen in field during the operation phase of the life cycle. See also Annex F (database).

C.2.2 Assumptions and limitations

Failure rate predictions are based on the following assumptions, resulting from focussing on physical failures occurring at random over time.

Assumptions of failure rate predictions are as follows:

- the prediction model assumes that a failure of any component will lead to a failure of the assembly;
- component failures are treated as independent of each other; no distinction is made between complete, partial and drift failures;
- components are used within their specifications;
- design and manufacturing processes of the components and assembly under consideration are under control;
- failure rates are assumed to be constant either for an unlimited period of operation (general case) or for a given limited period of interest (e.g. useful life). Although this is known to be realistic for some components for others it is not. However the assumption greatly simplifies the task;
- apart from a few exceptions the wear-out failure period is never reached by electric components; in the same way it is accepted, again apart from some exceptions, that the added risks of failure during the first few months of operation can be disregarded.

Limitations of failure rate predictions are as follows:

- they cannot provide proof that a reliability goal has been achieved;
- due to the statistical nature of the information available, prediction works best for large component and assembly counts;
- results are dependent on the trustworthiness of the source data;
- the assumption of constant component failure rates may not always be true; in such cases this method may lead to incorrect results and other models may need to be used to determine useful life;
- failure rate data and stress models may not exist for new component types;
- stresses that are not considered may predominate and influence the failure rate.

C.2.3 Process for failure rate prediction

The process for reliability prediction using failure rates consists of the following steps:

a) Define and understand the assembly to be analysed:
    - obtain information on structure, such as functional and reliability block diagrams, if available, in order to check if series assumption is valid;
    - obtain bill of materials;

- obtain component specifications or data sheets for all components used in cases where parts stress analysis is to be carried out;
- obtain circuit diagrams and schematic diagrams if needed;
- define the boundaries from the assembly specifications and schematic diagrams;
- identify the functions and specification of the assembly, in particular understanding what a failure is.

b) When carrying out failure rate prediction at operating conditions, obtain information on operating conditions for each component when different from stated reference conditions:
  - identify the operating temperatures;
  - determine the actual electrical stresses;
  - determine mission profiles if necessary;
  - identify relevant environmental stresses;
  - select the data source according to the guidance given in Annex H;
  - use the stress models as defined in 5.2;
  - sum up the component failure rates.

c) Document the results, justification for choices and any assumptions made:
  - no guidance on presentation of results is given since many organizations define their own report structure or use those predefined in commercial software;
  - the justification process for the data sources and methods used should be documented;
  - any assumptions made should be listed so that the validity of the prediction can be assessed.

C.2.4 Prediction models

C.2.4.1 General

The failure rate of the assembly is calculated by summing up the failure rates of each component in each category. This applies under the assumption that a failure of any component is assumed to lead to equipment failure otherwise known as a chain or series configuration.

The following models assume that the component failure rate under reference or operating conditions is constant. Justification for use of a constant failure rate assumption should be given. This may take the form of analyses of likely failure mechanisms, related failure distributions, etc.

C.2.4.2 Failure rate prediction at reference conditions

Prediction at reference conditions (also called part count prediction) allows a prediction at a very early stage in the design process and is therefore very useful for feasibility studies, comparing design options and prioritizing analytic activities. Further it allows regulatory authorities to evaluate a design for example for a SIL level (see IEC 61508) without detailed knowledge of the design.

If the time to failure is exponentially distributed over the considered time interval then the failure rate for an assembly in a series configuration under reference conditions is calculated as follows:

$$\lambda_{\mathrm{S,ref}} = \sum_{i=1}^{n} \left(\lambda_{\mathrm{ref}}\right)_i \tag{C.1}$$

where

$\lambda_{\mathrm{S,ref}}$ is the failure rate of an assembly under reference conditions;

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

n is the number of components.

The reference conditions adopted are typical for the majority of applications of components in equipment. It is assumed that the failure rate used under reference conditions is specific to the component, i.e. it includes the effects of complexity, technology of the casing, different manufacturers and the manufacturing process, etc.

C.2.4.3 Failure rate prediction at operating conditions

Components may not always operate under the reference conditions. In such cases, the real operational conditions will result in failure rates different from those given for reference conditions (also called part stress prediction). 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 needed.

The failure rate for assemblies under operating conditions is calculated as follows:

$$\lambda_{\mathrm{S}} = \sum_{i=1}^{n} (\lambda)_i = \sum_{i=1}^{n} \left(\lambda_{\mathrm{ref}} \times \pi_{\mathrm{U}} \times \pi_{\mathrm{I}} \times \pi_{\mathrm{T}} \times \pi_{\mathrm{E}} \times \pi_{\mathrm{S}} \times \pi_{\mathrm{ES}}\right)_i \tag{C.2}$$

where

λ_{ref} is the component 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;

n is the number of components.

In Clauses 6 to 20 specific stress models and values for component categories are given for the π-factors and should be used for converting reference failure rates to field operational failure rates. However, if more specific models are applicable for particular component types then these models should be used and their usage justified and documented.

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

C.2.5 Other methods of reliability prediction

C.2.5.1 Similarity analysis

Similarity analysis includes the use of in-service equipment performance data to compare newly designed equipment with predecessor equipment for predicting end item reliability when the uses and stresses are similar. The method of similarity analysis is described in IEC 62308.

C.2.5.2 Simulation

Simulation is an empirical approach to equipment modelling that can allow the building of real-world models and attempt to use them to predict what is likely to happen to equipment in the future. The underlying techniques used in this process involve random sampling from failure distributions, and representation of equipment structure using such techniques as mathematical models, reaction kinetics models and empirical models. These techniques allow the building of fairly realistic models of complex equipment that can be used to understand their failure behaviour under various operating conditions and predict what the reliability will be at some future time.

C.2.5.3 Testing

Failure rate data can also be obtained from tests. It can be from testing of equipment or components. Normally testing of equipment is carried out by the equipment manufacturer while testing of components is usually carried out by the component manufacturer.

The test conditions will seldom be the same as the reference conditions; often the test will be accelerated, i.e. with increased stresses compared to the reference conditions. In these cases the failure rate information has to be transformed to reference conditions using the equations given in Clauses 6 to 20. The failure rate should be estimated based on statistical models such as, for example, the exponential distribution, the Weibull distribution, the normal distribution or the lognormal distribution.

In many cases no failures will occur during the test and the manufacturer will then often state the failure rate as 60 % upper confidence limit. When comparing test data (or field data) coming from different samples a guide can be found in IEC 60300-3-5 and IEC 61710.

When reporting failure rates based on test, the test conditions should be listed together with the statistical estimation of the failure rates and any transformation from test conditions to reference conditions. The empirical factors used for this transformation should be justified.

Care should be taken that the stress in an accelerated test does not introduce failure modes that are not relevant for the use of the component.

C.2.5.4 Physics of failure

Physics of failure (PoF) is an approach to reliability prediction modelling where the goal is to use physical principles with appropriate failure probability density distributions to design for failure-free operation and/or specify reliability targets and to predict failure times for components. It uses knowledge of root-cause failure processes in an attempt to identify the "weakest link" of a design to ensure that the planned equipment life is exceeded by the design. The approach can also be used for new components made from new materials, technologies and processes if basic physical and stress information is available. This methodology addresses the useful life of a product (see Annex F).

C.2.6 Validity considerations of reliability models and predictions

To use any quantitative reliability prediction method it is necessary to be aware of its validity. Like all engineering models, the failure rate models are approximations of reality, and are based on the best field data that could be obtained for a wide variety of parts and equipment. This data is then analysed and adapted, with many simplifying assumptions, to create usable models. Then when a model is used, further assumptions for the design parameters such as stress and temperature are made.

Thus a reliability prediction for equipment should not be treated as an absolute value for its field failure rate. It is generally agreed that these predictions can be good when used for relative comparisons, such as comparing design alternatives, or comparing equipment. Note also that reliability predictions do not account for unsuitable design decisions, substandard quality control for purchased parts, bad workmanship, poor product level quality control, overstressed field operation, etc.

Arguments for the reliability models and predictions, as given in this document, are as follows:

- often reliance is placed on failure rate data gathered from a variety of sources representing average conditions, however the accuracy and validity of such data may be questionable;
- for new technology components, failure rate data may not be available for all components as even the most recently published data is inevitably out of date;
- while the failure rate models given may indicate that a low failure rate can be achieved through a reduction in a single stress, in practice other stresses may predominate and render single stress reductions alone ineffective in achieving high reliability;
- the methods provide only broad estimates of reliability;
- the assumption of constant failure rate during the useful life of an item is not always valid but such an assumption provides suitable values for comparative analysis.

C.3 Component considerations

C.3.1 Component model

In this document a component is considered to consist of the actual component itself (e.g. silicon die), the encapsulation (e.g. case) and connection points. How the connection points are attached to the circuit board, also called the attachment system (e.g. solder joint), are treated separately in Clause 14 and this means that failures in the attachment system should be treated as component failures when using this document.

It is assumed that any failure rate used under reference conditions is specific to the component, i.e. it includes the effect of component complexity, technology of the casing, materials used, component construction, manufacturers and the manufacturing process, etc.

Care should be taken when using failure rate data from some data sources since some sources include the attachment system in the component failure rates and some do not.

C.3.2 Components classification

Component identification is the most important element of any codification system because it establishes a unique identification for every component. The identification consists of the minimum data required to establish clearly the essential characteristics of the component, i.e. those characteristics that give it a unique character and differentiate it from all others. A number of component classification systems are briefly described in Annex I.

This document recommends the use of IEC 61360 (all parts) which provides a clear and unambiguous definition of characteristic properties of all elements of electrotechnical equipment from basic components to subassemblies and full equipment. This document only uses the component-related aspects of IEC 61360 (all parts). The component coding elements of IEC 61360 (all parts) are described in Annex I.

C.4 General consideration about failure rate

C.4.1 General

The failure rate of an electric component depends on many influences, such as operating phase, failure criterion, duration of stress, operating mode (continuous or intermittent), ambient temperature and temperature cycling rate, humidity, electrical stress, cyclical switching rate, mechanical stress, air pressure and special stresses. It should be noted that a failure rate value, without knowledge of the conditions under which it was observed or is to be expected, provides no real information. For this reason, the values of the relevant factors of influence should always be given when stating a failure rate. It is possible to state how the failure rate depends on some of these influences. This dependence applies only within the specified limit values of the components.

Estimated values of the failure rates can be derived either from life tests or from field data. These estimated failure rates only apply under the conditions that applied during the tests or field observation. The rules according to which such estimates are derived depend on the statistical distribution function applying, i.e. whether "constant failure rate period" (exponential distribution) or "early life and wear-out failure period" (for example, Weibull distribution) exist. If the distribution over time of the failures is known, and estimated values of the failure rate have been calculated, the result should be interpreted statistically.

The dimension of failure rates is the number of failures per unit time, but it is worth noting that the time measure can be replaced by cycles, number of operations, etc. depending on the component type. Generally component failure rates are given in one of two standard forms, either as number of failures per 10^6 h or in number of failures per 10^9 h.

C.4.2 General behaviour of the failure rate of components

The general behaviour of the failure rate can be modelled by the Weibull distribution (see IEC 61649:2008, Clause 8). Its shape parameter, β, models three periods in the lifecycle, which can be explained as follows:

a) Early life failure period ($\beta < 1$)

For some components, at the start of the operating period, a higher failure rate is sometimes observed which decreases with time. Early life failures occur due to manufacturing processes and material weaknesses that do not result in failures in tests performed before shipping.

There are a few components that will exhibit decreasing failure rate in use. This is usually due to problems in the component manufacturing process as well as to handling problems (ESD, mechanical damages, etc.). This document does not support prediction of these component types and if early life failures are still to be expected for a component, the beginning of the phase of constant failure rate should be specified.

This document assumes constant failure rates hence it is assumed that any early life failures are removed by process control or by screening (see IEC 61163-2).

b) Constant failure rate period ($\beta = 1$)

Here, as the term suggests, the failure rate is constant. In some cases this occurs because competing failure rates produce an averaging effect that make it appear as if the failure rate is constant when the underlying failure rates of the individual competing failure modes are not.

Generally electric components operate in the constant failure rate phase (from end of early life failure period to start of wear-out failure period) and are dealt with in this document. This behaviour can be most easily modelled by the exponential distribution and procedures for verification of constant failure rate can be found in IEC 60605-6. For components showing limited variations of the failure rate within the useful life, for example electromechanical components showing wear-out, the assumption of constant failure rate can be maintained by using the average failure rate during the useful life.

c) Wear-out failure period ($\beta > 1$)

This period shows an increasing failure rate due to the dominating effects of wear-out, ageing or fatigue (see also Annex F).

This document assumes that for most components the failure rate is averaged for the time interval specified in the data sheet. Since this document only covers the useful life of the component, it is important to know when the useful life ends for a given component due to wear-out. Some suppliers define this point as where a certain percentage of failures have occurred (e.g. 10 %). Others define the end-of-life as being when the failure rate has increased by a certain factor (e.g. failure rate doubled).

This limitation to the useful life of the component is reasonable since for the vast majority of components, the wear-out failure period (during which failures take on a systematic character) is far away from the periods of use (which can typically range from 3 to 20 years).

There are three cases in which the occurrence of wear-out failures should be taken into account (the failure rate of which increases with time):

1) For some families, if due care is not taken, the wear-out mechanisms may give rise to systematic failures after too short a period of time: metallization electro-migration in active components, for example. This risk needs to be eliminated by a good product design, and it is important to ensure this by qualification testing. In other words, it should not be taken into account for a prediction, and should be eliminated by qualification testing and by technical evaluation, which are, therefore, of critical importance.
2) For some (very few) component families, the wear-out failure period is relatively short. For these families, this document explains how to express the period for which the failure rate can be considered constant. This useful life is subject to influencing factors. Such families include relays, aluminium capacitors (with non-solid electrolyte), laser diodes, optocouplers, power transistors in cyclic operation, connectors and switches and keyboards.
3) In some cases a component operates solely in the wear-out phase due to its physical or chemical nature. This group include chemically-based components, components where use is made of a physical degradation mechanism and nearly all components where there is a mechanical interaction. These component types will always be in the wear-out phase and so the failure rate will always be increasing. This can often be confirmed by Weibull analysis of failure data (see IEC 61649 for details).

The time points which separate these operating periods cannot be determined exactly. In general terms the time dependence curve for any single component type could be significantly different. When interpreting reliability figures it is important to determine the physical reality of failure modes and distributions.

For more details on these different phases refer to IEC 61649 and IEC 62308.

C.4.3 Expected values of failure rate

It is recommended to state failure rate data for components under environmental and operating conditions close to the conditions in field use. This results in the most relevant predictions. Therefore data from previous products and from field data from the organization doing the analysis is preferred.

Values determined from a life test with a single sample – or the confidence limits derived from it – often do not provide enough information. Therefore the resulting dispersions of the predicted values for modules and equipment may be too great.

Failure rate data, stated according to this document, should therefore be taken as statistical "expected values" for operation under the given reference conditions for the time period given and the total population, i.e. it is to be expected that in future use, under the conditions given, the averages obtained will be the values cited.

C.4.4 Sources of variation in failure rates

A failure rate generated from collecting data on equipment will be dependent upon all the circumstances under which the equipment operates. Consequently, the failure rate data should only be used for predictions on equipment in which the circumstances are similar. if the circumstances are different then the predicted failure rate will need to be adjusted.

Unfortunately, the circumstances of a data collection are rarely adequately described, Therefore, any data will be based on some explicit assumptions, some implicit assumptions, and some assumptions that are not addressed in this document.

It is important to appreciate that a failure rate is not an intrinsic and immutable property of a piece of equipment. An engineer involved either in collecting or using data should fully understand the factors that influence failure rate derivation and use.

Circumstances that can create variations in failure rates are:

- Component detail

  When collecting data, it is possible that information that is important to the differentiation of failure rate is lost. This is often the case when a taxonomy or categorization is used to group component types.

- Suitability for service

  Suitability for service is related to the quality of a component. When making a prediction the analyst should, wherever possible, try to assess the validity of the assumptions made for the particular situation and establish if the equipment represented by the data was properly fabricated, used appropriate materials of construction, was properly maintained, was operated within design conditions and was designed to appropriate standards.

- Failure mode combinations

  Great care therefore should be taken when using failure data to ensure that the definition of failure modes used to gather the failure data is the same as the definition of failure modes that are being expected and is not a mix of different failure mode definitions. This is of particular importance when handbook data or failure data provided by an external source is used. If the types of failure mode definition cannot be identified, then the outcome of any prediction may not match the actual observed behaviour. See 4.1 and Annex A for more details on failure modes.

- Maintenance

  The maintenance strategy for equipment will significantly affect both the number and severity of failures. An inadequate preventive maintenance programme will not prevent failures, a cursory routine inspection programme may detect some potential failures, and a full preventive maintenance programme may pick up potential failures as incipient failures rather than waiting until they occur.