IEC 60544-5

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REDLINE VERSION

INTERNATIONAL STANDARD

Electrical insulating materials – Determination of the effects of ionizing radiation –
Part 5: Procedures for assessment of ageing in service

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ELECTRICAL INSULATING MATERIALS –
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FOREWORD

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IEC 60544-5 has been prepared by IEC technical committee TC 112: Evaluation and qualification of electrical insulating materials and systems. It is an International Standard.

This third edition cancels and replaces the second edition published in 2011. This edition constitutes a technical revision.

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

a) added recent references in 7.4 showing that some electrical condition monitoring methods show promising correlations with ageing;
b) updated recommendations for implementation of a sample deposit in 9.2, installation of a sample deposit in 9.3 and testing of samples from the deposit in 9.4;
c) updated list of references.

The text of this International Standard is based on the following documents:

Draft	Report on voting
112/523/CDV	112/553/RVC

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

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 60544 series, published under the general title *Electrical insulating materials – Determination of the effects of ionizing radiation*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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- withdrawn,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

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INTRODUCTION

Organic and polymeric materials provide a significant proportion of the insulation used in electrical systems. These materials are sensitive to the effects of irradiation and the response varies widely between different types. It is therefore important to be able to assess the degree of degradation of these insulating materials during their service lifetimes. This part of IEC 60544 provides recommended procedures for assessing ageing of insulating materials in service.

There are a number of approaches to the assessment of ageing of polymer-based components exposed to radiation environments [1], [2], [3], [4][1]. These are based on the better understanding of the factors affecting ageing degradation which has been developed over several decades. In nuclear power plants, qualification programmes are normally used for the selection of components, including those based on polymeric materials. These initial qualification procedures, such as IEEE Std 323™-1974[2] [5] and IEEE Std 383™-1974**Error! Bookmark not defined.** [6], were originally written before there was sufficient understanding of ageing mechanisms. Most of the methods discussed in this document are therefore used to supplement the initial qualification process.

This document is the fifth in a series dealing with the effect of ionizing radiation on insulating materials.

IEC 60544-1 (Radiation interaction and dosimetry) constitutes an introduction dealing very broadly with the problems involved in evaluating radiation effects. It also provides guidance on dosimetry terminology, several methods of determining exposure and absorbed dose, and methods of calculating absorbed dose in any specific material from the dosimetry method applied.

IEC 60544-2 (Procedures for irradiation and test) describes procedures for maintaining seven different types of exposure conditions during irradiation. It also specifies the controls that should be maintained over these conditions so that when test results are reported, reliable comparisons of material performance can be made. In addition, it defines certain important irradiation conditions and test procedures to be used for property change determinations and corresponding end-point criteria.

IEC 60544-3 has been withdrawn and incorporated into the second edition of IEC 60544-2.

IEC 60544-4 (Classification system for service in radiation environments) provides a recommended classification system for categorizing the radiation endurance of insulation materials.

1 Numbers in square brackets refer to the Bibliography.

2 IEEE Std 323-1974 and IEEE Std 383-1974 are now withdrawn and have been superseded by more recent revisions.

**ELECTRICAL INSULATING MATERIALS –
DETERMINATION OF THE EFFECTS OF IONIZING RADIATION –**

Part 5: Procedures for assessment of ageing in service

1 Scope ~~and object~~

This part of IEC 60544 covers ageing assessment methods which can be applied to components based on polymeric materials (e.g. cable insulation and jackets, elastomeric seals, polymeric coatings, gaiters) which are used in environments where they are exposed to radiation.

The object of this document is aimed at providing methods for the assessment of ageing in service. The approaches discussed in Clause 5 through Clause 9 cover ageing assessment programmes based on condition monitoring (CM), the use of sample deposits in severe environments and sampling of real-time aged components.

2 Normative references

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

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

IEC 60544-2, *Electrical insulating materials – ~~Guide for determining~~ Determination of the effects of ionizing radiation on insulating materials – Part 2: Procedures for irradiation and test*

IEC TS 61244-1, *Determination of long-term radiation ageing in polymers – Part 1: Techniques for monitoring diffusion-limited oxidation*

IEC TS 61244-2, *Determination of long-term radiation ageing in polymers – Part 2: Procedures for predicting ageing at low dose rates*

~~IEC 60780, *Nuclear power plants – Electrical equipment of the safety system – Qualification*~~

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

No terms and definitions are listed in this document.

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

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

3.2 Abbreviated terms

~~For the purposes of this document, the following abbreviations, taken from IEC 60780, apply.~~

BWR	boiling water reactor
CBQ	condition-based qualification
CM	condition monitoring
CSPE	chlorosulphonated polyethylene
DBE	design basis event
DLO	diffusion-limited oxidation
DRE	dose rate effect
~~DSC~~	~~Differential scanning calorimeter~~
EPR	ethylene propylene rubber
EQ	environmental qualification
~~EVA~~	~~Ethylene vinyl acetate copolymer~~
~~IM~~	~~Indenter modulus~~
~~LOCA~~	~~Loss of coolant accident~~
NPP	nuclear power plant
OIT	oxidation induction time
OITP	oxidation induction temperature
~~PE~~	~~Polyethylene~~
PVC	polyvinyl chloride
PWR	pressurized water reactor
TGA	thermo-gravimetric analysis
VVER	water-cooled, water-moderated energy reactor (type of pressurized water reactor developed by Russia)
XLPE	cross-linked polyethylene

4 Background

4.1 General

There are a number of factors that need to be considered when assessing ageing of polymeric components in radiation environments. In 4.2 through 4.5, some of these factors are briefly discussed and references made to more detailed information.

To accelerate radiation-ageing environments, the normal approach is to increase the radiation dose rate, often combined with an increase in temperature. The two most important potential complications arising from such increases involve diffusion-limited oxidation (DLO), which is described in 4.2, and chemical dose rate effects (DRE), which are described in 4.3. The implications of these factors on the use and interpretation of condition monitoring (CM) techniques are also discussed. Accelerated ageing programmes are briefly discussed in 4.4 and 4.5.

4.2 Diffusion-limited oxidation (DLO)

When polymers are exposed to an oxygen-containing environment (e.g. air), some oxygen will be dissolved in the material. In the absence of oxygen-consuming reactions (oxidation), the amount of dissolved oxygen will be proportional to the oxygen partial pressure surrounding the polymer (well known from Henry's Law). Ageing will lead to oxidation reactions in the polymer, whose rate will increase significantly as the dose rate and temperature of ageing are increased. If the rate of consumption of dissolved oxygen in the polymer is faster than the rate at which oxygen can be replenished by diffusion from the surrounding atmosphere, the concentration of dissolved oxygen in the interior regions will decrease with time (the oxygen concentration at the sample surface will remain at its equilibrium value). The reduction in internal oxygen concentration can lead to reduced or negligible oxidation, referred to as "diffusion-limited oxidation".

The importance of this effect is dependent on the sample thickness (thinner samples giving smaller DLO effects) and the ratio of the oxygen consumption rate to the oxygen permeability coefficient P, which is the product of the oxygen diffusion and solubility parameters. Accelerated radiation environments involve increases in dose rates, which increase the oxygen consumption rate. If the temperature remains constant as the dose rate is increased, the oxygen permeability coefficient will be unchanged. This means that DLO effects will become more important as the dose rate is raised. ~~These effects are described in more detail in IEC 61244-1.~~ For more detail about these effects, IEC TS 61244-1 shall be consulted.

The effects of DLO may also need to be considered when carrying out CM measurements. This is not an issue for the many CM techniques which measure properties at ambient temperature, such as those based on density and modulus measurements. On the other hand, several CM techniques such as oxidation induction time (OIT) and thermogravimetric analysis (TGA) use quite elevated temperatures during the measurements. For these techniques, it is quite possible to have DLO effects present during measurement of the CM parameter. For this reason, detailed test methods for CM have been developed [8] to ensure that the sample preparation and test procedure avoid DLO effects. DLO shall be addressed when developing correlation curves for CM methods, to ensure that representative data are obtained for both radiation and thermal ageing.

4.3 Dose rate effects (DRE)

The existence of radiation dose rate effects and methods for dealing with these effects are described in IEC TS 61244-2. This standard shall be consulted for more detail about these effects. Generally, DRE are separated into two types. The first type, which is commonly observed in accelerated radiation-ageing experiments, is due to the DLO effects described in 4.2. These DLO-based effects represent a physical, geometry-dependent DRE.

The second type of interest to the current discussion concerns chemical DRE. Such chemically based DRE are much less common. A documented case of chemical DRE is found in PVC and low density polyethylene materials, caused by the slow breakdown of hydroperoxide intermediate species in the oxidation reaction [9]. The existence of such chemical DRE shall be checked at the start of any accelerated ageing programme. If there are no data available in the literature for the specific materials of interest, this can be checked by including tests at low dose rates in the ageing programme.

4.4 Accelerated radiation ageing

Accelerated ageing programmes in the laboratory tend to use acceleration factors much lower than are normally used in equipment qualification. This may avoid some of the problems associated with DLO and DRE. The ageing produced may then be a better simulation of the long-term ageing that occurs under service conditions. The data that are obtained in accelerated ageing tests can be used with predictive models to enable assessments to be made of the behaviour of the materials under service conditions.

Accelerated ageing programmes require a matrix of test data to be generated over a range of environmental conditions as described in IEC TS 61244-2. As a minimum, data are needed for at least three different dose rates at the normal operating temperature but additional data on thermal ageing and radiation ageing at elevated temperature enables better use to be made of the available predictive modelling methods. The dose rates and temperatures used for accelerated ageing should be selected using the principles described in IEC 60544-2 to ensure that homogeneous oxidation occurs. For each environmental condition used, test data shall be obtained at several different ageing times, the longest of which should be sufficient to introduce significant degradation. A typical test programme could take more than 18 months to complete, dependent on the radiation resistance of the materials being tested.

The data required in the test matrix are determined by the type of component being evaluated. The appropriate test parameters are given in IEC 60544-2 for various types of polymeric materials and components.

4.5 Accelerated thermal ageing

When carrying out thermal ageing as part of an accelerated ageing programme, it is important that an appropriate value of the activation energy is used in assessing the temperature and timescale of the accelerated test. In some materials, the ageing mechanism at high temperatures is different to that which would occur under plant conditions and in many materials the activation energy decreases significantly at lower temperatures [10], [11].

Samples which have been exposed to accelerated thermal ageing shall be allowed to stabilize before any CM tests are carried out. Some polymeric materials are hygroscopic and show a marked dependence of their properties on the moisture content [8]. This is primarily of concern for a few materials used in older nuclear power plants, but may also be important for those CM methods that are sensitive to the moisture content of the material.

5 Approaches to ageing assessment

There are a number of complementary methods available for ageing assessment as described in their respective clauses. Each of these methods has its own advantages and limitations. Selection of one or more of the methods will be dependent on the requirements of the individual users.

Several approaches to ageing assessment in-service are described in this document. These are:

- identifying components of concern to prioritize the application of ageing management programmes (see Clause 6);
- condition monitoring to assess the condition of materials which have aged for extended time periods under actual use environments (see Clause 7);
- predictive modelling to use data from laboratory based accelerated ageing programmes to estimate ageing under real-time ageing conditions (see Clause 8);
- sample deposit to provide samples for the measurement of ageing under real-time ageing conditions (see Clause 9).

6 Identifying components of concern

6.1 General

Within a nuclear power plant, there are many components containing polymeric insulating materials, for example there are over 1 000 km of electrical cables in a typical NPP. It is not practical to assess the ageing of every individual component, and many will not be exposed to significant environmental ageing conditions. It is therefore necessary to prioritize any ageing management programme by identifying those components which are of most concern.

6.2 Priorities for ageing management

Not all components have the same priority for ageing management. In general, those components performing safety functions during and following an accident are of most concern, together with those important to continued operation. Any components outside of these categories would initially be assigned to a low priority for ageing management activities.

The normal operating environment of the components shall be examined to identify the expected impact of the environment on their ageing. Those components identified as being subject to severe ageing are assigned the highest priority, whereas those subject to moderate ageing can then be assigned to a medium priority.

For this prioritization to be carried out effectively, environmental monitoring is essential (see 6.3), combined with knowledge of the ageing behaviour of the components. Initial assessment may make use of design calculations for temperatures and dose rates. The ageing information may come from equipment qualification data or from supplementary accelerated ageing tests carried out in the laboratory.

6.3 Environmental monitoring

Ageing of insulating materials in an NPP is dominated by temperature, radiation dose and radiation dose rate for ~~organic and~~ polymeric materials. A major requirement for ageing management is a detailed knowledge of the actual temperatures and dose rates at locations within the plant where high priority components are situated.

The temperature and dose rate distribution within the plant shall be obtained using temperature recorders and dosimeters. Operational fluctuations and seasonal variations shall be included by carrying out these measurements over several fuel cycles. It may be necessary to repeat such measurements when changes are made to the plant, for example power upgrades.

Small self-contained temperature recorders are available and are a practical and flexible method for localized temperature recording to supplement bulk temperature monitoring equipment that is already installed in the plant.

Radiation monitoring is best achieved with alanine dosimeters, which are suitable for long term measurements. These dosimeters are not significantly affected by temperature, can be sealed to avoid the influence of humidity and are suitable for monitoring over a wide dose range. The radicals formed under irradiation in alanine are stable over time periods in excess of a year and can be measured using electron spin resonance ~~(IEC 60544-1)~~. For more detail about radiation monitoring, IEC TS 61244-1 shall be consulted.

6.4 Localized severe environments

Identification of localized severe environments (hotspots) where high priority components are located is an important aspect of ageing assessment. Such locations can be identified in a number of ways, including interviews of plant personnel, operational reviews, review of plant layout drawings and plant walkdowns [12], [13], [14], [15]. Each will provide a different perspective on hotspot conditions. Feedback from plant maintenance personnel is an important aspect of identifying early signs of degradation.

6.5 Worst case components

Having prioritized the components most likely to be affected by ageing, carried out environmental monitoring and identified localized severe environments, the components will have been assigned to either a high, medium or low priority for further ageing management. All components assigned to a high priority shall be subjected to ageing management activities such as CM or planned replacement.

The evaluation process can be refined as more information becomes available. For example, if CM of high priority cables indicates that degradation is much less severe than expected, it may be appropriate to move these components to a lower priority category.

7 Condition monitoring techniques

7.1 General

CM techniques are used to assess the condition of materials which have aged for extended time periods under actual use environments, such as in nuclear power plants, accelerators, reprocessing plants~~, etc~~. The approach makes use of test methods which have been shown to correlate well with ageing degradation.

CM in ageing assessment can be used in a number of ways, ranging from short term trouble shooting to long term on-going qualification programmes.

7.2 Establishing correlation curves for CM methods

In order to use CM methods effectively, it is important to develop correlation curves between the monitoring parameter measured and the prime indicator of degradation or functionality. For low-voltage polymeric cable materials, the prime indicator of degradation is generally considered to be tensile elongation at break, since changes in electrical properties are small before physical failure of the cable in many cases. In seal materials, the compression set has proved to be a useful indicator of the degradation in sealing properties introduced by ageing. Suitable degradation parameters for other components are given in IEC 60544-2.

Correlation curves shall be determined by measurements of the prime indicator and the relevant CM parameter on samples aged under identical conditions, as shown schematically in Figure 1. The measurements shall cover a range of degradation levels, from the unaged condition to a severely degraded condition. It is recommended that at least five sets of data at different ageing times be used in establishing the correlation curve (Figure 2), preferably for several different temperatures and radiation dose rates. An example of a correlation curve for a CSPE cable sheath material is given in Annex A.

Correlation curves are normally established using accelerated testing. Such tests shall be carried out using the procedures described in IEC 60544-2. Alternatively, correlation curves can be established as part of the sample deposit procedure for ageing assessment, as described in Clause 9, or as part of the initial equipment qualification process.

7.3 CM methods

There is a wide range of methods which have been evaluated for CM of polymeric components, particularly for cable materials [4], [17]. Of the many methods examined, several have been identified as being potentially suitable for practical use. Measurement standards for the most developed of these methods are described in detail in the various parts of the IEC/IEEE 62582 series [8]. For these methods, data correlating the monitoring parameter with degradation of the polymeric component have been built up and the practical limitations explored. The most developed methods are:

- indenter modulus;
- oxidation induction time (OIT) and oxidation induction temperature (OITP);
- elongation at break.

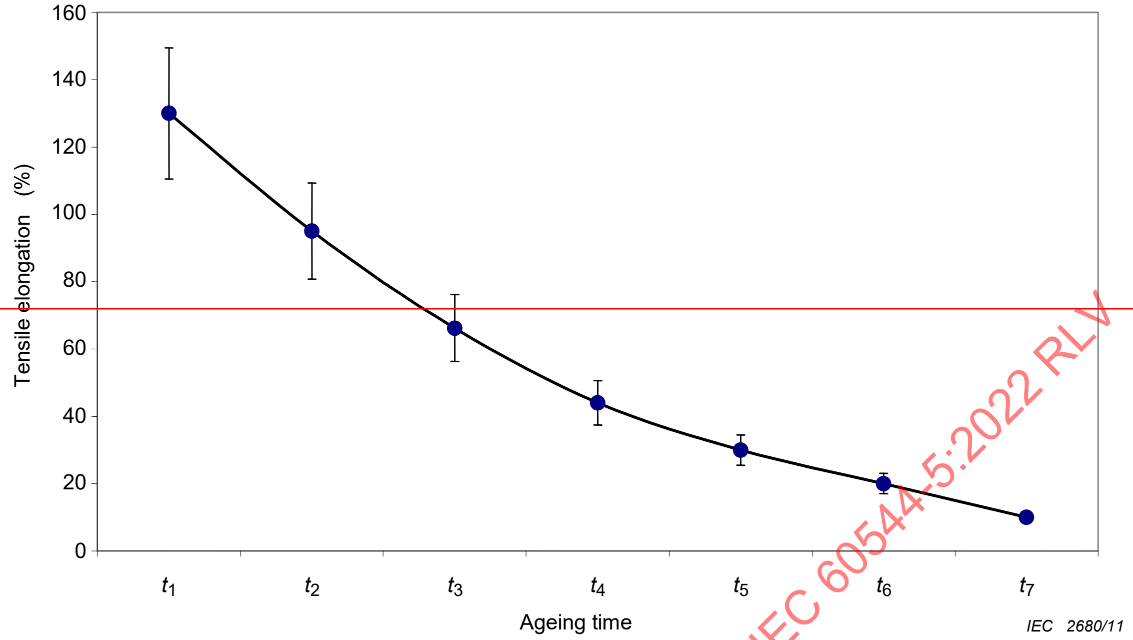
NOTE There are many other methods which have been investigated for CM and suitable measurement standards for some of these are expected to be developed over the next few years. A number of these are described in IAEA-NP-T-3.6 and IAEA-TECDOC-1825, together with their limitations [4], [17].

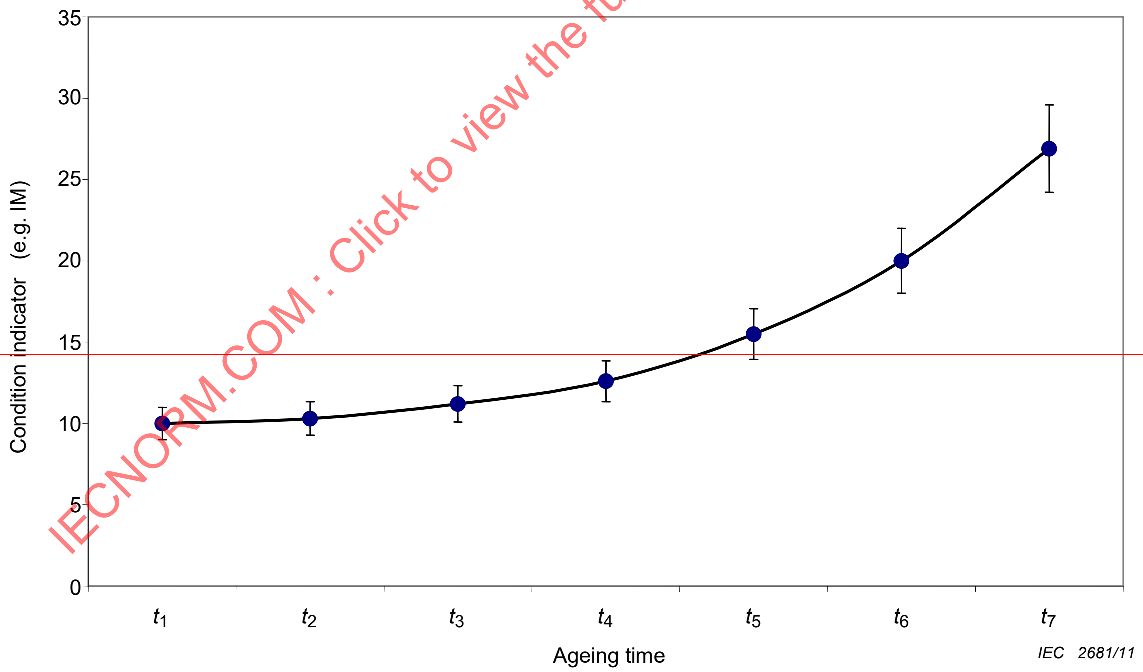
Visual inspection (including tactile and other sensory inspection) is a qualitative monitoring method which can be a valuable tool in assessing localized ageing degradation within nuclear power plants using walkdowns. The practical considerations for in-plant visual inspections (walkdowns) are described in more detail in [12], [13], [14], [15].

Electrical methods for assessing degradation in cable systems and their associated end-devices are described in IEC 62465 [18]. These methods primarily relate to cable systems (connectors, penetrations, etc.) rather than degradation of the insulating materials but some methods are showing great promise in correlating with thermal ageing degradation [18], [19].

7.4 Using CM for short-term troubleshooting

In short-term tests, the emphasis of CM is in identifying the extent of a problem or in demonstrating that a problem does not exist. For example, the indenter has been used to determine the extent of damage to cables from degradation arising from damaged thermal insulation on a steam line near a cable in a BWR nuclear power plant. By carrying out indenter measurements along this cable, a profile of the damaged area was obtained. This enabled replacement of a limited section of cable rather than replacing the entire cable run. Another example was the use of in-situ electrical CM methods to determine the functionality of a range of cables in an NPP that had been in operation for 40 years. The results showed that 60 % of the cables tested were not significantly aged and recommendations could be made for replacement of those that had aged significantly [20].


160
140
120
100
80
60
40
20
0
Tensile elongation (%)
t_1
t_2
t_3
t_4
t_5
t_6
t_7
Ageing time
IEC 2680/11


35
30
25
20
15
10
5
0
Condition indicator (e.g. IM)
t_1
t_2
t_3
t_4
t_5
t_6
t_7
Ageing time
IEC 2681/11

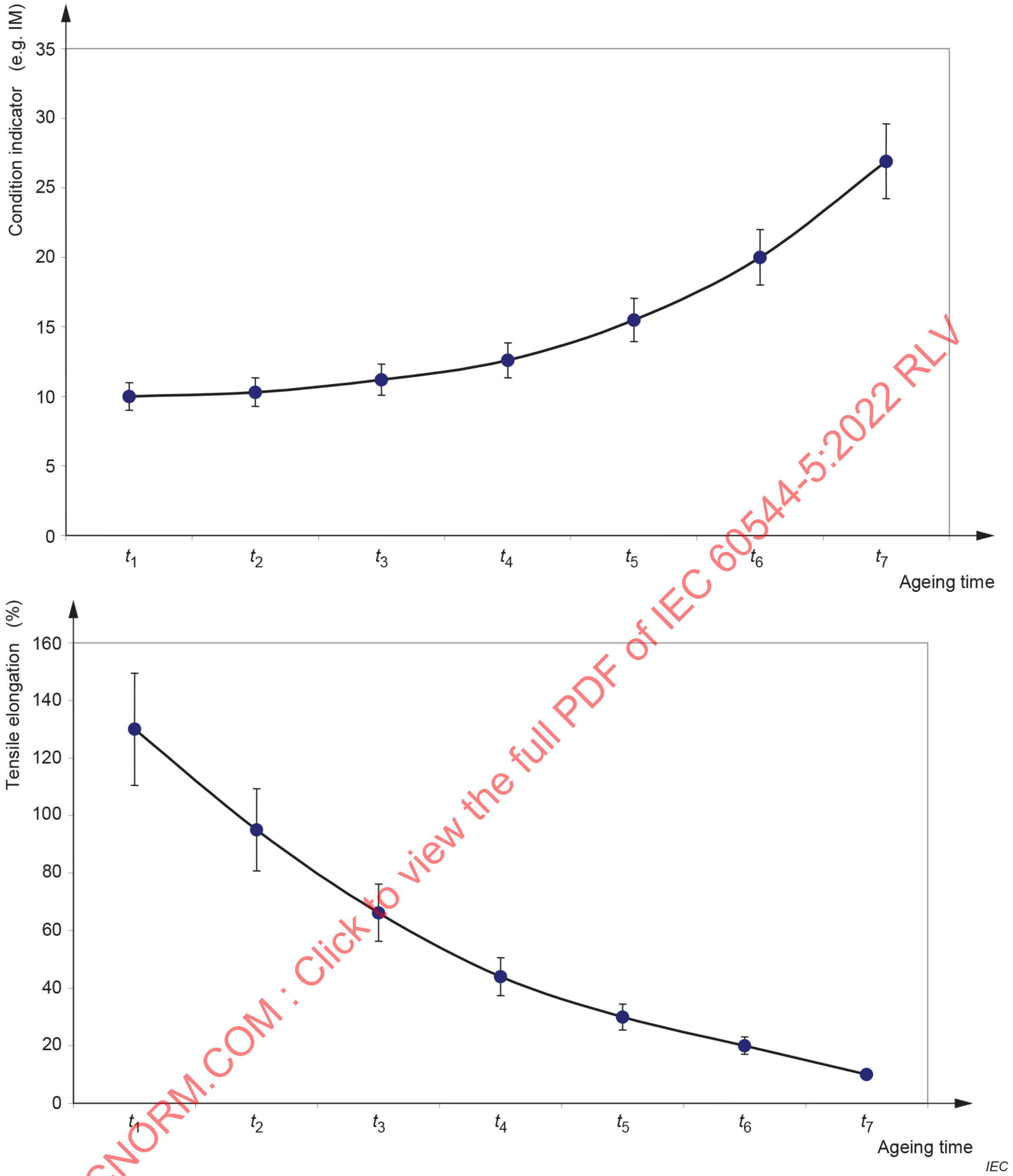


Figure 1 – Development of ageing data on changes in tensile elongation and a condition indicator (e.g. indenter modulus) – Schematic representation

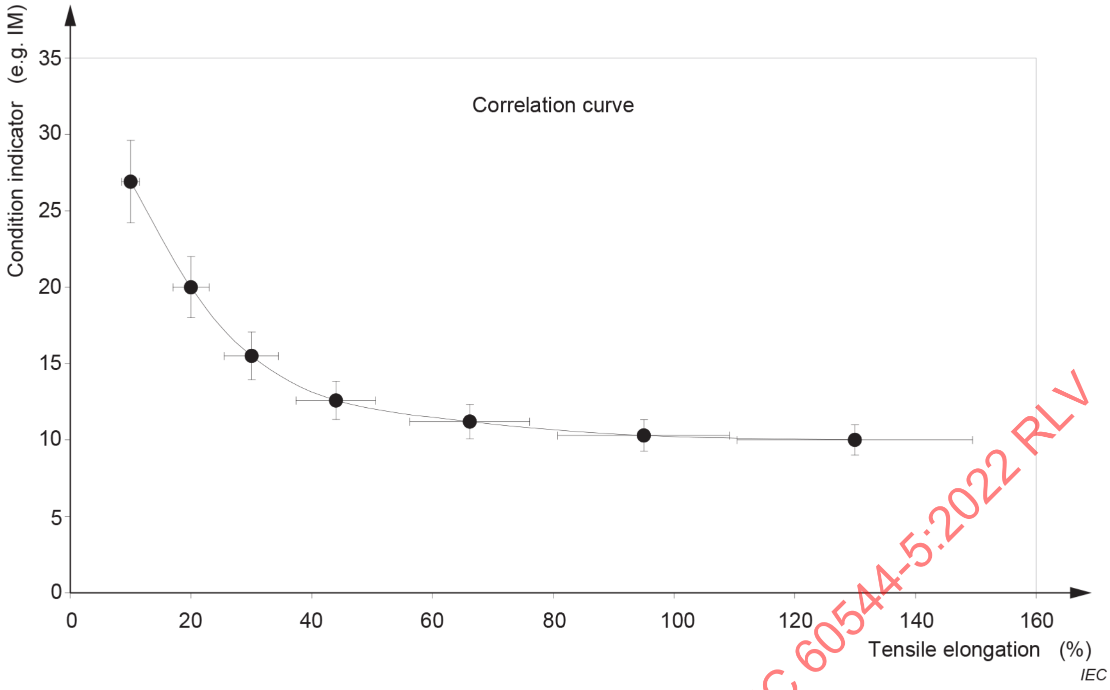


Figure 2 – Correlation curve derived from data in Figure 1 – Schematic representation

In some cases, the use of design criteria (e.g. calculation of self-heating of power cable from current loading) can be very conservative, indicating that the insulation would be expected to show significant degradation. Checks on the component using CM methods can be used to demonstrate that the materials have not degraded to the extent predicted, avoiding unnecessary replacement. This is particularly important where a short, qualified life has been determined during EQ.

7.5 Using CM for long-term degradation assessment

CM methods can also be used in on-going test programmes which span the lifetime of the plant. Typical uses of CM methods in such programmes are

- trending of component condition relative to a qualified condition determined during initial EQ procedures;
- comparison of CM data with predictive modelling, based on accelerated ageing data in the laboratory and a knowledge of the environmental conditions seen by the component;
- monitoring of components in a sample deposit located in a severe environment in the plant (this is most frequently used for cables and small electrical components).

Figure 3 illustrates how the elongation at break can be estimated from a CM parameter such as the indenter modulus.

Condition based qualification (CBQ) is becoming the recommended method for equipment qualification for new NPPs [12], [13]. For this approach to EQ to be used, CM techniques shall be applied during the pre-ageing phase of qualification to determine the shape of the ageing curve and the limiting value of CM parameters at which the component can survive a DBE, i.e. the qualified condition. Trending of the condition of the component relative to this qualified condition is an essential part of CBQ.

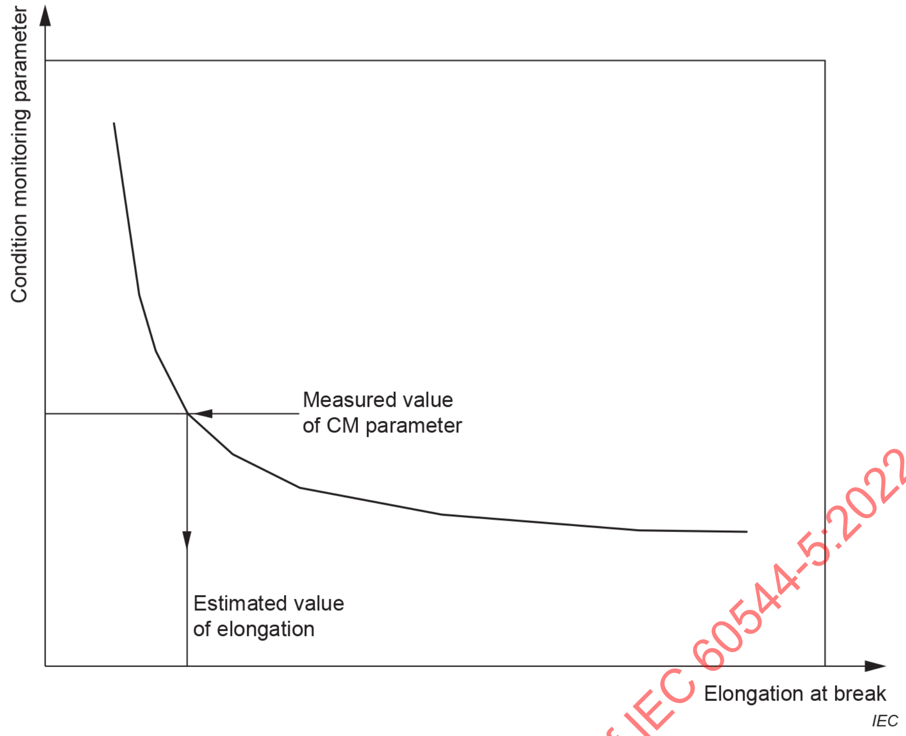


Figure 3 – Estimation of elongation from a correlation curve

8 Predictive modelling

Data obtained during laboratory accelerated ageing tests can be used to generate model parameters for predictive ageing models, such as those described in IEC TS 61244-2. These models can be used to predict the degradation of specific materials under various ageing conditions of temperature and radiation dose rate. By using the data obtained from environmental monitoring of the actual temperatures and dose rates in the plant, the degradation expected to occur in real-time ageing can be assessed.

This approach can also be used to estimate the effect of changes in the environmental conditions, for example a short-term increase in temperature arising from damage to thermal insulation on a nearby steam pipe.

The detailed accelerated ageing tests required to obtain the model parameters are most likely to be carried out on materials for use in new plants. The use of such models combined with design data on environmental conditions can be used during the design phase of a new plant to identify potential problem areas where re-siting of equipment would be appropriate, for example re-routing of a cable run to avoid a localized hotspot.

Three predictive models which make use of a matrix of accelerated ageing data are described in detail in IEC TS 61244-2, together with the limitations and data requirements for use of these models:

- a power law model that has proved useful for materials exposed to radiation environments where thermal ageing is negligible;
- a time dependent superposition model which can model combined thermal and radiation ageing for those materials with a single dominant ageing mechanism;
- a dose dependent superposition model which is particularly useful in the low dose rate radiation ageing range where thermal ageing is important, and for materials with complex ageing behaviour.

9 Sample deposit

9.1 General

The testing of materials from a sample deposit in the plant is an alternative approach to assessment of ageing in service. This makes use of samples specifically installed in the plant for destructive testing and/or CM as part of an ageing management programme.

Assessment of the long-term properties of components using a sample deposit has advantages over accelerated ageing programmes. Its use means that the components age under real plant conditions but can, nevertheless, be checked and monitored without impairing plant operation. Such deposits are often installed in an area of the plant which has a relatively severe environment compared with most other areas where such materials are used. In this case, the sample in the deposit will age more rapidly and therefore will have a lead time over the bulk of the material in the plant.

Most deposits are primarily used for evaluation of cables and small electrical components and are mainly set up in a plant which has been in operation for less than five years. However, a deposit can also be of use in an older plant, provided that the samples are pre-aged using accelerated ageing before installation in the deposit (9.3). Samples in deposits are particularly useful for on-going qualification programmes.

9.2 Requirements of a deposit

A major prerequisite for the implementation of a sample deposit is a good knowledge of the radiation dose and temperature distribution at the deposit position and at positions in the plant where the material being tested is in routine use.

Environmental monitoring can be used to select positions in the plant that are exposed to ~~a higher dose~~ more severe environmental conditions than most of the real positions. It may even be possible to find a location where the temperature is also similar to the maximum design temperature. Experience has shown that the loop line between the reactor pressure vessel and the steam generator is suitable for this purpose in pressurized water reactors (PWRs) and the reactor water clean-up system in boiling water reactors (BWRs). In VVER type reactors, the main circulation pipe, either hot or cold leg, is also a suitable location for a deposit.

In selecting a position for the deposit, ~~care shall be taken to~~ ensure that the environmental conditions at the deposit will produce degradation which simulates real conditions. ~~In particular, care~~ Particular consideration shall be ~~taken in exposing~~ given to the exposure of some XLPE and some EPR based components to radiation ageing at elevated temperature if their normal use is at lower temperatures. These materials can show a reverse temperature effect [21], [22], [23], with degradation occurring more rapidly at the lower temperatures. For XLPE materials, ~~the deposit shall~~ it is recommended that deposits be placed at both the lowest and the highest ambient temperature normally seen in plant operations. It is recommended that several positions for deposits are determined within the plant that also represent high dose rates or high temperatures for materials other than XLPE.

9.3 Pre-ageing samples for a deposit

When a deposit is set up in an NPP which has been in operation for more than five years, it will be necessary to pre-age the samples to be placed in the deposit to a level equivalent to the actual age of the plant. For NPPs that have been in operation for less than five years, it is assumed that polymeric components have not significantly aged. The accelerated ageing used to pre-age the samples shall use low acceleration factors. The temperature and dose rate being simulated shall be based on the actual values in the plant, as determined from environmental monitoring (see 6.3). It may be possible to use real-time aged cables that have been removed from the plant as samples in the deposit. This is only practical if the temperature and radiation dose rate to which they have been exposed is known.

9.4 Installation of a sample deposit

The deposit shall be arranged so that the samples are exposed to a reasonably uniform radiation field (e.g. if using the loop line in a PWR as the radiation source, they are kept at a constant distance from the loop). This can be readily done by using cable trays strapped to the circumference of the loop line. The specific design of the deposit can easily be adapted to the local conditions in the plant. Samples shall be placed in a single layer to avoid self-shielding.

The deposit needs to be equipped with a representative selection of the materials (e.g. cable samples, small electrical components) used in radiation environments. The number and type of samples required needs to be sufficient to ensure that enough material is available for the scheduled removal of samples over the required period of up to 60 years (for a deposit in a new plant). It is prudent to include extra samples to allow for future improvements in CM methods or for life extension requirements. Annex B illustrates the type of samples usually included in a deposit.

In assessing the number and type of samples required, the intervals at which samples are to be removed and the tests that are to be performed need to be established. For example, for cables, samples of about 0,3 m to 0,5 m in length are quite satisfactory for CM measurements ~~of tensile elongation at break. Most of the CM methods currently available~~ that are non-destructive or need only small amounts of material; however, electrical tests will need longer lengths. Preparation of samples for elongation at break from an aged cable can be difficult [17], so it is advisable to include pre-prepared dumb-bell samples in the deposit if such measurements are required. If samples are required for a DBE test with electrical measurements, a minimum length of 3,05 m is required. Any whole cable samples included in a deposit shall have their ends sealed.

The deposit shall be fitted with dosimeters to record the profile of the radiation dose within the deposit and temperature monitoring is also required. This environmental monitoring shall be continued over at least two years to get a representative picture of the long-term environmental conditions within the deposit. ~~Care shall be taken to~~ Ensure that there is a free flow of air into the deposit. Suitable contamination protection is desirable but shall not restrict air access.

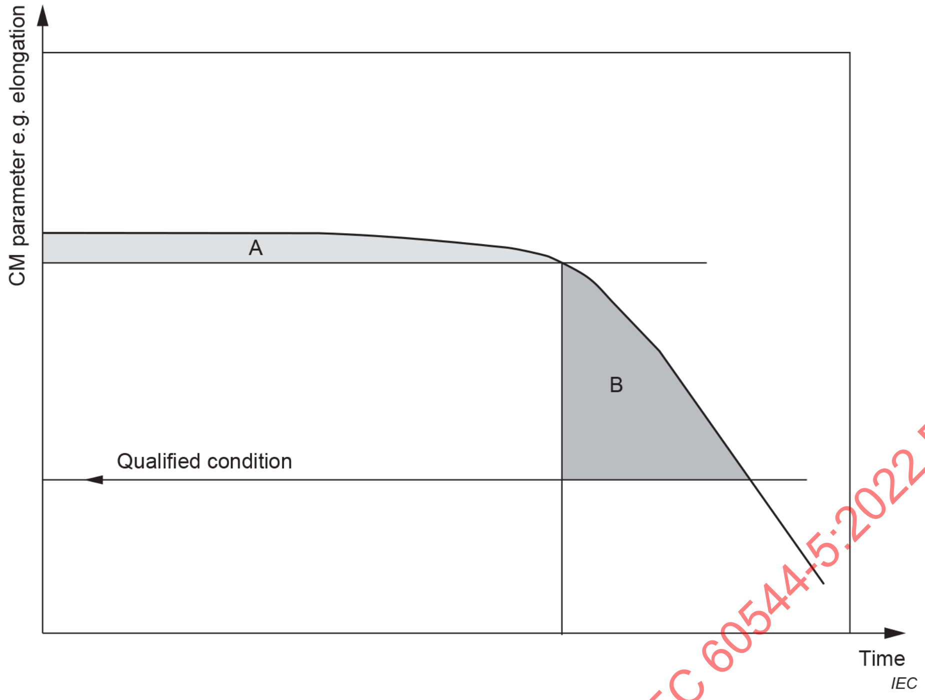
9.5 Testing of samples from the deposit

Initially, baseline data for all of the materials installed in the deposit shall be determined using unaged material. This baseline data shall utilize all of the CM tests which will be used on the materials in the deposit. It is advisable to retain samples of unaged material to enable baseline data to be generated in the future for newly developed CM methods.

At regular intervals, samples will be removed for destructive tests (e.g. tensile elongation measurements) or subjected to CM tests. The test intervals will generally be limited by the accessibility of the sample deposit. In most plants, the deposit will only be available for access when the plant is shut down. The type of testing schedule required is illustrated in Annex B.

9.6 Determination of sampling intervals

For the cable types currently in use, it is reasonable to remove the first samples from the deposit five years after the start of plant operation, since the type and qualification tests that have already been performed provide an acceptable confidence interval for at least this period. The recommended interval between tests for a deposit in a new plant is five to eight years. This interval shall be decreased if the materials are showing signs of more rapid degradation than expected. Once degradation starts to be observed the sampling interval shall be reduced, as indicated in Figure 4. A revised sampling interval of one to two years is then recommended. The precise boundaries of zones A and B illustrated schematically in Figure 4 shall be defined by the shape of the degradation curve for the specific material and by the qualified condition for that material.



NOTE In zone A, samples are taken at five to eight year intervals; in zone B, the interval is decreased to one to two years.

Figure 4 – Modification of sampling interval dependent on values of the CM indicator – Schematic representation

9.7 Real time aged materials

The deposit method is primarily suitable for new plants where unaged samples are readily available for the material types that are to be included in the deposit. For older plants, where unaged samples are not available for use in a deposit, an alternative is to evaluate the actual long-term ageing behaviour by removing samples from the plant. The disadvantages of this sampling procedure are that it constitutes an intervention into the plant and that the samples have to be replaced with suitably qualified materials. However, it may be necessary to use this method if, for special reasons, validated results have to be available within a short time (e.g. for older plants without existing EQ).

If there are data available on environmental conditions within the plant, a position can be selected where the material has been exposed to the worst-case condition. For cable materials, such positions are usually in the direct vicinity of the loop lines (PWR) or in the reactor water cleanup system (BWR). Cable samples from real positions are normally irradiated quite inhomogeneously, for example a cable run converging on the loop line. Before removing the cable sample, the dose distribution shall be determined and the cable location identified clearly in a reproducible manner to allow the test results to be interpreted correctly.

CM methods that are non-destructive or use only micro-samples can be used to evaluate ageing degradation where sample removal for destructive testing is not practical. Baseline data are still required.

Annex A
(informative)

Example of a CM correlation curve

An example of a correlation curve in Figure A.1 for a CSPE cable material shows the correlation between indenter measurements and changes in the tensile elongation at break obtained during an accelerated ageing programme [24]. A good correlation has been obtained for both radiation and thermal ageing of this CSPE material. This correlation curve also illustrates the degree of scatter that is likely to be observed in real data.

In-plant CM measurements on this material using the indenter can be compared with the predicted degradation that allows residual life to be estimated. The predicted degradation is obtained from use of ageing models (such as those described in IEC TS 61244-2), combined with knowledge of the environmental conditions in the plant. Alternatively, the condition can be compared to a qualified condition determined during EQ.

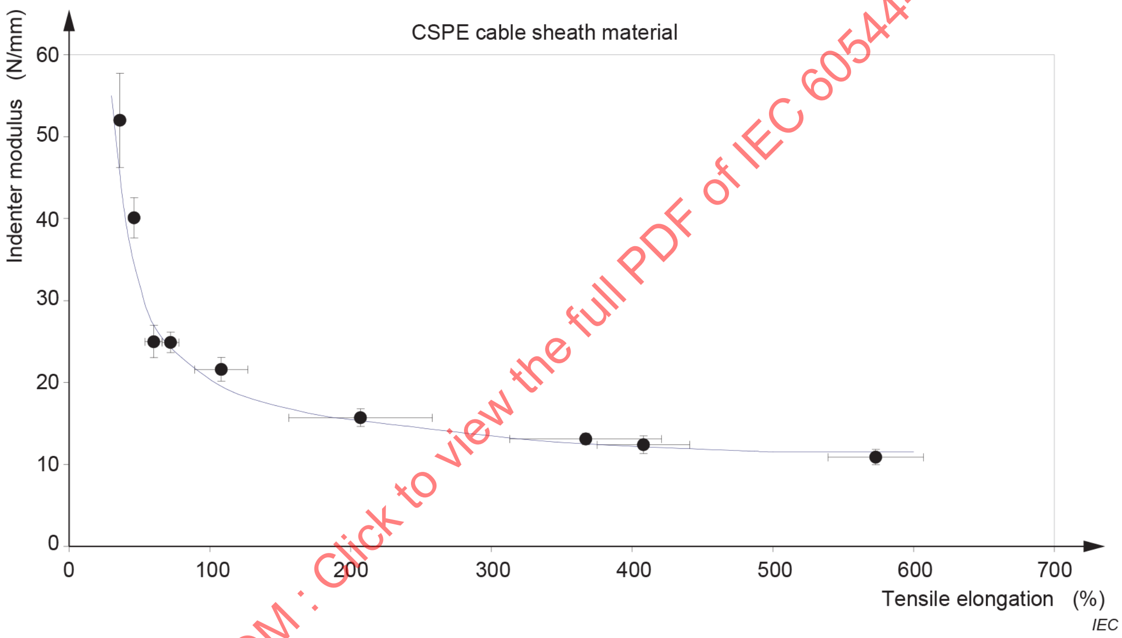


Figure A.1 – Correlation curve for indenter modulus against tensile elongation for a CSPE cable jacket material [24]

Annex B
(informative)

Use of a deposit

B.1 Typical sample in a deposit

A number of sample deposits have been installed in NPPs, mainly for cable materials. The detail of what is included in the deposits will vary from plant to plant but some typical examples are illustrated below.

A typical cable deposit might include the following types of samples:

- batches of pre-prepared dumb-bell samples for elongation tests;
- short sections of whole cable (typically 0,3 m to 0,5 m in length) for indenter and other CM measurements (these samples can also be used for preparation of dumb-bell samples after ageing, if that is possible in practice);
- longer sections of whole cable for periodic electrical tests (typically 1 m to 2 m in length, but if space is available longer lengths will allow for a wider range of tests);
- whole cable (typically > 3 m in length) for future DBE testing.

Alternatively, longer lengths of cable can be utilized in a deposit and short lengths cut off for elongation tests and other CM tests at intervals.

B.2 Typical testing schedule for a deposit

For a plant cable deposit, the testing schedule could take the following form.

- Samples are removed for CM measurements on each component type. Initially, these CM tests should be non-destructive (e.g. indenter or other CM techniques, as appropriate to the component type) or require only small samples (e.g. OIT tests), to preserve the material in the deposit.

The amount of material available in a deposit is often very limited; it is therefore important to conserve material as much as possible in the early stages of its use.

- If the non-destructive or micro-sample tests indicate that degradation is starting to occur, samples for elongation at break tests should be removed and tested.
- The values of the CM parameters are compared with the baseline data for that component. If significant degradation has occurred, additional tests may be carried out for example a DBE test.

It is important that the CM measurements are carried out using the methods specifically recommended for ageing management programmes, see for example [8].

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IEC 60544-5

Edition 3.0 2022-06

INTERNATIONAL STANDARD

NORME INTERNATIONALE

**Electrical insulating materials – Determination of the effects of ionizing radiation –
Part 5: Procedures for assessment of ageing in service**

**Matériaux isolants électriques – Détermination des effets des rayonnements ionisants –
Partie 5: Procédures pour l'évaluation du vieillissement en service**

IEC 60544-5:2022-06(en-fr)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ELECTRICAL INSULATING MATERIALS –
DETERMINATION OF THE EFFECTS OF IONIZING RADIATION –

Part 5: Procedures for assessment of ageing in service

FOREWORD

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IEC 60544-5 has been prepared by IEC technical committee TC 112: Evaluation and qualification of electrical insulating materials and systems. It is an International Standard.

This third edition cancels and replaces the second edition published in 2011. This edition constitutes a technical revision.

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

a) added recent references in 7.4 showing that some electrical condition monitoring methods show promising correlations with ageing;
b) updated recommendations for implementation of a sample deposit in 9.2, installation of a sample deposit in 9.3 and testing of samples from the deposit in 9.4;
c) updated list of references.

The text of this International Standard is based on the following documents:

Draft	Report on voting
112/523/CDV	112/553/RVC

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

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 60544 series, published under the general title *Electrical insulating materials – Determination of the effects of ionizing radiation*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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

INTRODUCTION

Organic and polymeric materials provide a significant proportion of the insulation used in electrical systems. These materials are sensitive to the effects of irradiation and the response varies widely between different types. It is therefore important to be able to assess the degree of degradation of these insulating materials during their service lifetimes. This part of IEC 60544 provides recommended procedures for assessing ageing of insulating materials in service.

There are a number of approaches to the assessment of ageing of polymer-based components exposed to radiation environments [1], [2], [3], [4][1]. These are based on the better understanding of the factors affecting ageing degradation which has been developed over several decades. In nuclear power plants, qualification programmes are normally used for the selection of components, including those based on polymeric materials. These initial qualification procedures, such as IEEE Std 323™-1974[2] [5] and IEEE Std 383™-1974[2] [6], were originally written before there was sufficient understanding of ageing mechanisms. Most of the methods discussed in this document are therefore used to supplement the initial qualification process.

This document is the fifth in a series dealing with the effect of ionizing radiation on insulating materials.

IEC 60544-1 (Radiation interaction and dosimetry) constitutes an introduction dealing very broadly with the problems involved in evaluating radiation effects. It also provides guidance on dosimetry terminology, several methods of determining exposure and absorbed dose, and methods of calculating absorbed dose in any specific material from the dosimetry method applied.

IEC 60544-2 (Procedures for irradiation and test) describes procedures for maintaining seven different types of exposure conditions during irradiation. It also specifies the controls that should be maintained over these conditions so that when test results are reported, reliable comparisons of material performance can be made. In addition, it defines certain important irradiation conditions and test procedures to be used for property change determinations and corresponding end-point criteria.

IEC 60544-3 has been withdrawn and incorporated into the second edition of IEC 60544-2.

IEC 60544-4 (Classification system for service in radiation environments) provides a recommended classification system for categorizing the radiation endurance of insulation materials.

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1 Numbers in square brackets refer to the Bibliography.

2 IEEE Std 323-1974 and IEEE Std 383-1974 are now withdrawn and have been superseded by more recent revisions.

ELECTRICAL INSULATING MATERIALS – DETERMINATION OF THE EFFECTS OF IONIZING RADIATION –

Part 5: Procedures for assessment of ageing in service

1 Scope

This part of IEC 60544 covers ageing assessment methods which can be applied to components based on polymeric materials (e.g. cable insulation and jackets, elastomeric seals, polymeric coatings, gaiters) which are used in environments where they are exposed to radiation.

The object of this document is aimed at providing methods for the assessment of ageing in service. The approaches discussed in Clause 5 through Clause 9 cover ageing assessment programmes based on condition monitoring (CM), the use of sample deposits in severe environments and sampling of real-time aged components.

2 Normative references

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

IEC 60544-2, *Electrical insulating materials – Determination of the effects of ionizing radiation on insulating materials – Part 2: Procedures for irradiation and test*

IEC TS 61244-1, *Determination of long-term radiation ageing in polymers – Part 1: Techniques for monitoring diffusion-limited oxidation*

IEC TS 61244-2, *Determination of long-term radiation ageing in polymers – Part 2: Procedures for predicting ageing at low dose rates*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

No terms and definitions are listed in this document.

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

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

3.2 Abbreviated terms

BWR	boiling water reactor
CBQ	condition-based qualification
CM	condition monitoring
CSPE	chlorosulphonated polyethylene
DBE	design basis event

DLO	diffusion-limited oxidation
DRE	dose rate effect
EPR	ethylene propylene rubber
EQ	environmental qualification
NPP	nuclear power plant
OIT	oxidation induction time
OITP	oxidation induction temperature
PVC	polyvinyl chloride
PWR	pressurized water reactor
TGA	thermo-gravimetric analysis
VVER	water-cooled, water-moderated energy reactor (type of pressurized water reactor developed by Russia)
XLPE	cross-linked polyethylene

4 Background

4.1 General

There are a number of factors that need to be considered when assessing ageing of polymeric components in radiation environments. In 4.2 through 4.5, some of these factors are briefly discussed and references made to more detailed information.

To accelerate radiation-ageing environments, the normal approach is to increase the radiation dose rate, often combined with an increase in temperature. The two most important potential complications arising from such increases involve diffusion-limited oxidation (DLO), which is described in 4.2, and chemical dose rate effects (DRE), which are described in 4.3. The implications of these factors on the use and interpretation of condition monitoring (CM) techniques are also discussed. Accelerated ageing programmes are briefly discussed in 4.4 and 4.5.

4.2 Diffusion-limited oxidation (DLO)

When polymers are exposed to an oxygen-containing environment (e.g. air), some oxygen will be dissolved in the material. In the absence of oxygen-consuming reactions (oxidation), the amount of dissolved oxygen will be proportional to the oxygen partial pressure surrounding the polymer (well known from Henry's Law). Ageing will lead to oxidation reactions in the polymer, whose rate will increase significantly as the dose rate and temperature of ageing are increased. If the rate of consumption of dissolved oxygen in the polymer is faster than the rate at which oxygen can be replenished by diffusion from the surrounding atmosphere, the concentration of dissolved oxygen in the interior regions will decrease with time (the oxygen concentration at the sample surface will remain at its equilibrium value). The reduction in internal oxygen concentration can lead to reduced or negligible oxidation, referred to as "diffusion-limited oxidation".

The importance of this effect is dependent on the sample thickness (thinner samples giving smaller DLO effects) and the ratio of the oxygen consumption rate to the oxygen permeability coefficient P, which is the product of the oxygen diffusion and solubility parameters. Accelerated radiation environments involve increases in dose rates, which increase the oxygen consumption rate. If the temperature remains constant as the dose rate is increased, the oxygen permeability coefficient will be unchanged. This means that DLO effects will become more important as the dose rate is raised. For more detail about these effects, IEC TS 61244-1 shall be consulted.

The effects of DLO may also need to be considered when carrying out CM measurements. This is not an issue for the many CM techniques which measure properties at ambient temperature, such as those based on density and modulus measurements. On the other hand, several CM techniques such as oxidation induction time (OIT) and thermogravimetric analysis (TGA) use quite elevated temperatures during the measurements. For these techniques, it is quite possible to have DLO effects present during measurement of the CM parameter. For this reason, detailed test methods for CM have been developed [8] to ensure that the sample preparation and test procedure avoid DLO effects. DLO shall be addressed when developing correlation curves for CM methods, to ensure that representative data are obtained for both radiation and thermal ageing.

4.3 Dose rate effects (DRE)

The existence of radiation dose rate effects and methods for dealing with these effects are described in IEC TS 61244-2. This standard shall be consulted for more detail about these effects. Generally, DRE are separated into two types. The first type, which is commonly observed in accelerated radiation-ageing experiments, is due to the DLO effects described in 4.2. These DLO-based effects represent a physical, geometry-dependent DRE.

The second type of interest to the current discussion concerns chemical DRE. Such chemically based DRE are much less common. A documented case of chemical DRE is found in PVC and low density polyethylene materials, caused by the slow breakdown of hydroperoxide intermediate species in the oxidation reaction [9]. The existence of such chemical DRE shall be checked at the start of any accelerated ageing programme. If there are no data available in the literature for the specific materials of interest, this can be checked by including tests at low dose rates in the ageing programme.

4.4 Accelerated radiation ageing

Accelerated ageing programmes in the laboratory tend to use acceleration factors much lower than are normally used in equipment qualification. This may avoid some of the problems associated with DLO and DRE. The ageing produced may then be a better simulation of the long-term ageing that occurs under service conditions. The data that are obtained in accelerated ageing tests can be used with predictive models to enable assessments to be made of the behaviour of the materials under service conditions.

Accelerated ageing programmes require a matrix of test data to be generated over a range of environmental conditions as described in IEC TS 61244-2. As a minimum, data are needed for at least three different dose rates at the normal operating temperature but additional data on thermal ageing and radiation ageing at elevated temperature enables better use to be made of the available predictive modelling methods. The dose rates and temperatures used for accelerated ageing should be selected using the principles described in IEC 60544-2 to ensure that homogeneous oxidation occurs. For each environmental condition used, test data shall be obtained at several different ageing times, the longest of which should be sufficient to introduce significant degradation. A typical test programme could take more than 18 months to complete, dependent on the radiation resistance of the materials being tested.

The data required in the test matrix are determined by the type of component being evaluated. The appropriate test parameters are given in IEC 60544-2 for various types of polymeric materials and components.

4.5 Accelerated thermal ageing

When carrying out thermal ageing as part of an accelerated ageing programme, it is important that an appropriate value of the activation energy is used in assessing the temperature and timescale of the accelerated test. In some materials, the ageing mechanism at high temperatures is different to that which would occur under plant conditions and in many materials the activation energy decreases significantly at lower temperatures [10], [11].

Samples which have been exposed to accelerated thermal ageing shall be allowed to stabilize before any CM tests are carried out. Some polymeric materials are hygroscopic and show a marked dependence of their properties on the moisture content [8]. This is primarily of concern for a few materials used in older nuclear power plants, but may also be important for those CM methods that are sensitive to the moisture content of the material.

5 Approaches to ageing assessment

There are a number of complementary methods available for ageing assessment as described in their respective clauses. Each of these methods has its own advantages and limitations. Selection of one or more of the methods will be dependent on the requirements of the individual users.

Several approaches to ageing assessment in-service are described in this document. These are:

- identifying components of concern to prioritize the application of ageing management programmes (see Clause 6);
- condition monitoring to assess the condition of materials which have aged for extended time periods under actual use environments (see Clause 7);
- predictive modelling to use data from laboratory based accelerated ageing programmes to estimate ageing under real-time ageing conditions (see Clause 8);
- sample deposit to provide samples for the measurement of ageing under real-time ageing conditions (see Clause 9).

6 Identifying components of concern

6.1 General

Within a nuclear power plant, there are many components containing polymeric insulating materials, for example there are over 1 000 km of electrical cables in a typical NPP. It is not practical to assess the ageing of every individual component, and many will not be exposed to significant environmental ageing conditions. It is therefore necessary to prioritize any ageing management programme by identifying those components which are of most concern.

6.2 Priorities for ageing management

Not all components have the same priority for ageing management. In general, those components performing safety functions during and following an accident are of most concern, together with those important to continued operation. Any components outside of these categories would initially be assigned to a low priority for ageing management activities.

The normal operating environment of the components shall be examined to identify the expected impact of the environment on their ageing. Those components identified as being subject to severe ageing are assigned the highest priority, whereas those subject to moderate ageing can then be assigned to a medium priority.

For this prioritization to be carried out effectively, environmental monitoring is essential (see 6.3), combined with knowledge of the ageing behaviour of the components. Initial assessment may make use of design calculations for temperatures and dose rates. The ageing information may come from equipment qualification data or from supplementary accelerated ageing tests carried out in the laboratory.

6.3 Environmental monitoring

Ageing of insulating materials in an NPP is dominated by temperature, radiation dose and radiation dose rate for polymeric materials. A major requirement for ageing management is a detailed knowledge of the actual temperatures and dose rates at locations within the plant where high priority components are situated.

The temperature and dose rate distribution within the plant shall be obtained using temperature recorders and dosimeters. Operational fluctuations and seasonal variations shall be included by carrying out these measurements over several fuel cycles. It may be necessary to repeat such measurements when changes are made to the plant, for example power upgrades.

Small self-contained temperature recorders are available and are a practical and flexible method for localized temperature recording to supplement bulk temperature monitoring equipment that is already installed in the plant.

Radiation monitoring is best achieved with alanine dosimeters, which are suitable for long term measurements. These dosimeters are not significantly affected by temperature, can be sealed to avoid the influence of humidity and are suitable for monitoring over a wide dose range. The radicals formed under irradiation in alanine are stable over time periods in excess of a year and can be measured using electron spin resonance. For more detail about radiation monitoring, IEC TS 61244-1 shall be consulted.

6.4 Localized severe environments

Identification of localized severe environments (hotspots) where high priority components are located is an important aspect of ageing assessment. Such locations can be identified in a number of ways, including interviews of plant personnel, operational reviews, review of plant layout drawings and plant walkdowns [12], [13], [14], [15]. Each will provide a different perspective on hotspot conditions. Feedback from plant maintenance personnel is an important aspect of identifying early signs of degradation.

6.5 Worst case components

Having prioritized the components most likely to be affected by ageing, carried out environmental monitoring and identified localized severe environments, the components will have been assigned to either a high, medium or low priority for further ageing management. All components assigned to a high priority shall be subjected to ageing management activities such as CM or planned replacement.

The evaluation process can be refined as more information becomes available. For example, if CM of high priority cables indicates that degradation is much less severe than expected, it may be appropriate to move these components to a lower priority category.

7 Condition monitoring techniques

7.1 General

CM techniques are used to assess the condition of materials which have aged for extended time periods under actual use environments, such as in nuclear power plants, accelerators, reprocessing plants. The approach makes use of test methods which have been shown to correlate well with ageing degradation.

CM in ageing assessment can be used in a number of ways, ranging from short term trouble shooting to long term on-going qualification programmes.

7.2 Establishing correlation curves for CM methods

In order to use CM methods effectively, it is important to develop correlation curves between the monitoring parameter measured and the prime indicator of degradation or functionality. For low-voltage polymeric cable materials, the prime indicator of degradation is generally considered to be tensile elongation at break, since changes in electrical properties are small before physical failure of the cable in many cases. In seal materials, the compression set has proved to be a useful indicator of the degradation in sealing properties introduced by ageing. Suitable degradation parameters for other components are given in IEC 60544-2.

Correlation curves shall be determined by measurements of the prime indicator and the relevant CM parameter on samples aged under identical conditions, as shown schematically in Figure 1. The measurements shall cover a range of degradation levels, from the unaged condition to a severely degraded condition. It is recommended that at least five sets of data at different ageing times be used in establishing the correlation curve (Figure 2), preferably for several different temperatures and radiation dose rates. An example of a correlation curve for a CSPE cable sheath material is given in Annex A.

Correlation curves are normally established using accelerated testing. Such tests shall be carried out using the procedures described in IEC 60544-2. Alternatively, correlation curves can be established as part of the sample deposit procedure for ageing assessment, as described in Clause 9, or as part of the initial equipment qualification process.

7.3 CM methods

There is a wide range of methods which have been evaluated for CM of polymeric components, particularly for cable materials [4], [17]. Of the many methods examined, several have been identified as being potentially suitable for practical use. Measurement standards for the most developed of these methods are described in detail in the various parts of the IEC/IEEE 62582 series [8]. For these methods, data correlating the monitoring parameter with degradation of the polymeric component have been built up and the practical limitations explored. The most developed methods are

- indenter modulus;
- oxidation induction time (OIT) and oxidation induction temperature (OITP);
- elongation at break.

NOTE There are many other methods which have been investigated for CM and suitable measurement standards for some of these are expected to be developed over the next few years. A number of these are described in IAEA-NP-T-3.6 and IAEA-TECDOC-1825, together with their limitations [4], [17].

Visual inspection (including tactile and other sensory inspection) is a qualitative monitoring method which can be a valuable tool in assessing localized ageing degradation within nuclear power plants using walkdowns. The practical considerations for in-plant visual inspections (walkdowns) are described in more detail in [12], [13], [14], [15].

Electrical methods for assessing degradation in cable systems and their associated end-devices are described in IEC 62465 [18]. These methods primarily relate to cable systems (connectors, penetrations, etc.) rather than degradation of the insulating materials but some methods are showing great promise in correlating with thermal ageing degradation [18], [19].

7.4 Using CM for short-term troubleshooting

In short-term tests, the emphasis of CM is in identifying the extent of a problem or in demonstrating that a problem does not exist. For example, the indenter has been used to determine the extent of damage to cables from degradation arising from damaged thermal insulation on a steam line near a cable in a BWR nuclear power plant. By carrying out indenter measurements along this cable, a profile of the damaged area was obtained. This enabled replacement of a limited section of cable rather than replacing the entire cable run. Another example was the use of in-situ electrical CM methods to determine the functionality of a range of cables in an NPP that had been in operation for 40 years. The results showed that 60 % of the cables tested were not significantly aged and recommendations could be made for replacement of those that had aged significantly [20].

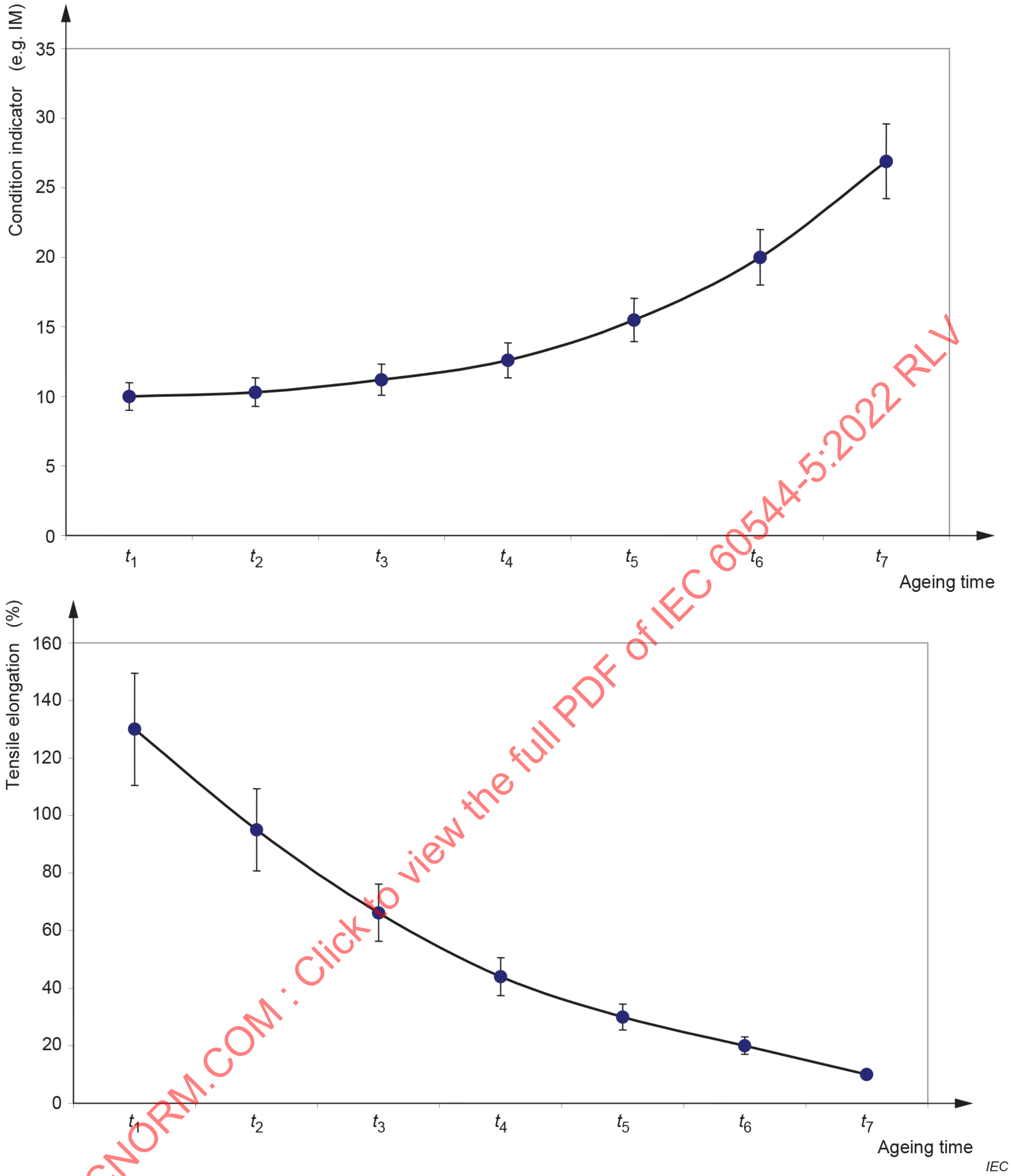


Figure 1 – Development of ageing data on changes in tensile elongation and a condition indicator (e.g. indenter modulus) – Schematic representation

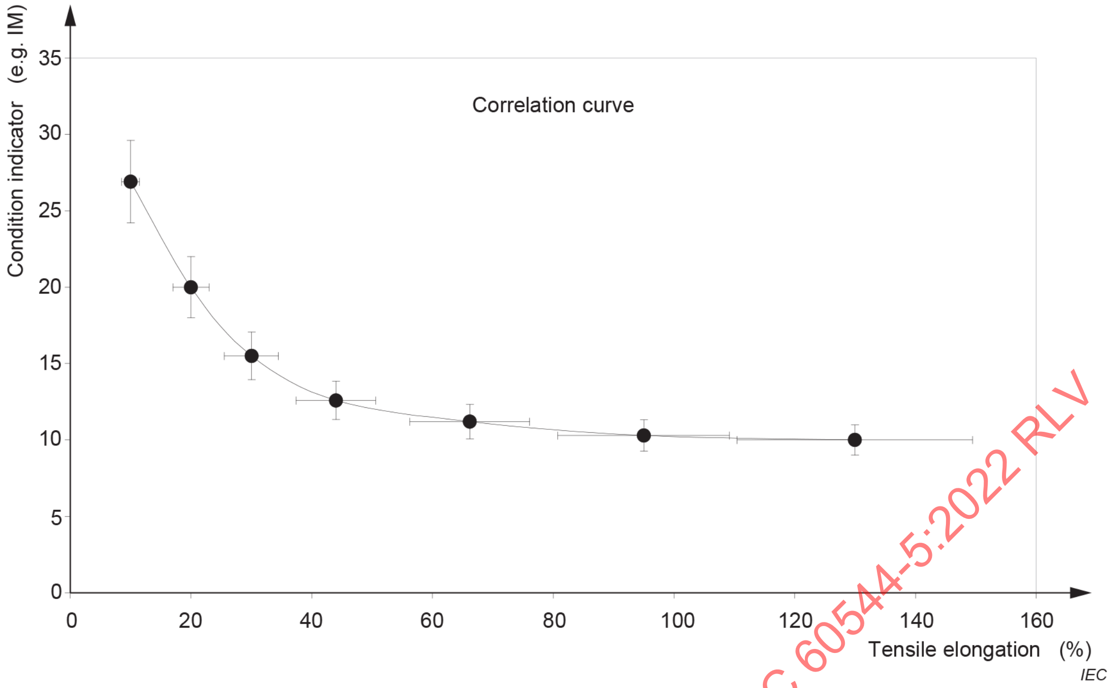


Figure 2 – Correlation curve derived from data in Figure 1 – Schematic representation

In some cases, the use of design criteria (e.g. calculation of self-heating of power cable from current loading) can be very conservative, indicating that the insulation would be expected to show significant degradation. Checks on the component using CM methods can be used to demonstrate that the materials have not degraded to the extent predicted, avoiding unnecessary replacement. This is particularly important where a short, qualified life has been determined during EQ.

7.5 Using CM for long-term degradation assessment

CM methods can also be used in on-going test programmes which span the lifetime of the plant. Typical uses of CM methods in such programmes are

- trending of component condition relative to a qualified condition determined during initial EQ procedures;
- comparison of CM data with predictive modelling, based on accelerated ageing data in the laboratory and a knowledge of the environmental conditions seen by the component;
- monitoring of components in a sample deposit located in a severe environment in the plant (this is most frequently used for cables and small electrical components).

Figure 3 illustrates how the elongation at break can be estimated from a CM parameter such as the indenter modulus.

Condition based qualification (CBQ) is becoming the recommended method for equipment qualification for new NPPs [12], [13]. For this approach to EQ to be used, CM techniques shall be applied during the pre-ageing phase of qualification to determine the shape of the ageing curve and the limiting value of CM parameters at which the component can survive a DBE, i.e. the qualified condition. Trending of the condition of the component relative to this qualified condition is an essential part of CBQ.

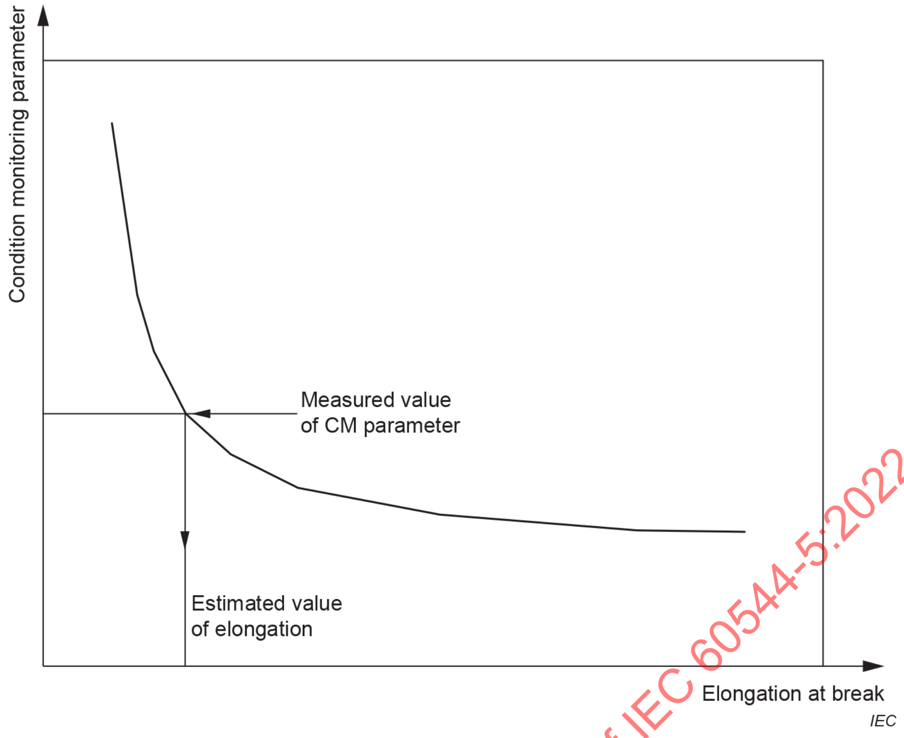


Figure 3 – Estimation of elongation from a correlation curve

8 Predictive modelling

Data obtained during laboratory accelerated ageing tests can be used to generate model parameters for predictive ageing models, such as those described in IEC TS 61244-2. These models can be used to predict the degradation of specific materials under various ageing conditions of temperature and radiation dose rate. By using the data obtained from environmental monitoring of the actual temperatures and dose rates in the plant, the degradation expected to occur in real-time ageing can be assessed.

This approach can also be used to estimate the effect of changes in the environmental conditions, for example a short-term increase in temperature arising from damage to thermal insulation on a nearby steam pipe.

The detailed accelerated ageing tests required to obtain the model parameters are most likely to be carried out on materials for use in new plants. The use of such models combined with design data on environmental conditions can be used during the design phase of a new plant to identify potential problem areas where re-siting of equipment would be appropriate, for example re-routing of a cable run to avoid a localized hotspot.

Three predictive models which make use of a matrix of accelerated ageing data are described in detail in IEC TS 61244-2, together with the limitations and data requirements for use of these models:

- a power law model that has proved useful for materials exposed to radiation environments where thermal ageing is negligible;
- a time dependent superposition model which can model combined thermal and radiation ageing for those materials with a single dominant ageing mechanism;
- a dose dependent superposition model which is particularly useful in the low dose rate radiation ageing range where thermal ageing is important, and for materials with complex ageing behaviour.

9 Sample deposit

9.1 General

The testing of materials from a sample deposit in the plant is an alternative approach to assessment of ageing in service. This makes use of samples specifically installed in the plant for destructive testing and/or CM as part of an ageing management programme.

Assessment of the long-term properties of components using a sample deposit has advantages over accelerated ageing programmes. Its use means that the components age under real plant conditions but can, nevertheless, be checked and monitored without impairing plant operation. Such deposits are often installed in an area of the plant which has a relatively severe environment compared with most other areas where such materials are used. In this case, the sample in the deposit will age more rapidly and therefore will have a lead time over the bulk of the material in the plant.

Most deposits are primarily used for evaluation of cables and small electrical components and are mainly set up in a plant which has been in operation for less than five years. However, a deposit can also be of use in an older plant, provided that the samples are pre-aged using accelerated ageing before installation in the deposit (9.3). Samples in deposits are particularly useful for on-going qualification programmes.

9.2 Requirements of a deposit

A major prerequisite for the implementation of a sample deposit is a good knowledge of the radiation dose and temperature distribution at the deposit position and at positions in the plant where the material being tested is in routine use.

Environmental monitoring can be used to select positions in the plant that are exposed to more severe environmental conditions than most of the real positions. It may even be possible to find a location where the temperature is also similar to the maximum design temperature. Experience has shown that the loop line between the reactor pressure vessel and the steam generator is suitable for this purpose in pressurized water reactors (PWRs) and the reactor water clean-up system in boiling water reactors (BWRs). In VVER type reactors, the main circulation pipe, either hot or cold leg, is also a suitable location for a deposit.

In selecting a position for the deposit, ensure that the environmental conditions at the deposit will produce degradation which simulates real conditions. Particular consideration shall be given to the exposure of some XLPE and some EPR based components to radiation ageing at elevated temperature if their normal use is at lower temperatures. These materials can show a reverse temperature effect [21], [22], [23], with degradation occurring more rapidly at the lower temperatures. For XLPE materials, it is recommended that deposits be placed at both the lowest and the highest ambient temperature normally seen in plant operations. It is recommended that several positions for deposits are determined within the plant that also represent high dose rates or high temperatures for materials other than XLPE.

9.3 Pre-ageing samples for a deposit

When a deposit is set up in an NPP which has been in operation for more than five years, it will be necessary to pre-age the samples to be placed in the deposit to a level equivalent to the actual age of the plant. For NPPs that have been in operation for less than five years, it is assumed that polymeric components have not significantly aged. The accelerated ageing used to pre-age the samples shall use low acceleration factors. The temperature and dose rate being simulated shall be based on the actual values in the plant, as determined from environmental monitoring (see 6.3). It may be possible to use real-time aged cables that have been removed from the plant as samples in the deposit. This is only practical if the temperature and radiation dose rate to which they have been exposed is known.

9.4 Installation of a sample deposit

The deposit shall be arranged so that the samples are exposed to a reasonably uniform radiation field (e.g. if using the loop line in a PWR as the radiation source, they are kept at a constant distance from the loop). This can be readily done by using cable trays strapped to the circumference of the loop line. The specific design of the deposit can easily be adapted to the local conditions in the plant. Samples shall be placed in a single layer to avoid self-shielding.

The deposit needs to be equipped with a representative selection of the materials (e.g. cable samples, small electrical components) used in radiation environments. The number and type of samples required needs to be sufficient to ensure that enough material is available for the scheduled removal of samples over the required period of up to 60 years (for a deposit in a new plant). It is prudent to include extra samples to allow for future improvements in CM methods or for life extension requirements. Annex B illustrates the type of samples usually included in a deposit.

In assessing the number and type of samples required, the intervals at which samples are to be removed and the tests that are to be performed need to be established. For example, for cables, samples of about 0,3 m to 0,5 m in length are quite satisfactory for CM measurements that are non-destructive or need only small amounts of material; however, electrical tests will need longer lengths. Preparation of samples for elongation at break from an aged cable can be difficult [17], so it is advisable to include pre-prepared dumb-bell samples in the deposit if such measurements are required. If samples are required for a DBE test with electrical measurements, a minimum length of 3,05 m is required. Any whole cable samples included in a deposit shall have their ends sealed.

The deposit shall be fitted with dosimeters to record the profile of the radiation dose within the deposit and temperature monitoring is also required. This environmental monitoring shall be continued over at least two years to get a representative picture of the long-term environmental conditions within the deposit. Ensure that there is a free flow of air into the deposit. Suitable contamination protection is desirable but shall not restrict air access.

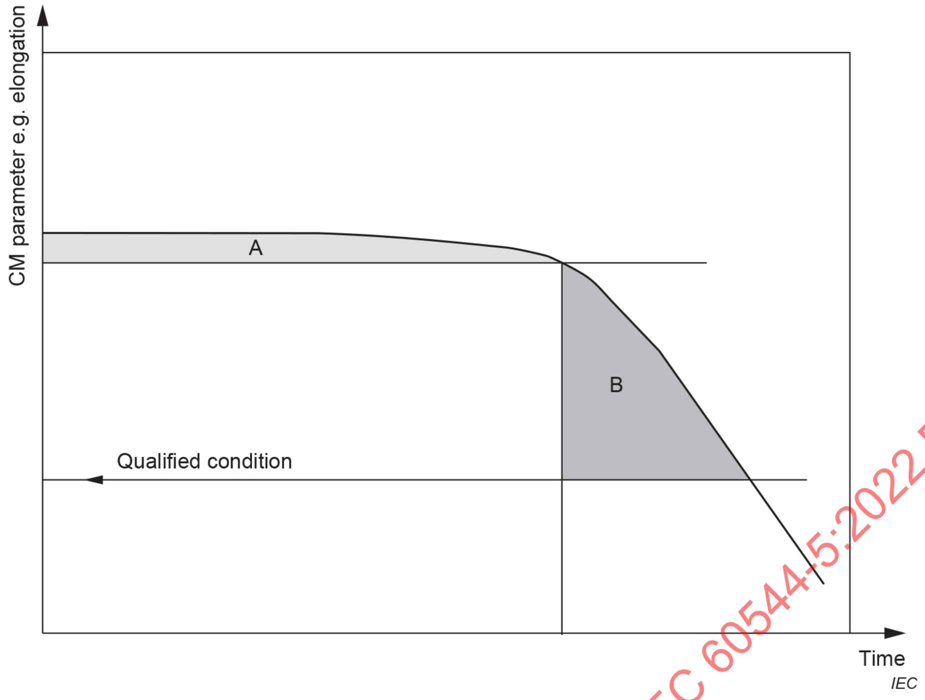
9.5 Testing of samples from the deposit

Initially, baseline data for all of the materials installed in the deposit shall be determined using unaged material. This baseline data shall utilize all of the CM tests which will be used on the materials in the deposit. It is advisable to retain samples of unaged material to enable baseline data to be generated in the future for newly developed CM methods.

At regular intervals, samples will be removed for destructive tests (e.g. tensile elongation measurements) or subjected to CM tests. The test intervals will generally be limited by the accessibility of the sample deposit. In most plants, the deposit will only be available for access when the plant is shut down. The type of testing schedule required is illustrated in Annex B.

9.6 Determination of sampling intervals

For the cable types currently in use, it is reasonable to remove the first samples from the deposit five years after the start of plant operation, since the type and qualification tests that have already been performed provide an acceptable confidence interval for at least this period. The recommended interval between tests for a deposit in a new plant is five to eight years. This interval shall be decreased if the materials are showing signs of more rapid degradation than expected. Once degradation starts to be observed the sampling interval shall be reduced, as indicated in Figure 4. A revised sampling interval of one to two years is then recommended. The precise boundaries of zones A and B illustrated schematically in Figure 4 shall be defined by the shape of the degradation curve for the specific material and by the qualified condition for that material.



NOTE In zone A, samples are taken at five to eight year intervals; in zone B, the interval is decreased to one to two years.

Figure 4 – Modification of sampling interval dependent on values of the CM indicator – Schematic representation

9.7 Real time aged materials

The deposit method is primarily suitable for new plants where unaged samples are readily available for the material types that are to be included in the deposit. For older plants, where unaged samples are not available for use in a deposit, an alternative is to evaluate the actual long-term ageing behaviour by removing samples from the plant. The disadvantages of this sampling procedure are that it constitutes an intervention into the plant and that the samples have to be replaced with suitably qualified materials. However, it may be necessary to use this method if, for special reasons, validated results have to be available within a short time (e.g. for older plants without existing EQ).

If there are data available on environmental conditions within the plant, a position can be selected where the material has been exposed to the worst-case condition. For cable materials, such positions are usually in the direct vicinity of the loop lines (PWR) or in the reactor water cleanup system (BWR). Cable samples from real positions are normally irradiated quite inhomogeneously, for example a cable run converging on the loop line. Before removing the cable sample, the dose distribution shall be determined and the cable location identified clearly in a reproducible manner to allow the test results to be interpreted correctly.

CM methods that are non-destructive or use only micro-samples can be used to evaluate ageing degradation where sample removal for destructive testing is not practical. Baseline data are still required.

Annex A
(informative)

Example of a CM correlation curve

An example of a correlation curve in Figure A.1 for a CSPE cable material shows the correlation between indenter measurements and changes in the tensile elongation at break obtained during an accelerated ageing programme [24]. A good correlation has been obtained for both radiation and thermal ageing of this CSPE material. This correlation curve also illustrates the degree of scatter that is likely to be observed in real data.

In-plant CM measurements on this material using the indenter can be compared with the predicted degradation that allows residual life to be estimated. The predicted degradation is obtained from use of ageing models (such as those described in IEC TS 61244-2), combined with knowledge of the environmental conditions in the plant. Alternatively, the condition can be compared to a qualified condition determined during EQ.

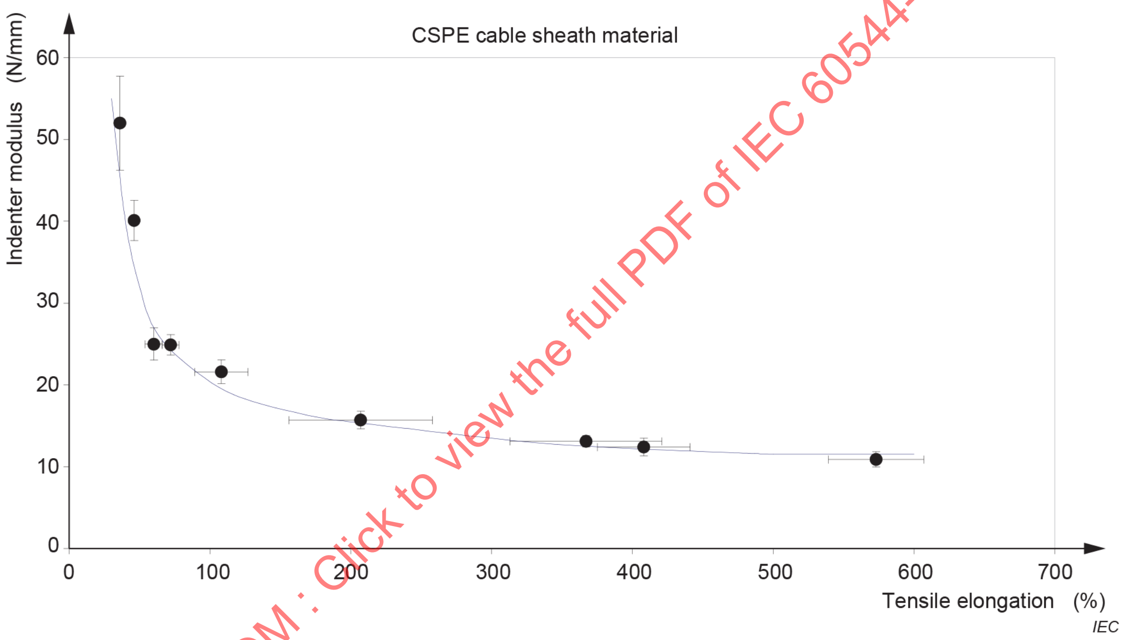


Figure A.1 – Correlation curve for indenter modulus against tensile elongation for a CSPE cable jacket material [24]

Annex B
(informative)

Use of a deposit

B.1 Typical sample in a deposit

A number of sample deposits have been installed in NPPs, mainly for cable materials. The detail of what is included in the deposits will vary from plant to plant but some typical examples are illustrated below.

A typical cable deposit might include the following types of samples:

- batches of pre-prepared dumb-bell samples for elongation tests;
- short sections of whole cable (typically 0,3 m to 0,5 m in length) for indenter and other CM measurements (these samples can also be used for preparation of dumb-bell samples after ageing, if that is possible in practice);
- longer sections of whole cable for periodic electrical tests (typically 1 m to 2 m in length, but if space is available longer lengths will allow for a wider range of tests);
- whole cable (typically > 3 m in length) for future DBE testing.

Alternatively, longer lengths of cable can be utilized in a deposit and short lengths cut off for elongation tests and other CM tests at intervals.

B.2 Typical testing schedule for a deposit

For a plant cable deposit, the testing schedule could take the following form.

- Samples are removed for CM measurements on each component type. Initially, these CM tests should be non-destructive (e.g. indenter or other CM techniques, as appropriate to the component type) or require only small samples (e.g. OIT tests), to preserve the material in the deposit.

The amount of material available in a deposit is often very limited; it is therefore important to conserve material as much as possible in the early stages of its use.

- If the non-destructive or micro-sample tests indicate that degradation is starting to occur, samples for elongation at break tests should be removed and tested.
- The values of the CM parameters are compared with the baseline data for that component. If significant degradation has occurred, additional tests may be carried out for example a DBE test.

It is important that the CM measurements are carried out using the methods specifically recommended for ageing management programmes, see for example [8].

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SOMMAIRE

COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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MATÉRIAUX ISOLANTS ÉLECTRIQUES – DÉTERMINATION DES EFFETS DES RAYONNEMENTS IONISANTS –

Partie 5: Procédures pour l'évaluation du vieillissement en service

AVANT-PROPOS

L'IEC 60544-5 a été établie par le comité d'études 112 de l'IEC: Évaluation et qualification des systèmes et matériaux d'isolement électrique. Il s'agit d'une Norme internationale.

Cette troisième édition annule et remplace la deuxième édition parue en 2011. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

a) des références récentes ont été ajoutées en 7.4 afin d'introduire des méthodes de surveillance de l'état qui montrent des corrélations prometteuses vis-à-vis du vieillissement;

b) les recommandations ont été mises à jour pour la mise en œuvre d'un dépôt d'échantillons en 9.2, l'installation d'un dépôt d'échantillons en 9.3 et les essais sur les échantillons du dépôt en 9.4;

c) la liste de références a été mise à jour.

Le texte de cette Norme internationale est issu des documents suivants:

Projet	Rapport de vote
112/523/CDV	112/553/RVC

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à son approbation.

La langue employée pour l'élaboration de cette Norme internationale est l'anglais.

Ce document a été rédigé selon les Directives ISO/IEC, Partie 2, il a été développé selon les Directives ISO/IEC, Partie 1 et les Directives ISO/IEC, Supplément IEC, disponibles sous www.iec.ch/members_experts/refdocs. Les principaux types de documents développés par l'IEC sont décrits plus en détail sous www.iec.ch/standardsdev/publications.

Une liste de toutes les parties de la série IEC 60544, publiées sous le titre général *Matériaux isolants électriques – Détermination des effets des rayonnements ionisants*, se trouve sur le site web de l'IEC.

Le comité a décidé que le contenu de ce document ne sera pas modifié avant la date de stabilité indiquée sur le site web de l'IEC sous webstore.iec.ch dans les données relatives au document recherché. A cette date, le document sera

- reconduit,
- supprimé,
- remplacé par une édition révisée, ou
- amendé.

INTRODUCTION

Les matériaux organiques et polymères représentent une proportion significative des isolations utilisées dans des systèmes électriques. Ces matériaux sont sensibles aux effets des irradiations, et leur réponse varie de manière significative selon le type de matériau considéré. Par conséquent, il importe de pouvoir évaluer le degré de dégradation de ces matériaux isolants pendant leur durée de vie en service. La présente partie de l'IEC 60544 fournit des procédures recommandées pour évaluer le vieillissement en service des matériaux isolants.

Il existe un certain nombre d'approches pour l'évaluation du vieillissement de composants à base de matériaux polymères exposés aux environnements sous rayonnement [1], [2], [3], [4][1]. Celles-ci sont fondées sur une meilleure compréhension des facteurs qui ont une incidence sur la dégradation due au vieillissement, qui s'est accentuée depuis plusieurs décennies. Dans une centrale nucléaire de puissance, des programmes de qualification sont utilisés pour le choix des composants, y compris ceux à base de matériaux polymères. Ces procédures de qualification initiales, telles que l'IEEE 323™-1974[2] [5] et l'IEEE 383™-1974[2] [6], ont été initialement rédigées avant d'avoir acquis une connaissance suffisante des mécanismes de vieillissement. La plupart des méthodes examinées dans le présent document sont, de ce fait, utilisées pour compléter le processus de qualification initial.

Le présent document constitue la cinquième partie d'une série qui traite de l'effet des rayonnements ionisants sur les matériaux isolants.

L'IEC 60544-1 (Interaction des rayonnements et dosimétrie) constitue une introduction qui traite très largement des problèmes liés à l'évaluation des effets des rayonnements. Elle fournit également des recommandations concernant la terminologie de la dosimétrie, plusieurs méthodes de détermination de l'exposition et de dose absorbée, ainsi que des méthodes de calcul de dose absorbée dans tout matériau spécifique selon la méthode de dosimétrie appliquée.

L'IEC 60544-2 (Méthodes d'irradiation et d'essai) décrit les procédures pour maintenir les sept types de conditions d'exposition pendant l'irradiation. Elle spécifie également les contrôles qu'il convient d'effectuer dans ces conditions afin de pouvoir établir des comparaisons fiables des performances de matériaux à partir des résultats d'essai consignés. En outre, elle définit certaines conditions d'irradiation importantes, ainsi que les procédures d'essai à utiliser pour déterminer les modifications de propriétés et les critères de point limite correspondants.

L'IEC 60544-3 a été annulée et incorporée dans la deuxième édition de l'IEC 60544-2.

L'IEC 60544-4 (Système de classification pour l'utilisation dans un environnement sous rayonnement) fournit un système de classification recommandé pour classer par catégorie les matériaux isolants selon leur comportement sous rayonnement.

1 Les chiffres entre crochets renvoient à la Bibliographie.

2 L'IEEE 323-1974 et l'IEEE 383-1974 ont été supprimées et remplacées par des révisions plus récentes.

MATÉRIAUX ISOLANTS ÉLECTRIQUES – DÉTERMINATION DES EFFETS DES RAYONNEMENTS IONISANTS –

Partie 5: Procédures pour l'évaluation du vieillissement en service

1 Domaine d'application

La présente partie de l'IEC 60544 traite des méthodes d'évaluation du vieillissement qui peuvent être appliquées aux composants à base de matériaux polymères (gaines et isolations de câble, joints en élastomère, revêtements polymères, garnitures) qui sont utilisés dans des environnements où ils sont exposés aux rayonnements.

L'objet du présent document est de fournir des méthodes pour évaluer le vieillissement en service des matériaux. Les approches examinées dans les Articles 5 à 9 concernent les programmes d'évaluation de vieillissement fondés sur une surveillance de l'état (CM, *Condition Monitoring*), l'utilisation de dépôts d'échantillons dans des environnements sévères et l'échantillonnage de composants vieillis en temps réel.

2 Références normatives

Les documents suivants sont cités dans le texte de sorte qu'ils constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60544-2, *Matériaux isolants électriques – Détermination des effets des rayonnements ionisants sur les matériaux isolants – Partie 2: Méthodes d'irradiation et d'essai*

IEC TS 61244-1, *Détermination du vieillissement à long terme sous rayonnement dans les polymères – Partie 1: Techniques pour contrôler l'oxydation limitée par diffusion*

IEC TS 61244-2, *Détermination du vieillissement à long terme sous rayonnement dans les polymères – Partie 2: Méthodes pour prédire le vieillissement à faible débit de dose*

3 Termes, définitions et termes abrégés

3.1 Termes et définitions

Aucun terme n'est défini dans le présent document.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse http://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse http://www.iso.org/obp

3.2 Termes abrégés

BWR (Boiling Water Reactor)	réacteur à eau bouillante
CBQ (Condition-Based Qualification)	qualification fondée sur l'état
CM (Condition Monitoring)	surveillance de l'état
CSPE (Chlorosulphonated Polyethylene)	polyéthylène chlorosulfoné

DBE (Design Basis Event)	evénement de référence
DLO (Diffusion-Limited Oxidation)	oxydation limitée par diffusion
DRE (Dose Rate Effect)	effet de débit de dose
EPR (Ethylene Propylene Rubber)	caoutchouc éthylène-propylène
EQ (Environmental Qualification)	qualification environnementale
CNP	centrale nucléaire de puissance
OIT (Oxidation Induction Time)	temps d'induction à l'oxydation
OITP (Oxidation Induction Temperature)	température d'induction à l'oxydation
PVC (Polyvinyl Chloride)	polychlorure de vinyle
PWR (Pressurized Water Reactor)	réacteur à eau sous pression
TGA (Thermo-Gravimetric Analysis)	analyse thermogravimétrique
VVER (Water-cooled, Water-moderated Energy Reactor)	réacteur ralenti à l'eau et refroidi par eau (type de réacteur à eau sous pression mis au point par la russie)
XLPE (Cross-Linked Polyethylene)	polyéthylène réticulé

4 Contexte

4.1 Généralités

Il existe un certain nombre de facteurs qu'il est nécessaire de prendre en considération lors de l'évaluation du vieillissement des composants polymères dans un environnement sous rayonnement. Dans les Paragraphes 4.2 à 4.5, certains de ces facteurs sont examinés de manière sommaire et des informations plus détaillées sont fournies en référence.

Pour accélérer les conditions de vieillissement sous rayonnement, l'approche normale consiste à augmenter le débit de dose de rayonnement, souvent combinée à une augmentation de la température. Les deux conséquences potentielles les plus importantes consécutives à telles augmentations sont l'oxydation limitée par diffusion (DLO), qui est décrite en 4.2, et les effets de débit de dose chimique (DRE), qui sont décrits en 4.3. Les conséquences de ces facteurs sur l'utilisation et l'interprétation des techniques de surveillance de l'état (CM) sont également examinées. Les programmes de vieillissement accéléré sont traités brièvement en 4.4 et en 4.5.

4.2 Oxydation limitée par diffusion (DLO)

Lorsque des polymères sont exposés à un environnement qui contient de l'oxygène (de l'air, par exemple), une certaine quantité d'oxygène se dissout dans le matériau. En l'absence de réactions qui consomment de l'oxygène (oxydation), la quantité d'oxygène dissout est proportionnelle à la pression partielle exercée par l'oxygène à la surface du polymère (bien connu par la Loi de Henry). Le vieillissement conduit à des réactions d'oxydation dans le polymère, dont la vitesse augmente significativement avec l'augmentation du débit de dose et de la température de vieillissement. Si la vitesse de consommation d'oxygène dissout dans le polymère est plus rapide que la vitesse à laquelle l'oxygène peut être réapprovisionné par diffusion en provenance de l'atmosphère ambiante, la concentration d'oxygène dissout dans les zones internes diminue avec le temps (la concentration en oxygène à la surface de l'échantillon demeure à sa valeur d'équilibre). La diminution de la concentration en oxygène interne peut conduire à une oxydation réduite ou négligeable, désignée sous le nom d'oxydation limitée par diffusion.

L'importance de cet effet dépend de l'épaisseur de l'échantillon (les échantillons plus minces donnent des effets de DLO plus faibles) et du rapport de la vitesse de consommation d'oxygène au coefficient P de perméabilité à l'oxygène, qui est le produit de la diffusion d'oxygène et des paramètres de solubilité. Les conditions de vieillissement accéléré sous rayonnement impliquent des augmentations de débits de dose, ce qui augmente la vitesse de consommation d'oxygène. Si la température demeure constante, mais que le débit de dose augmente, le coefficient de perméabilité à l'oxygène ne varie pas. Cela signifie que les effets de DLO deviennent plus importants à mesure que le débit de dose augmente. Pour plus d'informations sur ces effets, l'IEC TS 61244-1 doit être consultée.

Il peut également être nécessaire de prendre en considération les effets de DLO lors des mesurages de CM. Cela ne constitue pas un problème pour la majorité des techniques de CM qui mesurent les propriétés à température ambiante, notamment les techniques qui reposent sur des mesurages de densité et de module. D'autre part, plusieurs techniques de CM telles que le temps d'induction à l'oxydation (OIT) et l'analyse thermogravimétrique (TGA) utilisent des températures relativement élevées lors des mesurages. Pour ces techniques, la présence d'effets de DLO pendant le mesurage du paramètre de CM est tout à fait possible. Pour cette raison, des méthodes d'essai détaillées pour la CM ont été élaborées [8] afin de s'assurer que la procédure de préparation et d'essai des échantillons évite les effets de DLO. La DLO doit être traitée lors de l'établissement des courbes de corrélation pour les méthodes de CM, afin de s'assurer que les données obtenues sont représentatives du vieillissement sous rayonnement et du vieillissement thermique.

4.3 Effets de débit de dose (DRE)

Les effets de débit de dose de rayonnement et les méthodes mises en œuvre pour traiter ces effets sont décrits dans l'IEC TS 61244-2. Cette norme doit être consultée pour obtenir plus d'informations sur ces effets. Généralement, les DRE sont classés en deux types. Le premier type, couramment observé lors des expériences de vieillissement accéléré par rayonnement, est dû aux effets de DLO décrits en 4.2. Ces effets fondés sur la DLO représentent un DRE physique, dépendant de la géométrie.

Le second type, intéressant pour la présente explication, concerne les DRE chimiques. Ces DRE à base chimique sont moins courants. Un cas documenté de DRE chimique se trouve dans les matériaux en polyéthylène basse densité et PVC, causé par la rupture lente de l'espèce intermédiaire hydroperoxyde lors de la réaction d'oxydation [9]. L'existence de tels DRE chimiques doit être vérifiée au début de tout programme de vieillissement accéléré. Si aucune donnée n'est disponible dans les ouvrages de référence relatifs aux matériaux spécifiques considérés, la vérification peut être effectuée en effectuant des essais à faible débit de dose dans le programme de vieillissement.

4.4 Vieillissement accéléré par rayonnement

Les programmes de vieillissement accéléré en laboratoire appliquent généralement des facteurs d'accélération significativement inférieurs à ceux couramment utilisés pour la qualification de l'équipement. Cela peut éviter certains problèmes associés à la DLO et aux DRE. Le vieillissement obtenu peut alors fournir une meilleure simulation du vieillissement à long terme qui se produit dans les conditions de service. Les données obtenues lors des essais de vieillissement accéléré peuvent être associées à des modèles prédictifs afin d'évaluer le comportement des matériaux dans les conditions de service.

Les programmes de vieillissement accéléré exigent une matrice de données d'essai, à produire sur une plage de conditions d'environnement, comme cela est décrit dans l'IEC TS 61244-2. Au minimum, des données sont nécessaires pour au moins trois débits de dose différents à la température de fonctionnement normal, mais des données supplémentaires sur le vieillissement thermique et le vieillissement sous rayonnement à haute température permettent d'optimiser les méthodes de modélisation prédictive disponibles. Il convient de choisir les débits de dose et les températures utilisés pour le vieillissement accéléré en appliquant les principes décrits dans l'IEC 60544-2 afin d'assurer une oxydation homogène. Pour chaque condition d'environnement utilisée, des données d'essai doivent être obtenues à différentes périodes de vieillissement; il convient que les périodes les plus longues soient suffisantes pour engendrer une dégradation significative. La réalisation d'un programme d'essais type peut prendre plus de 18 mois, en fonction de la tenue aux rayonnements des matériaux soumis à l'essai.

Les données exigées dans la matrice d'essai sont déterminées par le type de composant évalué. Les paramètres d'essai appropriés sont fournis dans l'IEC 60544-2 pour différents types de matériaux polymères et composants.

4.5 Vieillissement thermique accéléré

Lors de la réalisation d'un vieillissement thermique dans le cadre d'un programme de vieillissement accéléré, il est important d'utiliser une valeur appropriée de l'énergie d'activation afin d'évaluer la température et l'échelle de temps de l'essai accéléré. Dans certains matériaux, le mécanisme de vieillissement à hautes températures est différent de celui qui se produit dans des conditions sur site et dans un grand nombre de matériaux, l'énergie d'activation diminue de manière significative à basses températures [10], [11].

Avant d'effectuer les essais de CM, les échantillons qui ont été exposés à un vieillissement thermique accéléré doivent se stabiliser. Certains matériaux polymères sont hygroscopiques et montrent une dépendance marquée de leurs propriétés vis-à-vis de la teneur en humidité [8]. Cela est problématique pour quelques matériaux utilisés dans les anciennes centrales nucléaires de puissance, mais peut également être important pour les méthodes de CM sensibles à la teneur en humidité du matériau.

5 Approches pour l'évaluation du vieillissement

Il existe un certain nombre de méthodes complémentaires disponibles pour l'évaluation du vieillissement; celles-ci sont décrites dans les articles respectifs. Chacune de ces méthodes possède ses propres avantages et limites. Le choix d'une ou de plusieurs des méthodes dépend des exigences de chaque utilisateur.

Le présent document décrit plusieurs approches pour évaluer le vieillissement en service des matériaux, notamment.

- l'identification des composants importants pour prioriser l'application des programmes de gestion du vieillissement (voir Article 6);
- la surveillance de l'état pour évaluer l'état de matériaux qui ont été vieillis pendant des durées prolongées dans des environnements d'utilisation réels (voir Article 7);
- la modélisation prédictive qui utilise les données issues de programmes de vieillissement accéléré en laboratoire afin d'estimer le vieillissement dans des conditions de vieillissement en temps réel (voir Article 8);
- le dépôt d'échantillons qui fournit des échantillons pour mesurer le vieillissement dans des conditions de vieillissement en temps réel (voir Article 9).

6 Identification des composants importants

6.1 Généralités

Dans une centrale nucléaire de puissance, de nombreux composants comportent des matériaux isolants polymères. Il y a par exemple plus de 1 000 km de câbles électriques dans une CNP type. Il n'est pas possible d'évaluer le vieillissement de chacun de ces composants. En outre, de nombreux composants ne sont pas exposés à des conditions significatives de vieillissement lié à l'environnement. C'est pourquoi il est nécessaire de prioriser les programmes de gestion du vieillissement en identifiant notamment les composants qui sont les plus importants.

6.2 Priorités pour la gestion du vieillissement

Tous les composants n'ont pas la même priorité pour la gestion du vieillissement. En général, les composants impliqués dans des fonctions de sûreté pendant et à la suite d'un accident sont les plus importants, ainsi que ceux qui sont essentiels à la poursuite de l'exploitation. Une priorité basse est initialement assignée aux composants qui ne relèvent pas de ces catégories, pour les activités de gestion du vieillissement.

L'environnement de fonctionnement normal des composants doit être examiné afin d'identifier l'incidence présumée de l'environnement sur leur vieillissement. La priorité la plus haute est assignée aux composants identifiés comme étant sujets à un vieillissement important, tandis qu'une priorité moyenne peut être assignée aux composants sujets à un vieillissement modéré.

Pour effectuer cette affectation de priorité de manière efficace, un contrôle radiologique de l'environnement est essentiel (voir 6.3), associé à une connaissance du comportement de vieillissement des composants. Une évaluation initiale peut utiliser les calculs de conception pour les températures et les débits de dose. Les informations de vieillissement peuvent provenir de données de qualification d'équipements ou d'essais de vieillissement accéléré supplémentaires effectués en laboratoire.

6.3 Contrôle radiologique de l'environnement

Le vieillissement des matériaux isolants dans une CNP est dominé par la température, la dose de rayonnement et le débit de dose de rayonnement pour les matériaux polymères. Une connaissance approfondie des températures et des débits de dose réels aux emplacements où sont situés les composants de priorité haute dans l'installation constitue une exigence essentielle à la gestion du vieillissement.

La répartition des températures et des débits de dose dans l'installation doit être déterminée au moyen d'enregistreurs de température et de dosimètres. Les fluctuations d'exploitation et les variations saisonnières doivent être prises en compte en effectuant ces mesurages sur plusieurs cycles du combustible. Il peut s'avérer nécessaire de répéter ces mesurages lorsque des modifications sont apportées à l'installation, par exemple des montées en niveau de puissance.

Des petits enregistreurs de température autonomes sont disponibles et constituent une méthode pratique et adaptable pour l'enregistrement de températures localisées afin de compléter l'appareillage encombrant de surveillance de la température, qui est déjà installé dans l'installation.

Une meilleure surveillance des rayonnements est obtenue avec des dosimètres à alanine, qui sont adaptés aux mesurages à long terme. Ces dosimètres ne sont pas significativement affectés par la température; ils peuvent être étanchéifiés afin d'éviter une influence de l'humidité et sont adaptés pour effectuer la surveillance sur une large plage de doses. Les radicaux formés lors d'une irradiation dans l'alanine sont stables pendant des durées qui dépassent un an et peuvent être mesurés en utilisant la résonance de spin électronique. Pour plus d'informations sur la surveillance des rayonnements, l'IEC TS 61244-1 doit être consultée.

6.4 Environnements sévères localisés

L'identification des environnements sévères localisés (points chauds) où sont situés des composants de priorité haute constitue un aspect important de l'évaluation du vieillissement. Ces emplacements peuvent être identifiés de plusieurs façons, notamment dans le cadre d'entretiens avec le personnel de l'installation, de revues opérationnelles, de revues des plans d'implantation de l'installation et des explorations de l'installation [12], [13], [14], [15]. Chacune fournit une perspective différente des conditions de points chauds. Les retours du personnel de maintenance de l'installation constituent un aspect important à prendre en compte pour identifier les signes précoces de dégradation.

6.5 Composants exposés aux conditions les plus défavorables

Après avoir priorisé les composants les plus susceptibles d'être affectés par le vieillissement, effectué un contrôle radiologique de l'environnement et identifié les environnements sévères localisés, les composants sont priorisés pour la gestion ultérieure du vieillissement par affectation d'une priorité haute, moyenne ou basse. Tous les composants de priorité haute doivent faire l'objet d'activités de gestion du vieillissement telles que la CM ou un remplacement planifié.