

Evaluation and qualification of electrical insulation systems

The European Standard EN 60505:2004 has the status of a
British Standard

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National foreword

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Foreword

The text of document 98/217/FDIS, future edition 3 of IEC 60505, prepared by IEC TC 98, Electrical insulation systems (EIS), was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 60505 on 2004-10-01.

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Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 60505:2004 was approved by CENELEC as a European Standard without any modification.

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

IEC 60068-1	NOTE	Harmonized as EN 60068-1:1994 (not modified).
IEC 60068-2	NOTE	Harmonized in HD 323.2 and EN 60068-2 series (not modified).
IEC 60068-2-10	NOTE	Harmonized as HD 323.2.10 S3:1988 (not modified).
IEC 60112	NOTE	Harmonized as EN 60112:2003 (not modified).
IEC 60212	NOTE	Harmonized as HD 437 S1:1984 (not modified).
IEC 60216	NOTE	Harmonized in HD 611 and EN 60216 series (not modified).
IEC 60587	NOTE	Harmonized as HD 380 S2:1987 (not modified).
IEC 60721	NOTE	Harmonized in HD 478 and EN 60721 series (not modified).
IEC 62114	NOTE	Harmonized as EN 62114:2001 (not modified).
ISO 62	NOTE	Harmonized as EN ISO 62:1999 (not modified).
ISO 175	NOTE	Harmonized as EN ISO 175:2000 (not modified).
ISO 4611	NOTE	Harmonized as EN ISO 4611:1999 (not modified).

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INTRODUCTION

The service life of electrical equipment is frequently determined by the life of its electrical insulation system (EIS) or systems. The life of an electrical insulation system can be affected by electrical, thermal, mechanical or environmental stresses acting either individually or in combination.

Intended, estimated or proven service life times are essential parameters for describing the life of electrical insulation systems. In the early days of electrotechnical engineering, life figures were rather vague. The limitation of the life of the insulation under thermal stress was one of the first indicators of the effect of ageing in some equipment in service. As experience in using EIS increased, it was appreciated that there was a need to select specific materials having satisfactory life time at a given temperature, to enable the required service life to be achieved and to allow for the calculation of the thermal capability of equipment.

IEC 60085 standardized a number of maximum temperature values and presented a list of electrical insulating materials (EIM) related to these temperatures (classes) which, when used for EIS, would "ensure an economical life for the insulation in a wide range of apparatus".

This was a clearly defined attempt to qualify EIS on the basis of (service) experience or tests and a quantification of an EIS life in terms of time. The limitation of this approach, based entirely on thermal stressing, was recognized and there was a demand for an improved life concept. This requirement and the impossibility of using the material tables in IEC 60085 at a time when many new, synthetic materials were being produced which did not fit neatly into the existing thermal classification, led to a worldwide effort to improve the situation. This led to the elaboration of the present standard, which serves as a guide to anyone developing standards and technical documents.

The user of this standard may evaluate existing test methods and provide correlation with his equipment. Therefore, the user of this standard is responsible for demonstrating the validity of the existing test method in accordance with the principles of this standard.

To determine the prospective life is a fundamental task when developing and designing an EIS. Estimated service life of an EIS needs to be established for several reasons:

- for type testing when introducing a new EIS into production;
- for quality assurance of production; and
- for estimating the remaining life for maintenance purposes.

EVALUATION AND QUALIFICATION OF ELECTRICAL INSULATION SYSTEMS

1 Scope

This International Standard establishes the basis for estimating the ageing of electrical insulation systems (EIS) under conditions of either electrical, thermal, mechanical, environmental stresses or combinations of these (multifactor stresses).

It specifies the principles and procedures that should be followed, during the development of EIS functional test and evaluation procedures, to establish the estimated service life for a specific EIS.

This standard is for use by all IEC technical committees responsible for equipment having an EIS.

2 Normative references

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

IEC 60068-2-1, *Environmental testing – Part 2: Tests – Test A: Cold*

IEC 60068-2-2, *Environmental testing – Part 2: Tests – Test B: Dry heat*

IEC 60068-2-14, *Environmental testing – Part 2: Tests – Test N: Change of temperature*

IEC 60068-2-27, *Environmental testing – Part 2: Tests – Test Ea and guidance: Shock*

IEC 60216-3, *Electrical insulating materials – Thermal endurance properties – Part 3: Instructions for calculating thermal endurance characteristics*

IEC 60216-5, *Electrical insulating materials – Thermal endurance properties – Part 5: Determination of relative thermal endurance index (RTE) of an insulating material*

IEC 60493-1, *Guide for the statistical analysis of ageing test data – Part 1: Methods based on mean values of normally distributed test results*

IEC 60544-1, *Electrical insulating materials – Determination of the effects of ionizing radiation – Part 1: Radiation interaction and dosimetry*

IEC 60664 (all parts), *Insulation coordination for equipment within low-voltage systems*

IEC 60727-1, *Evaluation of electrical endurance of electrical insulation systems – Part 1: General considerations and evaluation procedures based on normal distributions*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply:

3.1 General terms

3.1.1

electrical insulation system

EIS

insulating structure containing one or more electrical insulating materials (EIM) together with associated conducting parts employed in an electrotechnical device

3.1.2

electrical insulating material

EIM

material with negligibly low electric conductivity, used to separate conducting parts at different electrical potentials

[IEV 212-01-01:1990, modified]

3.1.3

reference EIS

established EIS evaluated on the basis of either a known service experience record or a known comparative functional evaluation

3.1.4

candidate EIS

EIS under evaluation to determine its service capability (with regard to electrical, thermal, mechanical, environmental or multifactor stresses)

3.1.5

intended life

design life of an EIS under service conditions

3.1.6

estimated life

expected service life derived from either service experience or the results of tests performed in accordance with appropriate evaluation procedures, or both, as established by the responsible organization or technical committee

3.1.7

evaluation

establishment of relationships between service requirements and life data obtained from service experience analysis or from the results of functional tests

3.2 Terms related to service stresses and ageing

3.2.1

ageing stress

electrical, thermal, mechanical or environmental stress whose action on an EIS causes irreversible property changes

3.2.2

potentially destructive stress

factor of influence in service which can cause the failure of the aged EIS, alone or in combination with other stresses

3.2.3

factor of influence

stress imposed by conditions of operation, environment or test that affects ageing or life of an EIS

NOTE The term “factor of influence” denotes external factors (such as ambient temperature) inducing stress in the EIS as different from stress factors being part of the duty cycle of the equipment (e.g. temperature rise due to load).

3.2.4

service conditions

combination of factors of influence and duty that are to be expected in a specific application of an electrical device

3.2.5

reference operating conditions

service conditions of the equipment to which the test conditions of the functional test procedure are related

3.2.6

service requirements

specified factors of influence, intended performance and duty of an electrical device

3.2.7

service experience

the quantitative and/or qualitative record during service, with or without failure of an EIS

3.2.8

ageing

irreversible changes of the properties of an EIS due to action by one or more factors of influence

NOTE 1 Some changes (e.g. hydrolytic changes) can be partly reversible if the ambient conditions change.

NOTE 2 Ageing leads to degradation of the EIS.

3.2.9

ageing factor

factor of influence that causes ageing

3.2.10

intrinsic ageing

irreversible changes of fundamental properties of an EIS caused by the action of ageing factors on the EIS

3.2.11

extrinsic ageing

irreversible changes of properties of an EIS caused by action of ageing factors on unintentionally introduced imperfections in the EIS

3.2.12

interaction

modifications of the type or degree of ageing produced by the combination of two or more factors of influence relative to their ageing effect if acting individually on separate objects

3.2.13

direct interaction

interaction between simultaneously applied factors of influence that differs from that occurring with sequentially applied factors of influence

NOTE All factors producing direct interaction are not necessarily ageing factors.

3.2.14

indirect interaction

interaction which occurs between simultaneously applied factors of influence, which remains unchanged when the factors are applied sequentially

3.3 Terms related to testing

3.3.1

functional test

procedure to obtain information about the suitability of an EIS under specified conditions

3.3.2

test object

sample of original equipment or part thereof, or model representing the equipment completely or partially, including the EIS, to be used in a functional test

3.3.3

accelerated ageing

result of an increase in the level and/or frequency of application of the factors of influence beyond normal service conditions

3.3.4

accelerated test

functional test applying accelerated ageing to shorten testing time

3.3.5

conditioning

subjecting a specimen to an atmosphere of a specified relative humidity or complete immersion in water or other liquid, at a specified temperature for a specified period of time

3.3.6

prediagnostic conditioning

variable or fixed stresses, which can be applied continuously or periodically to an EIS to enhance the ability of a functional test to detect the degree of ageing

NOTE Prediagnostic conditioning may cause additional ageing.

3.3.7

diagnostic factor

variable or fixed stress which is applied to an EIS to establish the degree of ageing

3.3.8

diagnostic test

periodic or continuous application of a specified level of a diagnostic factor to a test object to determine whether or when the end-point criterion has been reached

3.3.9

end-point criterion

moment when a system is no longer able to fulfil its service purposes

3.3.10
end of life
value of either a property or a change of property defining the end of life of a test object in a functional test

3.3.11
test cycle
in a test, repetitive period of application of one or more factors of influence, either sequentially or simultaneously, and of diagnostic factors

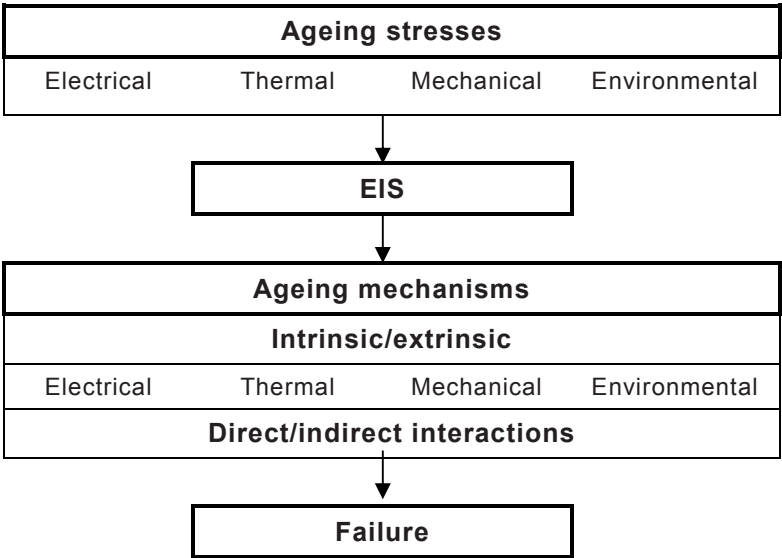
3.3.12
subcycle
defined period within test cycle

NOTE The subcycle may be, for instance, a period of application of high temperature and humidity for influencing the system properties, or application of high voltage for diagnostic purposes

4 Ageing

4.1 Ageing mechanism

Ageing is defined as the irreversible changes of the properties of an EIS due to action by one or more factors of influence. Ageing stresses may cause either intrinsic or extrinsic ageing. In most EIS extrinsic ageing predominates. A schematic representation of the basic process is shown in Figure 1.



IEC 1313/04

Figure 1 – Ageing of an EIS

The type and level of contamination and/or the extent of imperfections in an EIS will, in many types of electrical apparatus, significantly affect the service performance. In general, the fewer and less severe the contaminant and/or defects in the EIS, the better the performance of the equipment. To avoid obtaining misleading results from functional tests, a candidate EIS should contain, as far as practicable, the full range of contaminants and/or defects expected when the actual system is used in service.

The ageing factors produce electrical, thermal, mechanical or environmental ageing mechanisms that eventually lead to failure. During ageing, applied stresses, which initially do not affect the EIS, can become ageing factors and, as a result, modify the rate of degradation.

When ageing is dominated by one ageing factor, this is referred to as single-factor ageing. Multifactor ageing occurs when more than one ageing factor substantially affects the ageing of the EIS. Ageing factors can act synergistically, that means, there can be direct interactions between the stresses. Interactions may be either positive or negative.

The ageing of a practical EIS may be complex and failure is usually caused by a combination of ageing mechanisms, even if there is only one dominant ageing factor as, for example, in single-factor ageing.

Where experience or existing knowledge of how a specific EIS will perform in service is limited, the user of this standard shall decide whether single or multifactor test procedures are appropriate for his specific equipment or apparatus.

NOTE The classification of the operational environments of electrical equipment is dealt with in IEC publications prepared by IEC/TC 75, and methods for environmental endurance testing of electrical equipment are described in IEC publications prepared by IEC/TC 50 (notably IEC/SC 50B), see bibliography.

When speaking of environmental effects, this is understood to comprise environments other than the normal standard laboratory atmospheres specified in IEC 60212.

A number of other standards that provide methods of exposure or characterization of insulation are listed in the bibliography.

In functional evaluation tests, ideally duplication of all the ageing mechanisms that occur in service should be included. In practice, this is often difficult to achieve, as the conditions when a particular ageing mechanism is operative cannot be completely known or understood. Several ageing mechanisms may occur either simultaneously or in sequence.

For example, assume that an EIS is subjected to electrical (E), thermal (T), mechanical (M) and environmental (A) stresses as shown in Figure 2. Initially, during step A, electrical ageing occurs which causes an increase in the dielectric losses and results in one or more localized temperature increases in the insulation. In these higher temperature regions, environmental and thermal stresses become ageing factors and accelerate chemical changes in the insulation (step B). The chemical changes can then act to increase or decrease the total ageing rate; an example is shown in Figure 3. When the mechanical properties of the affected insulation have deteriorated to critical levels that depend on the mechanical stresses, local cracks appear (step C). Subsequently, when these cracks reach a critical size, partial discharges will occur and eventually lead to complete failure (step D). Thus the ageing, shown in Figure 3, is not linear with time.

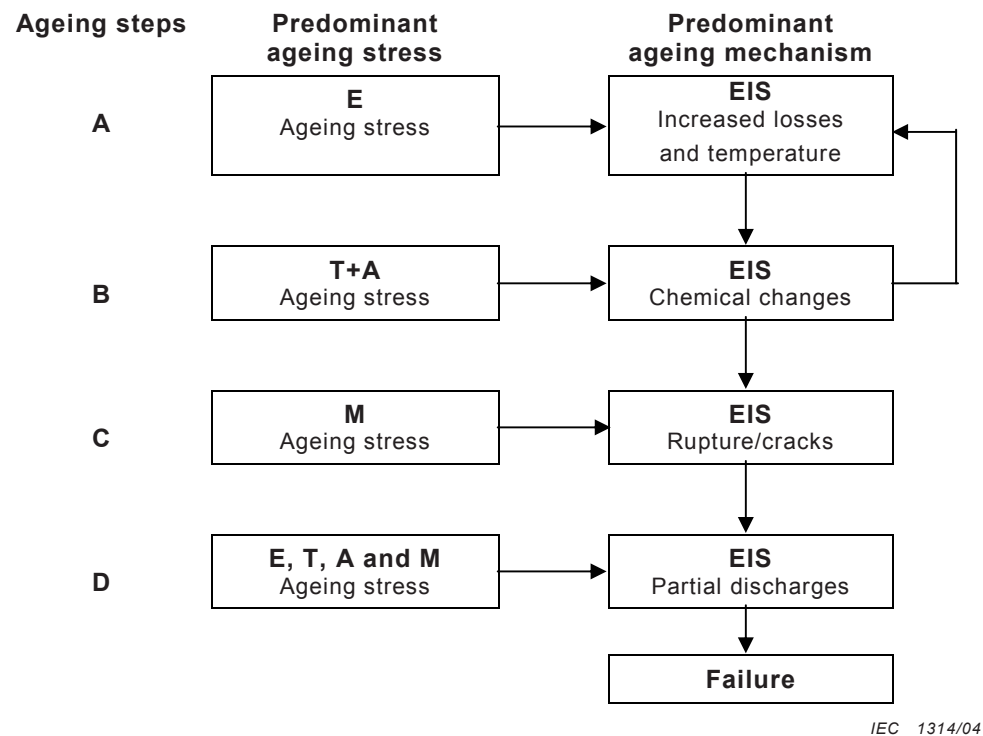


Figure 2 – Example of possible ageing mechanisms as a function of time

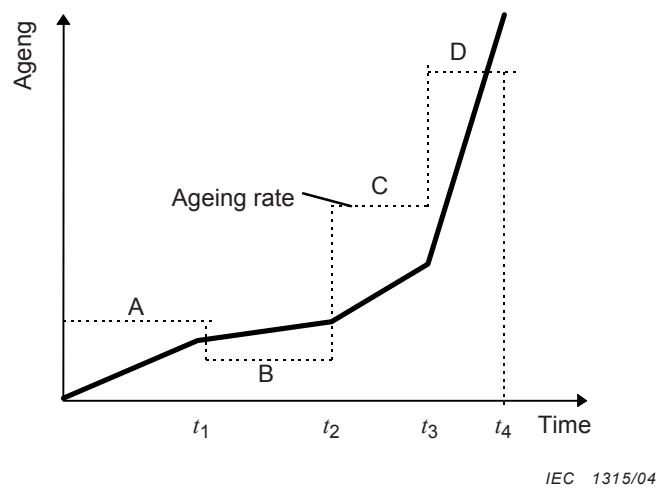
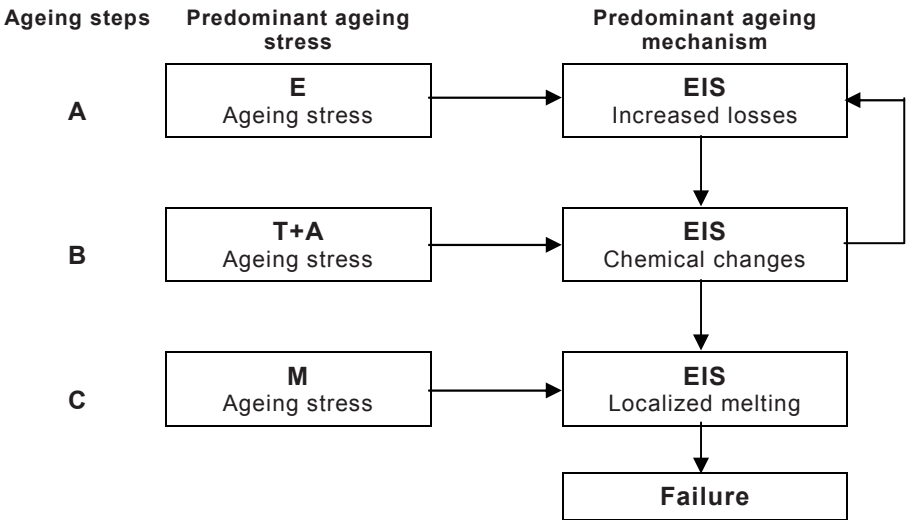


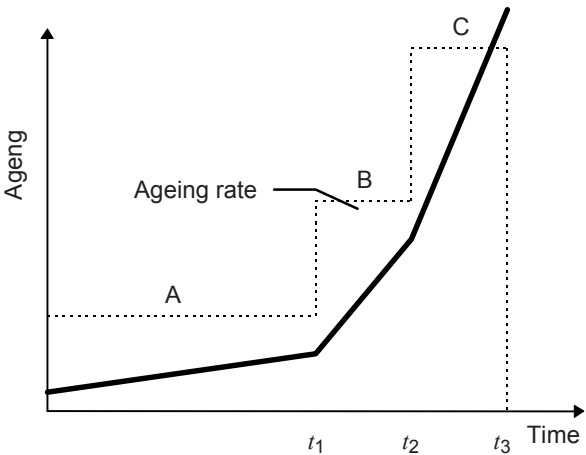
Figure 3 – Ageing as a function of time for Figure 2

Alternatively, as shown in Figure 4, the chemical changes in step B can further increase the dielectric losses and result in a rapid increase in temperature, leading to localized melting. As a consequence, during step C, the loss of mechanical strength is sufficient to cause failure. The ageing/time characteristic is shown in Figure 5.



IEC 1316/04

Figure 4 – Example of possible ageing mechanisms as a function of time



IEC 1317/04

Figure 5 – Ageing as a function of time for Figure 4

These two examples of multifactor ageing are difficult to duplicate in functional tests.

The choice of test conditions does not always produce the duration of the phases in the same proportions and, in extreme cases, can introduce other modes of failure not normally observed under operating conditions. This can result in significant errors when predicting the service life of an EIS from functional tests.

4.2 Assessment of ageing mechanisms

Annex B presents four flow charts, Figures B.1, B.2, B.3 and B.4, which describe respectively in some detail intrinsic and extrinsic electrical, thermal, mechanical and environmental ageing of an EIS. Each chart is based on the service experience of different types of EIS and shows possible mechanisms of deterioration and failure that can occur for the different types of ageing and the interactions between ageing factors. Although several failure mechanisms are shown, the charts are not intended to be exhaustive of mechanisms that might be found in actual service conditions of all equipment. It is important to note that ageing that leads to the possible failure is usually caused by more than one mechanism.

These charts should be used as follows:

- a) as a checklist to determine the ageing mechanisms of equipment and apparatus; the mechanisms can occur sequentially or simultaneously;
- b) to develop functional and accelerated ageing tests or test cycles; the magnitudes and types of applied stresses and their duration will depend upon how they affect the ageing mechanisms;
- c) to develop suitable diagnostic tests or test cycles to assess the condition of the EIS.

Based on a knowledge of service experience, operating conditions and the properties of the components of the EIS under consideration, the user of this standard should select one or more charts that show the main ageing factor or factors. The various ageing mechanisms that lead to failure should be carefully examined, taking into account the levels of contaminants and defects in the EIS. A revised chart, which only includes the relevant ageing mechanisms, should then be produced as an aid in the development of the functional ageing and diagnostic test cycles. Typical examples are shown in Figures B.5 through B.8.

If there is insufficient information available concerning service experience and/or the possible ageing mechanism, then the ageing conditions should be based upon the most severe levels of stresses expected in service for which the EIS has been designed.

4.3 Accelerated ageing

Application of life models to fit accelerated life tests is to provide quantities for the evaluation of material endurance (or performance under service conditions), particularly in relation to comparative tests performed on a reference material, of known service performance.

4.3.1 Electrical ageing (see Figure B.1)

Electric ageing (either a.c., d.c. or impulse) involves:

- a) the effects of partial discharges when the local field strength exceeds the breakdown strength in the liquid or gaseous dielectric adjacent to, or included in, the EIS;
- b) the effects of tracking;
- c) the effects of treeing;
- d) the effects of electrolysis;
- e) the effects, related to those above, on adjacent surfaces of two insulating materials where tangential fields of relatively high value can occur;

- f) the effects of increased temperatures produced by high dielectric losses;
- g) the effect of space charges.

Figure B.1 shows intrinsic/extrinsic electrical ageing where electrical stresses are considered to be the main ageing factor. Consider the example of a simple EIS consisting of two parallel plane conductors embedded in an insulating material. Protrusions are known to occur on the surfaces of conductors, and impurities (e.g., dust particles, etc.) can be included within the insulation. Figure B.1 can now be simplified to the chart shown in Figure B.5 that shows that charge injection leading to electrical treeing is the main ageing mechanism. The accelerated ageing should, therefore, be carried out by using ageing factors that increase charge injection, for example by high voltage, and the diagnostic tests should be designed to enable measurement of the effect of the injected charge and/or the partial discharge characteristics.

In many practical EIS, the electrical ageing process that leads to failure is complex, as shown by Figure B.5. No rigid mathematical models have yet been developed which predict fully how the ageing factors affect the life of an EIS. However, one empirical relationship, the inverse power model, is often used to relate a.c. and d.c. electrical stress with life. This states that:

$$L \propto V^{-n}$$

where

- L is the life expectancy;
- V is the voltage;
- n is the voltage life exponent.

The inverse power law model predicts a linear relationship between life and voltage when plotted on log-log graph paper. Other models may be used.

Electrical ageing may also be accelerated by testing at a higher frequency than that experienced in normal service. The frequency increase shall have been shown to provide no change of the ageing mechanism, in the stress range, for both candidate and the reference system.

In special cases it may be possible to perform electrical endurance tests with stepwise increasing stress for each test object. A definite mathematical relationship between stress level and time to failure and a method of reducing test results to a common time or a common stress level value is also necessary to specify. Annex D describes an example of such a procedure. Either fixed or increasing stress levels may be used in cyclic tests

4.3.2 Thermal ageing (see Figure B.2)

Thermal ageing involves

- a) the progress of chemical and physical changes as a consequence of chemical degradation reactions, polymerization, depolymerization, diffusion, etc.,
- b) thermomechanical effects caused by the forces due to thermal expansion and/or contraction.

The increases in the rate of chemical and physical processes proceeding towards the state of thermodynamic equilibrium are the major causes of thermal ageing. Many uncomplicated ageing processes (e.g. first order chemical reactions) follow within restricted temperature intervals the Arrhenius equation, i.e.:

$$L = A \exp(-E/kT)$$

where

L is the life expectancy;

A is a constant;

E is the activation energy;

k is the Boltzmann constant;

T is the thermodynamic temperature.

The expected life at a particular temperature can be found by extrapolation of data plotted using log life versus $1/T$ coordinates. For further information, see IEC 60216.

The suggested values for the evaluation of the EIS can be selected from those shown in Table 1. To produce accelerated ageing, a minimum of three higher temperatures shall be chosen for the tests. The lowest temperature should be selected such that a failure criterion will be reached after a minimum of 5 % of the intended service life of the candidate system or a minimum of 5 000 h for the lowest temperature. The next two highest temperatures should be chosen at 20 K intervals. If more than three test temperatures are needed, then 10 K intervals may be used. Preferred ageing temperatures are listed in Table 1.

NOTE 1 Testing has confirmed that for many EIS, the life is halved for a rise in temperature, which is approximately constant within a restricted temperature range dependent on the EIM involved. For the majority of these EIS, the temperature rise halving the life has a value between 8 K to 15 K.

NOTE 2 In some cases, the above test procedure may not be optimal, for instance in the case of short-life equipment where it may lead to unrealistic high ageing temperatures.

For EIS, where one or more EIM have transition temperatures (e.g. melting, boiling, crystallization), the maximum test temperature should be below the relevant transition temperature(s).

Table 1 – Ageing temperatures

Service temperatures °C	55	75	90	105	120	130	155	180	200	220	250
(Thermal class)	55	75	90 (Y)	105 (A)	120 (E)	130 (B)	155 (F)	180 (H)	200	220	250
Ageing temperatures °C	135	155	170	185	200	210	235	260	280	300	330
	125	145	160	175	190	200	225	250	270	290	320
	115	135	150	165	180	190	215	240	260	280	310
	105	125	140	155	170	180	205	230	250	270	300
	95	115	130	145	160	170	195	220	240	260	290
	85	105	120	135	150	160	185	210	230	250	280
	75	95	110	125	140	150	175	200	220	240	270