SKI Report 02:4

Research

Qualification of Electrical Components in Nuclear Power Plants

Management of Ageing

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SKi

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SKI Perspective

Background

The management of ageing is an important area for the safety work at nuclear power plants. During several years the utilities in Sweden and the Swedish Nuclear Power Inspectorate has in co-operation performed a research project on this topic.

The purpose

The purpose of the work has been to produce a background material for planning and management of qualification work on components inside the containment. The principles are never the less also applicable for components outside the containment that are exposed to increased environmental effects during events.

The report is divided into two parts; "the report" and "basic material".

Result

The work was finished and reported in Swedish in a limited publication 2000, Ingemansson Rapport H-14061-r-I. As the performed work was regarded to be of more general interest it is published again as a research report by the Swedish Nuclear Power Inspectorate. To be used in the international co-operation in nuclear safety it was also translated into English by the inspectorate, which is this report. The re-published Swedish report has the reference SKI Rapport 01:17.

The publication as a report in the inspectorate's research series does not change the status of the report as a research result and shall not be regarded as an official standpoint of the inspectorate.

A continuation of the work is not presently planned. The experience from the use of the existing results together with the international development will be reviewed. Based on this a decision on possible needs for complementary studies will be taken.

Effects on SKI's work

The purpose of the work is to provide background material for the development of strategies and implementation of qualification programs at the utilities, and not to be a direct input to the inspectorate's activities.

The review of the safety activities at the utilities will be performed in this area as for all other areas important to the safety of the nuclear power plants.

Project Information

The work has been performed in co-operation between the Swedish utilities and the Swedish Nuclear Power Inspectorate.
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SKI Report 02:4

Research

Qualification of Electrical Components in Nuclear Power Plants

Management of Ageing. The Report.

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Summary

This report deals with methods for evaluation of suppliers' documentation of qualified life in connection with purchase of safety related electrical devices, methods which can be used after installation for on-going control of ageing, methods for updating of qualified life and methods for extension of qualified life.

A detailed documentation of the underlying material, useful data etc. is available in the report H-14061-r-E. A reference to the relevant clause in H-14061-r-E where detailed information can be found is given in this report for the programmes and tools included.

The work behind this report has been financially supported in common by Forsmark Kraftgrupp AB, OKG Aktiebolag, Ringhals AB, Barsebäck Kraft AB and Statens Kärnkraftinspektion. The project has been governed by a steering committee with the following composition:

Jan Bendiksen, Ringhals AB
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Gunnar Ståhl, responsible for the project at Westinghouse, and Kjell Spång, responsible for the project at Ingemansson Technology AB, have also been members of the steering committee.

Contents

1 Introduction

The purpose of this report is to briefly describe various programmes and tools for assessment of accomplished and documented qualification with respect to ageing of electrical components from suppliers' data and for completion of accomplished and documented qualification. The purpose is furthermore to describe tools for validation of components' ability to withstand ageing and, where needed, for complementary qualification of already installed ("old") electrical components.

A detailed documentation of the underlying material, useful data, etc. can be found in SKI Report 02:4B [1]. A reference is made to the relevant clauses in 02:4B where detailed information is given for the programmes and tools presented in this report for various situations.

The purpose of qualification with respect to ageing is to secure a qualified life which is verified by testing and analysis. This can be accomplished through

- Initial qualification for the total desired life by analysis and laboratory testing at which the influence of ageing is established through artificial ageing of the test specimen. The influence of environments of importance to ageing is accelerated according to some method, after which the test object's ability to perform under a simulated Design Basis Event (DBE) is verified. Condition monitoring at prescribed times after installation can be used to improve the security of the qualified life.
- Combination of initial qualification for a qualified life that is shorter than the total desired life (installed life) and a successive extension of the qualified life through condition monitoring or repeated testing of samples of installed components (on-going qualification).

The more complex the component is from the point of view of ageing (assembled from several ageing sensitive materials with different ageing characteristics) or the less knowledge there is about the ageing characteristics of the materials involved the more important are follow-up activities after installation (condition monitoring). For various reasons, the acceleration factor used in artificial ageing should be limited, see [1], clause 4.5.2.1 (thermal ageing) and 4.5.3 (ageing in ionising radiation). If it cannot be proved by investigations that high acceleration factors can be used with acceptable accuracy, the factor should be limited to maximum 250 at thermal ageing.

2 Limitations in qualified life

The target for qualified life established by initial qualification tests is limited to what can be verified by laboratory testing. The life for which the component can be regarded safely qualified is limited by the applicability of methods for accelerated artificial ageing and by the time available for this. For components subjected to ageing it is sometimes not possible to design artificial tests that ascertain a qualified life equal to installed life. A gradual extension of qualified life can be achieved after installation through on-going qualification and/or condition monitoring.

3 Condition monitoring for successive control or extension of qualified life

Condition monitoring is used to assure that the degradation of components has not gone so far that their intended function in a DBE is insecure. Use of condition monitoring requires that a useful parameter for measuring the degradation of the component is available. It shall be demonstrated that the component at a certain level of degradation measured by this parameter still manages to be subjected to a prescribed DBE and therewith functions in intended way and maintain the characteristics (e.g. values on dielectric parameters) required during a DBE.

The most commonly used condition monitoring parameters are

- Indenter modulus
- Elongation-at-break (e/e_0)
- OIT
- Dielectric loss factor

In [1], chapter 5.2.2 (Identification of condition indicators and their change with time), chapter 5.4 (Observation of ageing of components through condition monitoring and inspections), it is indicated how the various condition monitoring indicators are defined, how they are measured, for which materials they are applicable, etc.

Instead of defining the qualified life of a component, one may define the qualified status of the component, given as a value of the condition indicator equal to the value that was measured immediately before the DBE testing.

4 On-going qualification

When a component's installed life approaches the qualified life, an extension of the qualified life can be achieved by selecting samples of the component from the most exposed positions (either ordinary components which are replaced or for the purpose especially installed components) and subjecting them to accelerated artificial additional ageing for a desired additional qualified life, followed by a DBE test. If the selected samples pass this test, the rest of the components in the containment, identical to the selected ones, are qualified for the additional life.

In cases where it is possible to use spare components in areas of the containment with more severe environmental conditions during normal operation (higher temperature, higher dose rate) than in areas where the safety related components are installed, the method can be used without subjecting the components to artificial ageing before DBE-testing.

In [1], chapter 5.5 (Extension of qualified life through on-going qualification), the method is described in detail.

5 Verification and validation of qualified life in connection with purchasing ("new" component)

5.1 Environmental prognosis and requirements on operation and qualified life

An environmental prognosis for the long-term (ageing influencing) environmental parameters in the most exposed positions is needed for taking ageing into account at purchase of a type of component for installation in a nuclear power plant. The prognosis establishes environmental conditions at normal operation. It should also include desired installed life and functional requirements with acceptance criteria at DBE. The environmental prognosis should include all environmental parameters that may be present in the actual component positions. [1], Chapter 4.5 (Program for artificial ageing in type testing) includes guidance for judgement of which environmental parameters may need to be taken into account.

Note. The term environmental prognosis refers to predicted environmental conditions during the product life to which development, design and testing shall be adapted. The term environmental parameter refers to external environmental conditions characterised by one or a few physical or chemical quantities (e.g. temperature, humidity, or vibration). The severity of the environmental parameter is normally determined by the measured values of these quantities.

5.2 Use of data from experience and knowledge of material

Databases containing component and material properties attained from field experience and from testing can be of valuable help in a first assessment of components of interest on the market. In [1], Chapter 10 (Databases) examples of some useful databases are given.

Material knowledge, especially knowledge of ageing characteristics of polymers, is another important basis for assessment of components on the market. The own and other's experiences should be invented and studied.

5.3 Assessment of the qualification documentation provided by the component deliverer.

In the normal case the documentation from the component deliverer includes programs for and records from environmental qualification testing. In order to assess the ageing qualification provided by the component deliverer, the following information is important:

- Component data
  - Parts and materials included
- Environmental test data

- Environmental parameters
- Severity

- Test methods
- Functional control and acceptance criteria

5.4 Assessment of environmental parameters of importance to ageing of the component

The type testing includes verification of the component's life through artificial ageing followed by functional control during a DBE simulation. The selection of environmental parameters to be simulated in the artificial ageing is based on an assessment of the environmental parameters that can affect the ageing of the component.

Thus, the selection of environmental parameters of interest is not only based on the location of the component, but also on the composition of the component, especially polymers involved.

5.5 Assessment of qualified life, verification of qualified life, and needs for a program for follow-up activities after installation.

The environmental severity is normally determined by the magnitude of the environmental parameter (e.g. temperature) and exposure time. The determination of the acceleration factor for the artificial ageing is based on properties of the ageing sensitive materials involved - for thermal ageing normally activation energies, for ageing in ionising radiation the influence of dose rate. Therefore, the deliverer should be asked to provide the basis for the acceleration factor applied, e.g.

- Activation energy selected and the basis for it
- Information on dose-rate effects for materials involved that may be sensitive to ionising radiation

The test method should be stated. If reference is made to a known standard, e.g. IEC 60068-2-2 for thermal ageing, test tolerances etc. are evident from the standard. If no reference is made to a known standard, the deliverer should provide information on test tolerances maintained, etc.

Functional data before, during and after DBE and how the measurements of the function has been made is essential information for an assessment of the relevance of the environmental qualification in relation to intended use and as a basis for possible on-going qualification.

Information should be available on the number of samples tested and on the variation in the results in relation to functional data before/during/after DBE. See [1], chapter 4.5.2.6 regarding uncertainty due to a limited number of samples tested.

For control of ageing during normal operation and in cases where it is not possible to safely verify a qualified life equal to installed life through initial testing, one may desire to introduce condition monitoring after installation. In order to clarify the possibilities of this for the actual component, the following should be requested

- Data from condition monitoring made at the artificial ageing before the DBE simulation, if available.
- Materials data of importance for selection of methods for condition monitoring, such as additives (e.g. antioxidants which enables OIT-measurements) in polymers involved.

It may also be of interest to find out if the composition of the component is such that non-destructive condition monitoring can be applied or if ageing sensitive parts are reasonably accessible for condition monitoring.

After obtaining these data it should be possible for the utility to make its own judgement of

- Qualified life in the predicted environment during normal operation (followed by DBE)
- Needs and possibilities for condition monitoring or on-going qualification

The qualified life established can be judged as

- Safe, i.e. determined with necessary margins, verified activation energies, consideration of dose-rate effects, etc. It is presumed that there is sufficient knowledge of expected environmental conditions.
- Less safe, due to weaknesses in the verification, e.g. through use of extreme acceleration factors, poorly founded activation energies, no regard to dose rate effects.

In some cases it will not be possible to establish a qualified life from the data provided by the deliverer.

5.6 Establishment and implementation of program for management of ageing after installation

If a safe qualified life has been established and is equal to or longer than intended installed life, the component can be accepted without any complementary program for ageing management after installation.

If a safe qualified life has been established but is shorter than intended installed life, the component can be accepted for its qualified life and condition monitoring or on-going qualification can be introduced for successively extending the qualified life or for establishing the time when the component must be exchanged.

Note. In cases where the ageing sensitive component parts are exchangeable, a program may instead be established for exchange of such parts before approaching the qualified life.

If the qualified life is less safe due to the use of extreme acceleration factors, an improved basis for qualified life may be attained through complementary type testing (e.g. using longer exposure duration with lower acceleration factor). Such complementary testing must also include a DBE simulation.

In cases where condition monitoring is suitable, it can be sufficient to perform an ageing simulation identical to the one made by the deliverer and measure the condition at the end of the ageing simulation. The component can then be regarded as qualified for this condition, provided that the condition is measured in the parts of the component which are essential for its function at DBE (see note below). A "safe qualified condition" can then be stated and the condition followed at suitable intervals after installation. The component shall be re-qualified or exchanged when the component approaches the qualified condition. An alternative is to perform an ageing simulation with moderate acceleration factors, measure the condition and establish the time at which the condition corresponds to what has been measured after the simulation according to the deliverer's method. From this test, a more safe qualified life can be established.

Note. If the thermal ageing is performed at too high temperature, the ageing mechanism may be different from when it is subjected to the ambient conditions of the installation. Furthermore, use of too high acceleration factors may cause the surface layer of organic materials to age strongly whilst the internal (for the function more essential) parts age considerably less than at an equivalent condition of the surface layer after normal use. The reason for this is heterogeneous oxidation at high temperatures and short ageing times. A corresponding phenomenon can appear at ageing in ionising radiation (dose-rate effects). These effects may lead to an overestimation of the functional ability of a component that shows certain degradation on the surface. An example is cables, if the condition is measured in the surface layer of the jacket. The dielectric condition of the conductor insulation determines the function during DBE and this may be much less affected by the artificial ageing with high temperatures than after normal use even if the condition of the surface of the jacket is the same.

If the deliverer's documentation and data do not give sufficient basis for determination of qualified life, the user has to initiate a complete type testing with age simulation followed by DBE simulation.

Even if a direct need for a program for condition monitoring or on-going qualification is not seen at the time of purchasing, it is wise to buy a few spare component samples which are stored in controlled (mild) environment. A need for complementary testing, condition monitoring, or on-going qualification may show up later.

6 Updating of the qualification of an installed component ("old component")

An installed component may need to be updated regarding its qualification for long term effects of environmental conditions (ageing). The reasons for a need for a program for such updating can be:

- The environmental conditions deviate from what was presumed when the qualified life was established. Updating of qualified life can be made simply by inserting the new environmental severity in the formula used for the calculation of the acceleration factor.
- Reconsideration of qualified life from earlier documented verification testing due to the use of too high acceleration factors, non-conservative acceleration factors, no consideration of dose-rate effects, etc.
- Updating of qualified life due to new knowledge in the area.
- The end of the qualified life is close.
- Installed life is longer than what was presumed from the beginning, implying demands for an extension of the qualified life.

An updating of the qualified life can be based on

- Analysis
- Measurement of the environment
- Complementary investigations of the ageing related characteristics of the materials included (e.g. activation energies, dose-rate effects)
- Condition monitoring, in cases where a basis for this exists in the qualification documentation (which is very seldom the case)

An extension of the qualified life can be based on

- Establishment of a program for condition monitoring, including investigations and testing needed for attaining a basis for such a program
- Establishment of program and basis for on-going qualification

As a summary, the updating of qualified life can be established according to one of the following programs (depending on reason for the updating)

A. Reson for updating: *New environmental data. Example: Measured temperature or measured dose-rate at normal operation is lower/higher than presumed when the qualified life was determined.*

Recalculation of the acceleration factor used in the type testing performed ([1], chapter 4)

Revision of the qualified life

B. Reason for updating: *Reconsideration of qualified life established from earlier documented verification due to use of too high acceleration factors or insufficiently conservative assumptions.*

Alternative 1:

Recalculation of acceleration factors through introduction of a higher degree of conservatism, information from the own or others' investigations, data bases ([1], chapter 10), etc. or through measurement of activation energies, etc, of materials involved.

Revision of qualified life

Alternative 2:

If condition monitoring is suitable and new identical components are available: Simulation of ageing according to earlier documented verification, measurement of the condition at the end of it. This is the qualified condition. ([1], chapter 9).

Alternative 2a:

Measurement of the condition of installed components and comparison with the qualified condition

Qualified life is substituted by qualified condition

Alternative 2b:

Ageing simulation with moderate acceleration factors, measurement of the condition and establishment of the qualified time corresponding to the qualified condition

Revision of qualified life

C. reason for updating: Adaptation to new or extended knowledge in the area

Compilation of relevant knowledge, including general knowledge, material data, etc. Change of assumptions on which establishment of qualified life are based ([1], chapter 10)

Revision of qualified life

D. Reason for updating: End of qualified life is close or there is a desire to extend installed life above what was anticipated at type testing

On-going qualification ([1, chapter 6.3.2)

Alternative 1:

New or stored identical components are available

Samples that have been located in the environmentally most exposed positions are removed and substituted by new identical components

Removed samples are aged artificially for an additional time corresponding to the desired extension t_1, after which they are subjected to DBE testing

If the result of the test is acceptable the qualified life of installed components is extended by the time t_1

Alternative 2:

New or stored non-identical components, fulfilling the same function, are available

The new non-identical components are subjected to type testing and qualified to a lifetime t_1.

Samples that have been located in the environmentally most exposed positions are removed and substituted by new non-identical components

Removed samples are aged artificially for an additional time corresponding to the desired extension t_1, after which they are subjected to DBE testing

If the result of the test is acceptable the qualified life of installed components is extended by the time t_1

Alternative 2 can be useful in cases of a type of component that exist in a large number in the plant, in which case it may be considerably better economy in extension of the qualified life with the described method than an exchange of all installed components.

In cases where the condition before the DBE-testing (qualified condition) in connection with the type testing is known or has been established according to B alternative 2, an extended qualified life can be established by removing samples which have been installed in the most severe exposed areas, age them artificially to an additional time corresponding to the desired extension (t_1), and measure the condition. If the qualified condition still is contained, the qualified life can be regarded as extended by the additional time (t_1).

7 Reference

[1] Spång, K., Ståhl, G. "Qualification of electrical components in nuclear power plants. Bases for management of ageing". SKI Report 02:4B, march 2002.

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Research

Qualification of Electrical Components in Nuclear Power Plants

Management of Ageing. Basic Material.

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Summary

This report reviews R&D results and experiences forming the bases for the preparation of Report 02:4A on management of ageing. It includes basic information and descriptions of value for persons who work with the questions and some data from investigations of the ageing characteristics of various materials: limit levels, dose-rate effects, activation energies, methods for condition monitoring, etc.

This report is restricted to safety related components containing ageing sensitive parts, mainly organic materials (polymers). For components located in the containment, the possibilities of continuous supervision are limited. The accessibility for regular inspections is also limited in many cases. Therefore, the main part of this report deals with the qualification of such components. In addition, some material is given on qualification located outside containment with better possibilities for frequent inspection and supervision.

A survey is made of activities, programs and tools for ageing qualification in connection with initial environmental qualification (type testing) as well as after installation (condition monitoring, extension of qualified life through on-going qualification). Tools are also given for supplementary ageing qualification of already installed components.

The work behind this report has been financially supported by Forsmark Kraftgrupp AB, OKG Aktiebolag, Ringhals AB, Barsebäck Kraft AB and Statens Kärnkraftinspektion. The project has been governed by a steering committee with the following composition:

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Gunnar Ståhl, responsible for the project at Westinghouse, and Kjell Spång, responsible for the project at Ingemansson Technology AB, have also been members of the steering committee.

Contents

1 General

1.1 Background and aims of this report

SKI Report 02:4A [1.1] deals with management of ageing at qualification of safety related electrical components in nuclear power plants. The aims of this report is a review of own and others' R&D experiences used for preparation of Report 02:4A. It includes basic information and descriptions that can be of value for persons who work with the questions and some data from investigations of the ageing characteristics of various materials: limit levels, dose-rate effects, activation energies, methods for condition monitoring, etc.

This report is restricted to safety related components containing ageing sensitive parts, mainly organic materials (polymers). To this category belong cables and cable joints and a number of components containing oils, seals (o-rings), etc. For components located in the containment, the possibilities of continuous supervision are limited. The accessibility for regular inspections is also limited in many cases. Therefore, the main part of this report deals with the qualification of such components. In addition, some material is given on qualification of components located outside containment with better possibilities for frequent inspection and supervision.

1.2 The lay-out and content of this report

This report shows the tools that are available for management of ageing of components in nuclear power plants, including

- Prediction of environmental conditions affecting ageing (thermal environment, ionising radiation, humidity, contamination, vibration)
- Program for artificial ageing before DBE testing
- Assessment of qualified life
- Activities for complementary initial qualification, for check of ageing after installation (inspection in connection with revision, environmental measurements and condition monitoring) and for extension of qualified life (on-going qualification).

This report also includes bases for choice of methods for artificial ageing, how to establish qualified life from this, and bases for choice of useful condition indicators for different types of materials.

Methods for condition monitoring after installation are essentially useful for rather simple components for which it is possible to identify and make measurements on age sensitive parts. Examples are cables, cable joints, cable splices, solenoids, o-rings, etc. For more complex components, activities after installation are normally limited to complementary initial qualification, control of the actual environment and extension of qualified life through on-going qualification.

This report mainly deals with ageing of components in the containment, but one chapter on ageing of components outside the containment has been included. Some of them can be located in areas where they are subjected to high temperature during normal operation and in areas affected by an accident.

This report is limited to age related issues, but also environmental conditions of short duration can affect sensitivity to ageing. A thermally aged component can be more sensitive to impact than a non-aged component. This is also the case at handling, e.g. bending of cables, dismantling for change of o-rings, etc. It may therefore be important that certain tests for qualification in short-term environments are made on pre-aged components. Environmental data for short duration environments can be found in Akustikbyrån TR 5.082.01 [1.2] (components in the containment) and TR 5.125.01 [1.3] (components outside containment). Test methods for short-term environments are given in IEC Publication 60068 (Environmental Testing Procedures), [1.4].

1.3 References

[1.1] Spång K., Ståhl G. "Qualification of electrical components in nuclear power plants. Management of ageing." SKI Report 02:4A, January 2002

[1.2] Krosness A., Spång K. "Miljökvalificering av komponenter i kärnkraftverk. Del I: Komponenter i reaktorinneslutningen", IFM Akustikbyrån TR 5.082.01, 2:nd edition, September 1980 (in Swedish)

[1.3] Westin, L. "Miljökvalificering av komponenter i kärnkraftverk. Del 2: Komponenter utanför reaktorinneslutningen", IFM Akustikbyrån TR 5.125.01, December 1980 (in Swedish)

[1.4] International Electrotechnical Commission IEC Publication 60068 " Environmental testing procedures"

2 Terminology

A number of terms related to ageing of components are used in this report and in 02:4A. They are explained below.

Qualified life	The period of time before a design basis accident for which the component has been shown to fulfil its functional requirements at given operational conditions. The end of the qualified life is equal to the time at which the component must be subjected to renewed qualification or be removed.
Installed life	Time until the component will be exchanged or the power plant is closed down.

Artificial accelerated ageing	Ageing performed in laboratory at higher temperature, dose-rate, vibration level, etc., than it will be subjected to under normal operating conditions.
Condition monitoring	Monitoring of the value of one or more condition indicators.
Condition indicator	Property that can be measured, is affected by ageing, and is related to the functional integrity of the component.
On-going qualification	Re-qualification of a component in order to extend the qualified life.
Design-basis events, DBE	Postulated events specified in the security report of the plant, which define the design criteria for buildings and systems.
Design-basis accident, DBA	A specifically defined case of DBE
LOCA (loss-of coolant-accident)	Loss of coolant that causes a design-basis event
Post-LOCA	Period after loss-of-coolant accident
MSLB (main-steamline-break)	Main steamline break

3 Strategies and programs for qualification of components with regard to ageing

3.1 Aims of programs for management of ageing

The aims of programs for management of ageing of safety related components is to ensure that the components are capable of functioning during normal operation, extreme operation, and DBE at any time after installation. Components containing for their function essential organic materials (polymers, oils, etc.) are sensitive to ageing caused by thermal influence and influence of ionising radiation. For such components, management of ageing is a very essential part of the qualification work.

3.2 Factors affecting ageing

Ageing of polymers affects hardness, elongation-at-break, modulus of elasticity, compression resistance, insulation resistance, voltage sensitivity, sensitivity to chemicals, sensitivity to aggressive gases, sensitivity to vibration, colour, dielectric constant, phase equilibrium, etc. The ageing can be affected by additives used in the polymer. Table 3.1 below summarises positive and negative influences.

Tabell 3.1 Factors affecting the ageing of components

Heat	Humidity	Inert gas[1)]	Radiation[2)]	Catalyst	Antioxidant
strongly negative	strongly negative	positive	strongly negative	negative	strongly positive

1)Investigations, presented in SKI 97:40 [3.1], show that use of nitrogen gas in the containment reduces the oxidative ageing substantially.
2) The effects of ionising radiation also depend on dose-rate.

3.3 Strategy for qualification

The ability of components to function in an accident environment at the end of their life cannot be assessed only from experience since there is very little practical experience of accidents.

We therefore have to use laboratory testing and follow-up of components' conditions in field in order to ensure their capability to perform during an accident.

In order to verify that the components perform in an accident at the end of their qualified life, they are artificially aged before they are subjected to DBE testing. The component can be regarded as qualified for the aged condition it had when it was subjected to the DBE testing. The purpose of follow-up activities after installation is to ensure that the component at no time has aged more than to the condition it had when it was subjected to DBE testing (condition monitoring) or to extend qualified life through complementary testing (on-going qualification).

DBE-testing is normally performed by exposing the components to a dose of ionising radiation equal to the DBE dose and thereafter (in an autoclave) to a temperature-time history often in overheated steam that simulates the ambient environment in a DBE. In some cases, also sprinkling is included as part of the DBE simulation. Components that shall be qualified to earthquake are also subjected to an earthquake simulation (seismic) test before the DBE test.

This report deals with elements that can be included in programs for ageing management including test planning and follow-up activities, applicable to components that shall be installed ("new components") as well as already installed components ("old components").

Qualification of "new components" comprise the following elements

Before installation:
Initial qualification (type testing) including artificial accelerated ageing, followed by DBE testing. Qualified life is established.

May be complemented by preparation for testing and condition monitoring after installation through identification of suitable condition indicators and measurement of their changes as a result of thermal ageing and ageing caused by ionising radiation plus installation of, or putting into store, spare components for on-going qualification.

After installation:
If required, complementary laboratory testing with longer term artificial ageing in order to increase the quality of the initial qualified life and reduce the conservatism in its establishment.

Measurement of environmental parameters in most exposed component positions.

Condition monitoring and/or extension of qualified life through repeated artificial ageing and DBE testing of spare components. The following elements are included in updating or completion of qualification of "old components"

- Survey and assessment of existing documentation from type test, including identification of ageing sensitive parts and materials of the component. Establishment of initially qualified life.

- Preparation for regular follow-up and complementary qualification through identification of suitable condition indicators, measurement and estimation of their change with ageing caused by elevated temperature and ionising radiation, inventory of access to identical components in store or with the deliverer.

- Complementary measurements of environmental parameters, condition monitoring, and on-going qualification in similar ways as for "new components".

References
[3.1] Spång, K. "Ageing of electrical components in nuclear power plants; Relationships between mechanical and chemical degradation after artificial ageing and dielectric behaviour during LOCA", SKI Report 97:40, October 1997

4 Type testing (Initial qualification)

4.1 General

At type testing (initial qualification), it shall be demonstrated that the component maintains its function during normal operation and at a DBE at the end of its qualified life.

For components that are affected by ageing, the type testing includes artificial accelerated ageing. The qualified life is established and verified at the type test high acceleration factors are used in order to achieve a long qualified life with rather short term tests. This is achieved through high temperatures and high dose-rates in relation to what the components are subjected to in normal operation.

Type testing is often performed on the basis of rather general grounds and methods. A large part of the components that are offered by the deliverers are environmentally qualified according to IEEE 323-1974 [4.1] or IEEE 323-1983 [4.2]. Reference is also made to specific component standards, e.g. IEEE 383-1974 [4.3] for cables.

The Swedish utilities have established guidelines for type testing of components, e.g. KBE EP-154 (1996) [4.4].

Reference is sometimes but not very often made to international standards, e.g. IEC 60780 [4.5], which has the same scope as IEEE 323 but corresponds better to European practice. Reference can also be made to other national standards and rules, e.g. KTA 3706 [4.6].

In the review below of initial qualification, on-going work on revision of IEC 60780 and IEEE 323 has been taken into account, as well as the extensive work which has been made within IAEA expert group on cable ageing reported in [4.7].

4.2 Establishment of functional requirements at normal operation and at DBE

The component's functional requirements are defined by the system it is part of and by its task, for safety related components especially its task in an accident. In order to create a functional margin also characteristics of importance for the functional safety are often prescribed, e.g. tightness of seals (o-rings, etc.), dielectric characteristics of insulators, normally insulation resistances.

Insulation resistance is defined between live units or between live units and earth. For cables, it is important that it is clearly stated for what cable length the insulation value is defined.

As shown in Figure 4.1 below from measurements, reported in SKI Report 97:40 [4.7], the insulation resistance decreases at increasing temperature. The insulation resistance also decreases when the material is subjected to humidity, especially under high pressure as is the case at DBE. This means that the insulation resistance during DBE is several orders of magnitude lower than at normal operating conditions also for a non-aged insulation material. If availability of components for type testing permits, it may therefore be important, in parallel to subjecting artificially aged component samples to simulated DBE, also to include non-aged samples in order to get information on whether the component's dielectric characteristics are affected by the ageing or only by the DBE.

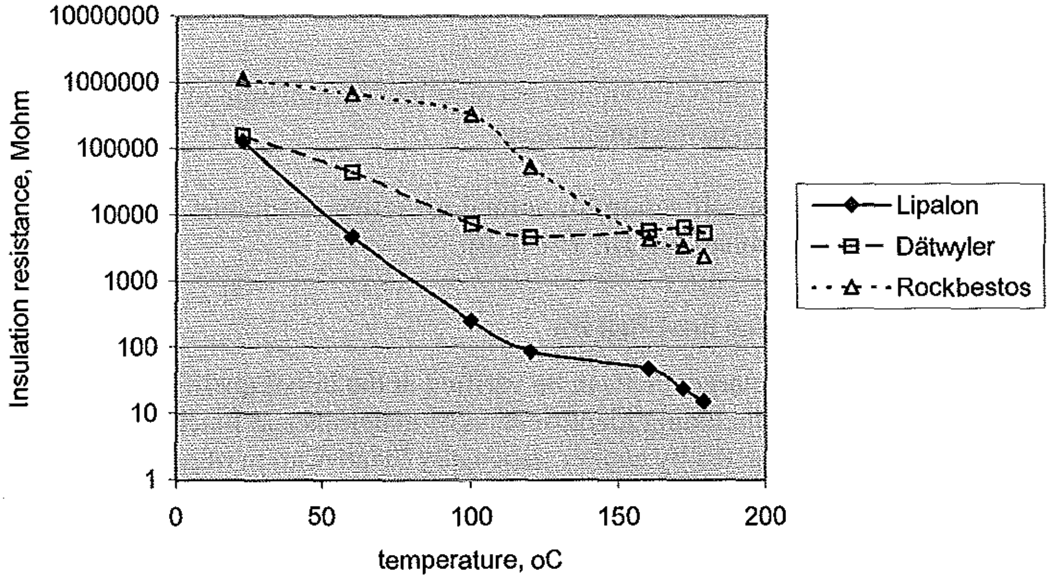

Figure 4.1. The temperature influence on the insulation resistance, measured between conductor and earth on a 1m cable, from [4.7]

It is important to define the functional requirements in a safe but not unnecessarily conservative way. In a number of practical cases, artificially aged components have during DBE simulation shown insulation resistances below general requirements that are often set at 1 Mohm or more. Circuit analyses and investigations afterwards have often showed that the margin when insulation resistance is set at 1 Mohm is very large. It would have been possible to make the requirement more reasonable from the beginning and by that to avoid having to either reject the component or go through the process of changing the criterion afterwards. It should in many cases be less costly and more satisfactory to make a more careful analysis of the requirements on the insulation resistance necessary for the component to maintain its intended function with good margin.

When measuring the insulation resistance of cables, it is important to take into account the length of the cable piece that is used for the testing and measurement compared to the length of the cable for which the requirements on insulation resistance is prescribed. One way is to always specify insulation resistance of cables in ohm*m or Mohm*km.

4.3 Prediction of environmental conditions during normal operation

Information is collected from measurements and an investigation is made of the conditions at the places where the components will be installed. If the knowledge is limited this must be compensated for by conservatism in the predictions. It may pay off to put considerable efforts in collection of measured data and to make a careful investigation of the conditions in the places where the components will be installed in order to increase the confidence and reduce the need for margins. A rather narrow prediction with limited margins can be reasonable if the program for management of ageing of the components includes future measurements.

In chapter 9 is stated what should be taken into account in determination of environmental severity for components located in the containment.

A generalised environmental specification for normal operating conditions, mainly based on IEC 721-3-3 [4.8], can be found in TBE 101 [4.9].

4.4 Establishing target for qualified life

In order to establish a realistic target that can be verified at the initial qualification, a study is required of the component, including identification of materials and functional characteristics that may be affected by ageing, especially identification of polymers involved. This includes obtaining data on the materials and their composition from the producer or the deliverer, inventory of experiences from own or others' investigations and tests, and complementary investigations and tests. Of interest are amongst others activation energies of the materials (for thermal ageing) and the dependence of the degradation on dose-rates (ageing in ionising radiation).

The target can be that the component shall be able to function as required in a DBE at the end of its installed life, e.g. as long as the power plant is in operation. For ageing materials it is sometimes not possible to construct artificial tests that ascertain a qualified life equal to installed life. The target of the initially qualified life should be limited to what can be verified in initial laboratory testing.

4.5 Program for artificial ageing in type testing

4.5.1 General

Time available for type testing normally does not permit a duration for the accelerated ageing before DBE testing longer than one or two months. There is a limit to how long ageing time that can be verified with a short term testing. Methods that can be used to take this into account are

- To use moderate acceleration factors and initially qualify for a limited life that is shorter than installed life and after installation implement a program for extension of the qualified life
- To use high acceleration factors and initially qualify for installed life and after installation improve the confidence in the qualified life by repeating the testing with moderate acceleration factor using long ageing time. A program for condition monitoring should then be implemented in order to check that the component at no time during the installed life has aged to a higher degree of degradation than indicated by the values of the condition indicators when the DBE test in the initial qualification was performed.

The ageing program should take into account the environmental factors of importance to ageing to which the component will be exposed during its installed life. Amongst the environmental parameters that may affect ageing of components containing organic materials are heat, humidity, vibration, ionising radiation, chemical factors, and combinations thereof.

4.5.2 Artificial thermal ageing

4.5.2.1 Model for accelerated thermal ageing

Thermal ageing is always considered. The acceleration is achieved through elevated temperature. An Arrhenius relationship between temperature and rate of degradation is most often assumed. The acceleration factor F is calculated from

$$F = \frac{t_2}{t_1} = e^{\frac{E}{k}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]} \qquad (4.1)$$

where t_1 = test time, t_2 = real time (qualified life), E = activation energy (in eV), k = Bolzman's constant $0{,}86 \cdot 10^{-4}$ eV/K, T_1 = temperature (in K) at normal operation, T_2 = test temperature.

A safety margin should be added to the test temperature or test time. The magnitude of the margin depends on a number of factors, e.g.

- Knowledge of the component's temperature during normal operation. The margin can be reduced if the temperature is controlled (and measured).
- Knowledge of the characteristics of involved organic materials, especially access to measured activation energies within the actual temperature range,
- Test tolerances, e.g. tolerances on the temperature in the working space of the climatic test chamber.
- The number of component samples tested.

The reliability of the verification of qualified life is limited by the factors above but also by uncertainties related to application of the Arrhenius formula to complex components, e.g. to components containing several materials with different activation energies. The uncertainty increases with increasing acceleration factor, i.e. with increasing difference between test temperature and operational temperature. It is of vital importance to limit the acceleration factor so that the same ageing or degradation processes occur at the accelerated ageing as in actual operating conditions. It is not acceptable to use a test temperature that results in completely different behaviour of the material than at operating temperatures, e.g. by reaching the glass phase or the melting phase.

If it cannot be shown by specific investigations that higher acceleration factors can be used with reasonable security, the factor should be limited to maximum 250.

An example is given below that illustrates the importance of knowledge of material parameters and environmental severity for establishment of qualified life from artificial thermal ageing:

Example:
A component contains a part important for the function, consisting of a polymeric material (e.g. an electrical insulation or a seal). The knowledge of the temperature and ionising dose rate at normal operation in the intended location of the component is limited. No tests are available showing the activation energy of the polymer and the dose-rate effects on the degradation of the material.

The operation temperature is predicted to a conservative value of +55°C, based on measurement in other positions and the variation of temperatures within the containment.

In literature, activation energies for similar polymers reported range from 0,75 eV to 1,6 eV (depending on exact composition of the polymer and on the temperature interval at which the activation energy has been determined). A conservative value of 0,7 eV is chosen.

Accelerated ageing is performed at a temperature of +110°C, which is assumed not to involve any risk of affecting the material in any other way than through successive thermal ageing. The acceleration factor is then 35, which means that the accelerated thermal ageing must continue more than half a year in order to reach a qualified life of 20 years. Figure 4.2 shows the variation of the acceleration factor with the assumed operating temperature and the test temperature.

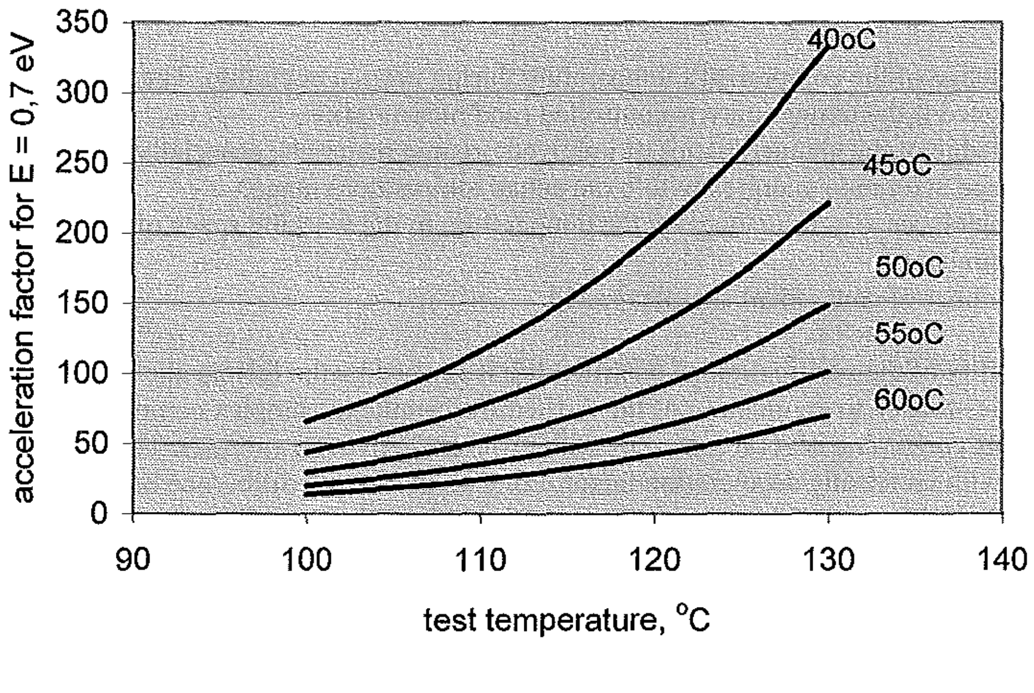

Figure 4.2. Influence of test temperature (from 100°C to 130°C) and operating temperature (from 40°C to 60°C) on acceleration factor at thermal ageing.

From the diagram it can be seen how the acceleration factor can be increased through reduction of the conservatism in predicted operating temperature and/or increase of the test temperature. An increase of the test temperature must be based on an assurance that no mechanisms occur that will affect the component in any other way than at normal operating temperature.

If, for instance, it is possible to reduce the predicted temperature at normal operating temperature to 45°C through careful studies or alternative selection of location the acceleration factor is increased to 77.

If further careful studies of the material show that the temperature during the accelerated thermal ageing to 120°C, the acceleration factor increases to 132.

Measurement of the activation energy within actual temperature interval is a further step towards reduction of necessary conservatism. Figure 4.3 shows how an increase of the acceleration energy value influences the acceleration factor.

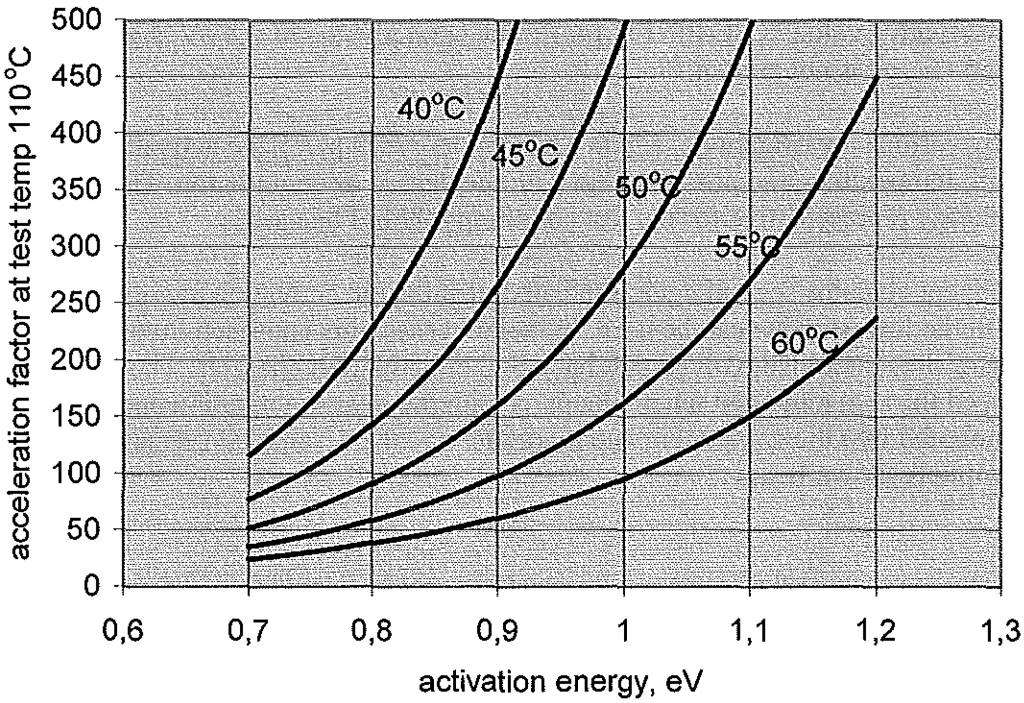

Figure 4.3. Influence of activation energy at different operating temperatures (from 40°C to 60°C) on the acceleration factor at thermal ageing.

Assume that a value on the acceleration energy close to 1 eV has been found at measurements in the relevant temperature range and 0,9 is used for calculation of the acceleration factor. The acceleration factor becomes a little above 250. Artificial ageing at 110°C during one month then qualifies for a life of 20 years.

4.5.2.2 Ambient temperature and component temperature

In cases where there are important heat sources in the vicinity from which the component is not shielded, or if the component is self-heated, knowledge of the surrounding air temperature is not sufficient for determination of the thermal environment. See clause 8.2.3, describing how to determine a suitable test temperature that takes self-heating into account.

4.5.2.3 Activation energy

The determination of the qualified life from artificial thermal ageing depends to a high degree on the assigned activation energy.

The activation energy can vary extensively for one and the same polymer depending on additives in terms of colour pigments, softening agents, fire inhibitors, antioxidants, etc. It is, therefore, very unsafe to use data from reported measurements that have been performed on not identical material combinations. If such data shall be used, it is important to collect information from several measurements of the polymer in various compositions and to select a conservative value. KBE EP-154 [4.4] states that a value of 0,8 eV shall be used if the activation energy is not known.

As shown by various investigations, e.g. in SKI Report 97:40 [4.7], the activation energy can vary with temperature and possibly also with the degree of degradation. Therefore, an activation energy representative for the test conditions should be used.

If the component contains several ageing sensitive details, the activation energy of the material with the lowest value can be used. In certain cases, this approach involves a severe over-testing of the materials involved that have higher activation energies. The over-testing can be reduced through a method where the parts with the lowest activation energies are pre-aged, mounted into the component and thereafter age the assembled component. A typical example is shown below.

Example:
A PS penetration contains the ageing sensitive materials epoxy (moulding), EPR (o-rings) and silicon rubber (o-rings). The average temperature in the penetration at normal operation is estimated to +55°C. Through measurements and a conservative judgement of the results it has been found that the activation energy of the epoxy is 1,2 eV, for the o-rings made from EPR 0,95 eV and for the o-rings made from silicon rubber 0,85 eV. The penetrations are complicated to remove and test. Installation of surplus samples for on-going qualification is not realistic due to their complexity and size. They are used for penetration of cables loaded by 500-550 A at the end of the fuel cycle and therefore self-heated, which makes it complicated to install surplus samples. Therefore, it is desired to qualify initially for a qualified life of 40 years and use condition monitoring successively after installation for further verification.

It is desirable to limit the acceleration factor to 250, resulting in a test duration of at least 40*365/250=60 days. Using Arrhenius formula it can be calculated that for the epoxy (activation energy 1,2 eV) a test temperature of 105°C is needed to reach the acceleration factor 250 (gives the acceleration factor 278). This temperature is used for the testing of the complete assembled unit. For the o-rings from EPR (activation energy 0,95 eV) testing at 105°C results in an acceleration factor 86 and the qualified life at testing for 60 days only gives a qualified life equal to 14 years. The corresponding qualified life for the silicon rubber becomes 9 years (activation energy 0,85 eV, acceleration factor just above 54). In order to reach a qualified life of 40 years for the complete penetration, the o-rings from EPR and silicon rubber must be pre-aged corresponding to 26 and 31 years, respectively, at +55°C, before mounting in the complete penetration (which is then aged for 60 days at +105°C before DBE-testing). In order to attain this, the o-rings from EPR and silicon rubber can be pre-aged for 38 days at +120°C and 45 days at +130°C, respectively.

For some components, only certain polymers involved are of interest to the integrity. For instance, for a cable the integrity of the conductor insulation is very important whilst the integrity of the jacket is less important.

Settlement of o-rings due to ageing is influenced by the tightening, which may need to be simulated in artificial ageing in order to get adequate information of the influence on the function of the o-ring.

4.5.2.4 Assessment of activation energies provided by the component supplier

Some suppliers of components and polymers provide activation energy values of the materials involved. The values provided are important as information of the supplier's bases for qualified life claimed. It may, however, be important to investigate the basis for the supplier's assumptions of activation energies. The activation energy values relevant to judgement of ageing may deviate from the supplier's data, e.g. because the latter is often based on elongation-at-break data compiled from testing of foils degraded at rather high temperatures.

The activation energies determined in foils of material used may furthermore deviate from the values we are interested in due to various factors, such as high temperature of a thermoplastic at extruding, addition of stabilisers, lubrication of tools during the component production, drilling, milling, punching of the component, etc. The values provided by the supplier can normally be used as guidance for identification of the material that limits the component's life. The material or materials that limits the life should be studied with respect to the activation energy in its delivered shape. This activation energy can be used for a more accurate determination of qualified life and furthermore provide a rigid basis for determination of control intervals in cases where the component shall be subjected to a condition monitoring program. Accurate determination of activation energies enables the intervals of condition monitoring to be optimised and establishment of margins for taking into account uncertainty in life determination.

4.5.2.5 Test tolerances

IEC 60068-2-2 Tests B: Dry heat [4.10] is applied in heat testing of components in most environmental test laboratories. Test chambers of good quality normally manage to maintain the requirements on temperature tolerances etc. given in this standard. This means that the test temperature is within ± 2°C of specified value. The margins needed for compensating the test tolerances are small and can normally be neglected in relation to other uncertainties.

4.5.2.6 Number of samples tested. Uncertainties due to variation.

Few investigations are available of the variation in degradation due to ageing of different component samples subjected to identical thermal ageing tests. In SKI Report 93:39 [4.11], it is shown how calculation of margins due to a limited number of test samples can be made.

A limited number of test samples means
- a difference between the mean value of degradation achieved and the true mean value (i.e. the mean value that would be achieved if a very large number of samples had been tested)
- a difference between the achieved standard deviation of degradation and the true standard deviation of degradation (i.e. the standard deviation achieved if a very large number of samples had been tested)

Thus, it is not possible only from the variation in the results from testing of a few samples to state the margins required. It is necessary also to take into account the limited number of samples tested.

The calculation of margins needed due to the limited number of samples tested can be made as follows:

Number of samples tested -	n
Mean value of measured condition indicator -	x_m
Standard deviation of measured condition indicator -	s
Probability that mean value plus margin on it is exceeded -	α
Probability that the standard deviation + margin on it is exceeded -	α

The true mean value is

$$\mu < x_m + \frac{t_{n-1,\alpha} \cdot s}{\sqrt{n}} = A \qquad (4.2)$$

The true variance is

$$\sigma^2 < \frac{(n-1) \cdot s^2}{\chi^2_{n-1,1-\alpha}} = B \qquad (4.3)$$

where

$t_{n-1,\alpha}$ is the student-t distribution for n degrees of freedom and probability α

$\chi^2_{n-1,1-\alpha}$ is the chi-squared distribution for n-1 degrees of freedom and the probability 1- α.

The probability that the mean value + k* standard deviation exceeds $A + k*B$ is α^2 (since the probability that A shall be exceeded is α and the probability that B shall be exceeded is α and mean value and variance are independent of each other).

Example:
A component shall be subjected to artificial ageing, followed by DBE simulation. The condition for accepting the component is that the insulation resistance measured between certain defined points shall not fall below 100 kΩ during DBE.

Five samples are tested. They show the following lowest insulation resistance values during DBE: 260, 287, 195, 370 and 205 kΩ. From the results, we want to find out if a randomly selected component sample would contain the requirement with 90 % probability ((1- α) = 0,90); for each of A and B above, this means that $\alpha = \sqrt{0,1}$, i.e. approx. 0,333. Thus, we shall estimate the true mean value and variance with 67% confidence.

The mean value and the standard deviation of the measured insulation resistances are 213 kΩ and 31 kΩ, respectively.

With 66,7% confidence, the true mean value is

$$\mu > 213 - \frac{t_{4,0,333} \cdot 31}{\sqrt{5}} = 213 - \frac{1{,}093 \cdot 31}{\sqrt{5}} = 198 \text{ k}\Omega$$

With 66,7% confidence, the true standard deviation is

$$\sigma < \sqrt{\frac{4 \cdot 31^2}{\chi^2_{4,0,667}}} = \frac{2 \cdot 31}{\sqrt{2{,}3}} = 41 \text{ k}\Omega$$

The value that is exceeded with 90% probability is $\mu - 1{,}28\sigma$, i.e. larger than 198-1,28*41=145 kΩ. Thus, a randomly selected component sample will with 90% probability have an insulation resistance value above 145 kΩ.

SKI report 93:39 [4.11] also shows how margins calculated from the results of deviations in degradation between samples tested can be transformed into margins in test temperature. The report also shows the results of application of the method of calculation of margins to experimental data from tests on three types of cables, two types of o-rings and one type of solenoid, all subjected to thermal ageing during 48 days at +120°C. The results show that the differences in degradation of the samples tested are not negligible even when the samples have been selected from the same delivery.

4.5.3 Ageing in ionising radiation

A prediction of the dose-rate of the ionising radiation during normal operation is needed as basis for qualification to a certain life. The dose-rate of the gamma-radiation is normally much below 0,1 Gy/h in most of the space within the containment. In the most exposed positions (close to steam-line pipes and in the upper part of the containment), the dose-rate may reach higher values (in the region of 1 Gy/h [4.12]).

Artificially accelerated testing for verification of ageing effects from ionising radiation includes subjection of the test object to the total expected life-time dose (before DBE) in short time, using considerably increased dose-rate in comparison with the normal operation conditions. The acceleration factor is defined as the ratio between the dose-rate at testing and the dose-rate at normal operation.

The safety margin that should be added in verification of qualified life depends on a number of factors, including

- Knowledge of dose-rate in normal operation. Less margin is required if the dose-rate is controlled (and measured) throughout the qualified life.
- Knowledge of the influence of the dose-rate on the degradation of the materials involved.
- Test tolerances, e.g due to uncertainty in dose-rate and in-homogeneity in the irradiation.
- Number of samples tested.

In general, no significant influence of ionising radiation has been found at total doses below 1 kGy [4.13]. An exception is components containing Teflon (sensitivity threshold down to a few kGy) or ordinary micro-processors (sensitivity threshold a few Gy). [4.13] gives the following threshold levels for polymers, below which the effects of ionising radiation are negligible.

Table 4.1 Threshold values for ionising radiation (from [4.13])

Elastomers		**Thermoplastics**		**Resins**	
Material	*kGy*	*Material*	*kGy*	*Material*	*kGy*
EPR/EPDM	10	XLPE/XLPO	10	Epoxy	2000
Neoprene	10	PVC	1	Polyimide (Kapton),PI	100
CSPE	5	Polyethylene, PE	3,8	Fenolic	3-3900
Nitrile (Buna N)	10	ETFE (Tefsel)	10	Polyester	1-790
Butyl	7			Melamine	67
Viton	1				
Silicone	10				

Westinghouse Atom has made corresponding investigations, also including most of the materials above. Their results are in good agreement with the values given in the table apart from PVC and Polyethylene (PE), where Westinghouse Atom indicates threshold levels of 10 kGy and 100 kGy, respectively. In addition, Westinghouse Atom indicates the following threshold levels:

PEEK, PEAK	100 kGy
PTFE	1 kGy
EVA	10 kGy

For the majority of organic materials, the degradation due to a given total irradiation dose depends on the dose-rate. Different approaches are used in different countries. IEEE 323 limits the dose-rate to 10 kGy/h, KTA [4.6] prescribes 0,5 kGy/h (100 h) for simulation of ageing dose. In Japan 1 kGy/h is prescribed. KBE EP-154 [4.4] prescribes 1 kGy/h. Recent investigations with use of very low dose-rates in England, Germany and France show dose-rate effects which require much lower dose-rates, in the order of 3-10 Gy/h, to become fully developed. For some materials, the dose-rate effects are rather moderate.

The dose-rate dependence of the degradation is less if the material is well stabilised with anti-oxidants.

Table 4.2 shows a compilation of available data on dose-rate dependence for materials used as insulators in cables and other components and in o-rings used in NPPs.

Table 4.2 Dose-rate dependencies

Material	Dose-rate dependence at comparison between high and medium high dose-rates[1)]	Dose-rate dependence at comparison between high and low dose- rates[1)]
EVA	small	large (30)
EPR/EPDM	small	moderate to large (3-8)
XLPE	small	moderate to large (3-10)
SiR	moderate (3)	large (12)
Viton		large
PEEK	small	small

1) High, medium high and low dose-rates refer to 1-10 kGy/h, around 100 Gy/h and 1-10 Gy/h, respectively.

The factors within brackets are ratios between total doses required for a reduction of elongation-at-break ratios (e/e_0) by 50%, using high dose-rates and medium dose-rates (in the left column) or high dose-rates and low dose-rates (in the right column).

The total doses (below 3 kGy) typical at normal operation for the main part of locations of safety-related components in the containment of Swedish nuclear power plants does not cause any significant degradation to the majority of the components also when dose-rate effects are taken into account. For components located in areas where they are exposed to higher dose during normal operation the total life-time dose should be calculated and compared to the DBE dose. If the latter is a factor ten or more higher, it will for most components be enough to simulate the DBE dose (with a dose-rate corresponding to the DBE conditions). For a few materials (e.g. EVA, PVC) a difference of a factor ten may not be enough for ignoring the dose and dose-rate effect during normal operation.

If the component shall only function in the initial phase of a DBE, the dose during normal operation may be important and it will be necessary to use enough margin to take dose-rate effects into account.

How to take into account uncertainty due to testing of a limited number of samples is clear from the former section on thermal ageing.

4.5.4 Other environmental factors that may be of importance for the degradation due to ageing

Humidity may increase the rate of ageing, as shown in a number of studies reported among others in IFM Akustikbyrån TR 5.299.03 [4.14]. Our safety related components are normally not subjected to high humidity during normal operation. In cases where exposure to humidity for a significant period of time is observed, e.g. from leaking steam-lines, the effect on ageing should be taken into consideration.

Exposure to sulphur dioxide may cause changes of contact resistance in contact surfaces of all metals except precious metals. Hydrogen sulphide affects primarily silver and alloys. Acceleration of corrosive environments can be achieved through

- Increased temperature
- Increased relative humidity
- Enhancement of the conditions for condensation (rapid temperature rise at high relative humidity)
- Increase of the concentration of corrosive gases/substances
- Mechanical stress

Methods for acceleration and testing in corrosive environments (salt mist, sulphur dioxide, hydrogen sulphide, etc.) can be found in various parts of IEC 60068.

The concentration of ozone in the air is often higher in coastal areas than inland. The reason is that ozone is absorbed more efficiently at transport over land than over water. Significant concentrations of ozone may be found in areas outside the containment. Ozone affects primarily elastomers.

Mechanical ageing means changes in properties due to mechanical influences, such as

- Bending can cause cracks or fragility of the material
- Wear can affect the electrical as well as the mechanical strength

- External influences, such as shocks, can result in permanent damage, primarily influencing the electrical properties of the materials.
- Vibrations can cause wear resulting in degradation of mechanical as well as electrical properties
- Static compression of polymers can result in permanent deformation

Test results reported in SKI Report 97:40 [4.7] indicate that thermally aged cables subjected to excessive intermittent vibration during operation may show poorer insulation during DBE simulation than identically thermally aged cables which have not been subjected to vibration. The tests are very limited, but the results indicate that one has to be aware of an increased risk of reduced ageing resistance of components placed in vibrating structures and components which for other reasons have been subjected to excessive vibration.

4.5.5 Test sequence and combined environments

During normal operation, components in the containment are subjected to ionising radiation and elevated temperature simultaneously. In laboratory testing the environmental stresses are normally applied in sequence. A number of studies show that for certain materials are the ageing effects are significantly larger if they are applied simultaneously than if they are applied in sequence. If it is not possible to apply the environments simultaneously they have to be applied in the most potentially damaging sequence and a margin should be added to account for synergetic effects.

There are also examples of investigations showing that simultaneous application of high temperature and dose-rate result in less degradation than sequential application. Therefore, it is not always the case that a combined accelerated test gives more realistic results.

A number of studies performed compare the effects on degradation of organic materials of the sequence high temperature - ionising radiation and of the sequence ionising radiation - high temperature. It is generally considered that the sequence ionising radiation - high temperature results in the highest degradation. This may be a suitable assumption if no information is available. However, our own measurements on cables type Hypalon (CSPE/CSPE), Dätwyler (EPDM/EPDM), and Rockbestos (CSPE/XLPE) show a varying picture [4.11].

4.6 DBE-test

Components required to function during DBE are subjected to a DBE-simulated test after ageing that normally includes irradiation to a dose equal to what is expected during a DBE plus margin, followed by a thermodynamic test in hot steam at high atmospheric pressure according to a specified profile. Operating conditions during DBE for our NPPs are described in TBE 102:1, [4.15] and the corresponding profiles for DBE testing are given in KBE EP-154, [4.4].

The dose-rate can be made equal to what is expected during DBE. Studies of possible synergism of the combination of ionising radiation and the thermodynamic conditions in DBE are not known, but it is noted that a significant margin is generally applied when prescribing the radiation dose for the DBE-simulation.

Requirements on function during 30 days of post-DBE are prescribed for certain components in Swedish NPPs. Accelerated ageing is not recommended to be used in testing for verification since we have no established method for accelerating the influence of humidity and it should not be too impractical to allow the full time needed (30 days). Methods for acceleration of humidity effects are given in [4.14], but they are component specific and not generally applicable.

4.7 References

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[4.18] EPRI NP-2129 "Radiation Effects on Organic Materials in Nuclear Plants", prepared by Georgia Institute of Technology, November 1981

[4.19] "Effects of low irradiation dose rates on microprocessors to simulate operation in nuclear installations. A safety approach", A. Laviron m.fl. Proceeding Opera 89, September 1989, pp 137-144

[4.20] Operability of Nuclear Power Systems in Normal and Adverse Environments. Albuquerque, New Mexico, September 20-October 3, 1986 Proceedings

[4.21] K.T. Gillen and R.L. Clough "Occurrence and implications of radiation dose-rate effects for material aging studies" Radiat. Phys. Chem, 18, 679 (1981)

5 Activities after installation in order to maintain qualification through complementary testing and control measurements

5.1 General

Type testing of components before installation provides a certain degree of confidence that the components manage to function satisfactorily in various situations including in a DBE. The degree of sensitivity to ageing, complexity, technical conditions and possibilities, costs of repeated measurements and testing in relation to costs of exchange of components etc. affect the extent and design of complementary programs for maintaining qualified life. The methods available after installation for improvement of the reliability of initially established qualified life and possibly to extend it are described below. They can form elements of a full program in which initial qualification and qualification activities after installation are complementary elements. They can also be used to complement the qualification activities related to installed components for which an assessment of the initial qualification points to a need for complementary qualification

Condition monitoring or repeated environmental testing can be used to maintain and possibly extend qualified life. In condition monitoring one or a few condition indicators are identified, whose change with thermal ageing and ageing in ionising radiation are determined and whose value during DBE testing can be regarded as the limit value of a qualified condition. The condition is measured regularly after installation in order to observe that the component is not aged more rapidly than indicated at the determination of qualified life in the type testing. For extension of qualified life, artificial ageing followed by DBE testing is repeated on component samples removed and substituted by new components or by components from store or by spare samples that have been installed for being used for this purpose. The methods are described more in detail in later chapters.

5.2 Preparation for testing and condition monitoring after installation.

5.2.1 Installation and storage of components for on-going qualification

On-going qualification though repeated testing after installation requires availability to component samples that have been subjected to at least the same ageing as the most exposed ordinary components for which the qualified life shall be verified or extended. Also destructive condition monitoring requires access to replacement components or spare components that have been installed specifically for the monitoring.

In cases where replacement components shall be used, i.e. when testing or measurements shall be performed on ordinary installed components, it is important that the replacement components are stored in controlled, mild conditions of temperature and humidity. It is also important that the components are well documented regarding identity with the components that have been tested earlier and with the components that have been installed.

An important requirement for on-going qualification and condition monitoring is reliable information (preferably through measurements) of the environmental history for the specimens selected for testing or condition monitoring and on the environmental history of the components that shall be qualified.

As shown below, artificial ageing as an element in repeated testing for on-going qualification can be substituted by using component samples that have been subjected to more severe environmental conditions in normal operation (in hot-spots) than the components that shall be qualified. If component samples are installed specifically for this purpose, it is important that the environment for the samples is kept under control.

5.2.2 Identification of condition indicators and their change with time

When condition monitoring shall be included in the program for maintaining qualified life, it is necessary to

- identify condition indicators applicable to the component
- get information on how the values of these condition indicators change with ageing
- establish limit values on the condition indicators at which safe function in DBE is verified

The most useful indicators, how they are monitored and their applicability to different polymers, is reviewed in Chapter 9. It is of considerable advantage if monitoring can be performed without affecting the component (non-destructive monitoring). This reduces the amount of work in connection with determination of changes with ageing, establishment of limit values and condition monitoring in the field. However, also destructive methods can be used.

Vibration of polymers that have been subjected to thermal ageing or ageing in ionising radiation can result in development of cracks. Components in the reactor containment are normally not subjected to significant vibration. It should be noted, however, that condition monitoring does not normally give information on development of cracks in polymers which can influence the dielectric behaviour. Degradation of dielectric properties due to cracking only shows up at measurement in humid atmosphere, especially in DBE-conditions.

5.3 Complementary testing and control measurements

Environmental measurements and complementary testing can be used after installation to improve the reliability of the qualified life and to revise the qualified life.

5.3.1 Measurement of the environment of installed components

Measurement of the environment, especially temperature and ionising radiation, in areas representative of the location of the components is an important activity for reducing the uncertainty of the qualified life determined from the type tests. Measurement of the environment of components is dealt with in Chapter 8.

5.3.2 Complementary long term testing in laboratory

The time available for artificial ageing at type testing is limited. Therefore, initially determined qualified life is either limited due to the limited time used in the artificial ageing or based on tests with high acceleration factors, involving a considerable degree of insecurity.

A possibility to substantially improve the quality of the life determined from the type tests is to perform a repetition of the type test after installation with considerably longer time used in the artificial ageing. This is of special importance when the degree of uncertainty is large due to a risk that the use of high acceleration factors involves testing in conditions that are not representative of the normal operation environment. Investigations reported by Sandia [5.1] indicate that acceleration of thermal ageing at high temperatures in some cases can involve similar effects as use of high dose-rates in artificial radiation ageing. The oxidation of the surface layer of the material may correspond to the acceleration but the oxidation of the inner parts of the material may be limited (diffusion limited oxidation).

Complementary long term tests in laboratory may also be justified for earlier installed components where a critical review of test reports indicates that the quality of the determination of qualified life is insufficient, e.g. because it is based on testing with very high acceleration factors. It may also be of interest to accept a component for installation based on the tests reported by the supplier (based on other user's requirements) which we consider qualify for a short term, but where we are not convinced that the tests performed by the supplier ensure safe function in DBE after a long installed time.

Establishment of suitable condition indicators and their change with time during artificial accelerated ageing is time-consuming and may therefore be difficult to accomplish in connection with type testing. If the intention is to use condition monitoring to follow the ageing of the components after installation, the investigations needed for establishment of condition indicators and their change with time can instead be made in connection with complementary long term testing.

5.3.3 Complementary measurements and studies of parameters of importance to determination of acceleration factors in artificial ageing (activation energies, dose-rate effects, synergistic effects, etc.)

There is normally not much time available in connection with determination of qualified life from results of type testing for making separate studies of the materials involved with respect to activation energies, dose-rate sensitivity, synergistic effects of combined radiation and temperature, etc. The assumptions made when determining qualified life from type testing or complementary long-term tests in laboratory can be subject to substantial insecurity. More secure values on these parameters can be attained through measurements after installation (on stored component samples).

5.3.4 Revision of qualified life

One or more of the above mentioned activities (environmental measurements, complementary long-term testing, measurement of material properties of importance for determination of acceleration factor) provides the basis for revision of qualified life that through the activities can be made more realistic and reliable. When qualified life is established by use of Arrhenius' relationship for thermal ageing, equation (4.1), a revised acceleration factor (F) is determined through insertion of revised values on temperature in normal operation and activation energy (T_1 and ϕ in equation (4.1)).

5.4 Observation of components' ageing through condition monitoring and inspections

Artificial testing in laboratory, performed with moderate acceleration factors and according to well-founded environmental prediction and test methods, gives a high degree of assurance that the components will function satisfactorily in normal operation, extreme operation and DBE for a limited installed time (qualified life). The uncertainty in life prediction and prediction of age related material degradation increases with installed time. Condition monitoring and inspections can be used to confirm that the ageing after a longer installed time has not proceeded at a higher rate than expected.

The choice of condition indicators depends on the component's ageing sensitive materials, accessibility, etc. If possible, non-destructive methods should be used, not requiring exchange of components monitored. Destructive methods, e.g. elongation-at-break, can be used if exchange components are easily accessible and it is reasonably simple to exchange the components or if a considerable number of spare components have been placed in representative locations.

Inspections in connection with revision shutdowns form an important complement to condition monitoring. Such inspections can be used to identify areas with harsh environments (hot spots). Inspections can be useful for identification of environmentally induced degradation of cables and components, damage to thermal insulation of hot tubes, etc., that can aggravate hot-spots. The following observations on cables etc. can indicate hot-spots: discoloration, leakage of softeners, cracks in surface materials, hardening. Also observations in the surrounding structure (colour changes, etc.) can indicate hot-spots.

5.5 Extension of qualified life through on-going qualification

The qualified life can be extended through a procedure where component samples placed in locations representative of the environmentally most exposed components are removed, artificially aged in laboratory and subjected to functional controls during DBE testing. This procedure is performed first time when the component approaches the installed time to which it has been qualified in the type test (initially qualified life) and is then repeated at prescribed time intervals until it no longer stands extended qualification or is exchanged for other reasons.

The method can be used for new installations. Spare components are then installed in severe environmentally exposed locations. As an alternative, the spare components can be placed in more severe exposed locations (hot-spots) than what is representative of the normal location of the components. In this case the artificial ageing before the DBE testing can be omitted, counting in the difference between the levels of exposure in the hot-spots and in normal positions.

The method can be used to extend the qualified life of installed components also in cases where there is no access to installed spare samples. There are two ways of doing this:

- To remove ordinary components for on-going qualification and exchange them with new components or components from store, if available.
- To install spare samples as above that have been aged artificially in laboratory (using very moderate acceleration factors) to a degree of ageing corresponding to installed time of the installed components. These samples can be used the next and following times the testing for life extension is performed.

It is important to know the environmental history of the components removed for on-going qualification and for typical locations of the installed components that shall be qualified. SKI Report 93:39 [5.2] compares tests with low acceleration factor and a test time shorter than required for a certain installation time t, followed by an on-going qualification, with type tests using high acceleration factor and a test time corresponding to t. In order to make the comparison against real conditions, a long-term test was made in real time. The results indicate that the method with low acceleration factor plus on-going qualification corresponds significantly better to the long-term exposure than the method with a high acceleration factor. The conclusion drawn is that the use of on-going qualification improves the realism significantly. In some cases (e.g. application to a cable type Hypalon) artificial ageing at high acceleration factors resulted in much less degradation than on-going qualification, even when rather conservative assumptions of activation energies were used.

5.6 References

[5.1] Kenneth T. Gillen, Mat Celina and Roger L. Clough ”Limitations of the Arrhenius Methodology”, WRSF Information Meeting, Bethesda, Maryland, October 26-28, 1998

[5.2] Spång, K. ”Methodology for artificial ageing of electrical components in nuclear power plants; Results of experimental studies”, SKI Report 93:39, December 1993

6 Summary of programs for management of ageing of "new" and "old" components

6.1 General

Complete programs for management of the ageing problem, built from applicable elements of available methodologies, can be developed in connection with purchase and qualification of new components for installation in NPPs. Also in the cases of already installed components, for which it is desired to follow up and complement existing qualification or to extend qualified life, applicable elements from earlier described methodologies can be used. A survey of the possibilities is made below.

The following situations are distinguished:

- A new component for which a qualification program shall be developed, including type testing as well as activities and measurements after installation.

- A new component for which an assessment shall be made of the performed and reported type testing made by the supplier or by another user. The assessment is based on our own requirements and needs and it may also be desired to make complementary testing and measurements after installation.
- A component at present installed in NPPs and for which reports on earlier performed environmental testing in connection with type testing are available. It is desired to reassess qualified life from the earlier tests and accomplish this by introducing follow-up activities and possibly also extend the qualified life.

6.2 "New" component

6.2.1 Complete environmental qualification program

A complete environmental qualification program for a new component can include
- Specification of a goal for the installed life,
- Type testing with establishment of the initial qualified life, see Chapter 3.
- Program for measurement of the environment of the component at normal operation.
- Extended laboratory ageing, followed by DBE test in order to improve the reliability and possibly reduce the required conservatism in establishment of the qualified life. May also include studies of activation energies, dose-rate effects, synergistic effects of simultaneously occurring environmental factors, etc.
- Program for condition control, including measurement of condition indicators in connection with type testing or extended laboratory ageing and program for condition monitoring in field (in connection with revision shutdown). In case of destructive condition monitoring, spare components have to be installed for use in the monitoring or a preparation is made enabling removal of ordinary components for the monitoring and exchange by components from the store.
- Alternatively, program for on-going qualification, including methodology and decision on how and when removal of components for the on-going qualification shall be done. Installation of spare component samples in connection with installation of ordinary components, after an analysis of the operational environments in actual areas and choice of location of the spare samples. The location should be representative of the most severe operational environments for the component type. The program includes artificial ageing and DBE-simulation in connection with the testing for extension of the qualified life.

6.2.2 Environmental qualification program for a new component for which a certain qualification documentation is available

Reports on qualification for general use in NPPs, including accelerated ageing and DBE-simulation, are often available from the supplier of components for use in NPPs. Programs for management of ageing can then include assessment of qualified life and programs for complementary testing and follow-up activities.

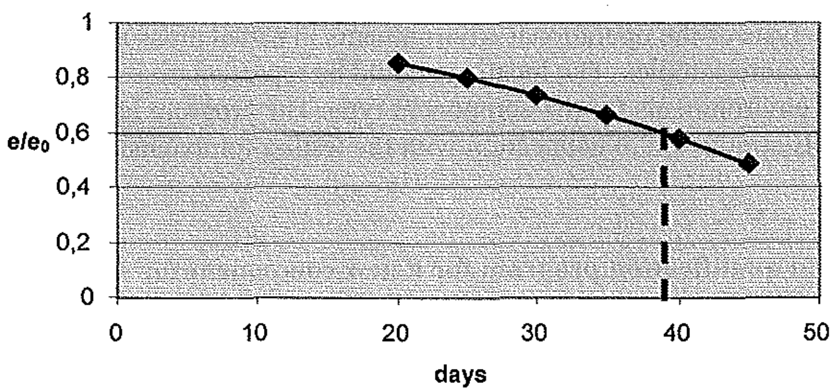
Follow-up activities may include measurement of the component environment in normal operation and introduction of condition monitoring (see scheme in clause 6.2.3) or on-going qualification. If condition monitoring shall be introduced a complementary testing is required in order to measure the change of the condition indicators with time at artificial ageing and their values just before the performed DBE-simulation.

If the component has been qualified to a certain life through use of a significantly higher acceleration factor than acceptable (e.g. significantly higher than 250 at thermal ageing), it is possible to bring back the qualification to an acceptable acceleration factor without repeating the DBE-simulation, as shown by the following example.

<u>Example</u>
A cable which in normal operation is expected to be exposed to maximum 50 °C (including margin) has been qualified by the supplier through artificial ageing during 4 days at 142 °C, followed by a DBE-simulation with acceptable performance. The activation energy for the jacket material and for the insulation material has been shown to be slightly above 1 eV. This gives the acceleration factor just below 3000 and this has been used for the statement from the supplier of a qualified life of 30 years.

In order to determine the qualified life at use of a moderate acceleration factor (< 250), the following test is made. Some samples of the cable are placed in a heat test chamber at a temperature of 142 °C and the condition is measured through an elongation-at-break test of the cable jacket and insulation before (elongation-at-break e_0 mm) and after 4 days ageing (e mm). e/e_0 turns out to be just above 0,6 for both jacket and insulation. Thus, the cable has passed a DBE-simulation with acceptable performance in this condition.

Some samples of the cable are placed in the heat test chamber at a temperature of 110 °C, corresponding to the acceleration factor 212 at the activation energy 1 eV. Samples are taken out each 5th day, starting after 20 days, and the elongation-at-break is measured. The results are shown in Figure 6.1.



<u>Figur 6.1</u> e/e_0 as function of exposure time at 110 °C

It is seen from Figure 6.1 that the cable can be exposed to 110 °C during almost 40 days before it has degraded to the condition for which it is qualified. Using the acceleration factor 212 this means that a qualified life equal to 20 years has been verified with a moderate acceleration factor.

6.2.3 Scheme for extension of qualified life through on-going qualification

At installation:

Installation of spare component samples located in areas representative of the most severe environments	Storing of components for exchange in on-going qualification	Installation of spare samples in "hot-spots" with more severe environment than for ordinary components

During normal operation:

Environmental measurements (environmental history)	Environmental measurements (environmental history)	Environmental measurements (environmental history)

At time t_1,in good time beforeinitially qualified life expires:

Removal of installed spare samples at time t Artificial ageing of these, corresponding to time Δt in actual environment	Removal of installed spare samples, which are exchanged by components from the store Artificial ageing of the removed samples, corresponding to time Δt in actual environment	Removal of installed spare samples at time t. The difference in the environment to which the component located in "hot-spot" has been exposed and in ordinary locations result in a difference Δt i life
Functional testing during DBE-simulation. If the result is accepted the qualified life of installed components is extended with the time Δt	Functional testing during DBE-simulation. If the result is accepted the qualified life of installed components is extended with the time Δt	Functional testing during DBE-simulation. If the result is accepted the qualified life of installed components is extended with the time Δt

6.3 "Old" (earlier installed) component

6.3.1 Complementary environmental qualification

For an installed component, which has been in operation for a time, it may be desired to complement, verify and possibly extend its qualified life. This can be done by reviewing the qualification documentation, performing complementary measurements and testing in case the qualification documentation does not provide a satisfactory basis and developing a program for condition monitoring or on-going qualification. The methods and their applicability on this situation is described earlier in this chapter.

6.3.2 Scheme for extension of qualified life through on-going qualification

On-going qualification for extension of qualified life of "old" components requires access to stored identical components or new components that can replace the components removed for tests for extension of qualified life. The scheme below illustrates various alternatives.

Before entering into laboratory testing for extension of qualified life, more precise and correct information on the component environment should be acquired through measurements during normal operation in exposed component positions. The results of the measurements are used for determination of acceleration factors to be used in the laboratory testing.

In the scheme below access to identical components in store is presumed. Installed components are assumed to have been in operation for the time period Δt_0.

Alternatively, on-going qualification can be performed in the same way as for "new" components through removal of samples of installed components that are replaced by components from the store. Removed samples are aged artificially (at elevated temperature) corresponding to the time • t in real conditions and subjected to functional testing during DBE-simulation. If the result is approved, the qualified life of the installed components is extended by the time Δt.

__Preparation for enabling on-going qualification (is made at the time t_0):__

Spare components from the store are artificially aged for a duration corresponding to the period from installation to t_0 and then installed in locations representative of the most severe environments.	Spare components from the store are artificially aged for a duration corresponding to the period from installation to t_0 and then installed in "hot-spots" with a more severe environment than for ordinary components

__At time t_1, in good time before the initially qualified life expires:__

Removal of installed spare samples at time t_1 for extended qualification. Artificial ageing of the samples corresponding to the time Δt in real environment	Removal of installed spare samples at time t_1 for extended qualification. Artificial ageing of the samples corresponding to the time Δt in real environment
Functional testing during DBE-simulation. If the result is accepted the qualified life of installed components is extended with the time Δt	Functional testing during DBE-simulation. If the result is accepted the qualified life of installed components is extended with the time Δt

6.4 On-going qualification of component parts

On-going qualification is normally applied to complete components. For complex components composed of sub-components of which only a few contain ageing sensitive parts, the on-going qualification activities may in certain cases be limited to the ageing sensitive sub-components. This requires a careful analysis showing that influence on the complete component's function under DBE from ageing of the ageing-sensitive sub-component can be established in a test where only the aged sub-component's performance under DBE-simulation is verified.

7 Components outside containment

7.1 Management of ageing

A comprehensive study of the environmental conditions of safety-related components located outside containment was performed in 1980 and reported in IFM Akustikbyrån TR 5.125.01 [7.1]. TBE 101 [7.2] specifies two classes of normal operation environment outside containment. (Severity A: areas where no hot process systems are installed, Severity B: hot process areas).

The effects of long term exposure may need to be taken into account for components that shall function for a long time, especially components located in areas affected by an accident. For components located in areas not affected by accidental conditions, qualification for ageing is normally not necessary. Qualification through analysis and regularly repeated functional controls and inspections should be sufficient.

Supervision of the functions of the components is, however, not always sufficient. Introduction of periodic inspection may be needed, where the components are dismounted and critical parts (e.g. silver coatings) are inspected and replaced when applicable limits of corrosion have been reached. Degradation of elastomers (e.g. o-rings) can be accelerated if the storage is unsuitable or if the o-rings have been mounted in "hot" electrical components outside critical areas.

For components located in areas affected by accident, such controls are not sufficient since they do not indicate if the component is able to perform its intended function in connection with an accident. For such components, there are reasons to ensure their function under simulated accidental conditions through knowledge of the ageing durability of materials involved or, preferably, through artificial ageing and testing in simulated accident conditions, possibly combined with condition monitoring according to earlier chapters of this report.

Very varying environmental conditions occur in areas outside containment in connection with accidents. Large variations occur between different accidental events and different power stations. Also within one and the same area local variations occur. In TR 5.125.01 [7.1] a subdivision is made of the areas affected by accidents in

- Primary event room – area with warm, pressurised systems or cold systems where steam-line breaks can occur. Components located close to the place of a steam-line break in a primary event room are subjected to the most severe accident environment.
- Relieve path – can consist of several areas in a chain. For relieve paths it is assumed that the outflow in connection with an accident as a minimum lasts until equilibrium is obtained. Diffusion may also take part directly via ventilation channels and across sewage systems.
- Flowing through area – area connected to a relieve path with possibilities of inflow and flowing through. Propagation of environmental conditions with gas/steam to the area is assumed to take place from relieve paths through the ventilation system. For liquids the level difference is the driving force.
- "Blind gut" – area connected to a relieve path with inflow possibilities but without possibilities of flowing through. This includes connecting corridors to relieve paths, etc.
- Leakage areas – areas which run the risk of being subjected to leakage from any of the other areas in an accident condition, primarily from a relieve path. Leakage of gas/steam may take place through a chink of a door etc. Water leakage may take place through cracks and seals in joists, etc.

A survey of the environments in various areas is documented or will be documented for the individual Swedish power plants.

According to TR 5.125.01 [7.1], the integrated 40-years dose of ionising radiation (gamma radiation) under normal plant operation in areas adjacent to the reactor containment is 50 Gy, in other areas less than 5 Gy. In areas with filter cells, ion exchanger, abatement tanks, higher integrated doses may occur. This is also the case in areas close to steam-lines.

The radiation doses reported are considerably below what is normally affecting the degradation of organic materials, with the exception of certain teflon materials.

The integrated dose in connection with an accident can reach 40 kGy very close to a conduit that circulates water containing fission products. 1 m from the conduit the level has dropped to one tenth. In other areas the accident dose is significantly lower – in the region of a few tenths of Gy. Accident environmental testing needs to include (be preceded by) ionising radiation only for components in particularly exposed positions.

Components in outdoor areas or in partly open and ventilated areas may be exposed to hydrogen sulphide, chlorides (salt mist), sand and dust. Combined with humidity this may reduce the components' life through corrosion and chemical effects.

The components may occasionally be exposed to welding gases (fluorides, nitrogen dioxides, ozone, phosgene, etc.) and to smoke and soot in connection with revisions. This can add to the degradation. The degradation can also be influenced by the presence of high contents of ozone in the air.

Elevated temperatures during normal plant operation can occur due to heat radiation from warm systems. In areas not containing warm systems 25 °C can be expected in summer, somewhat cooler in winter, assuming that the component is not located close to a window so that it is exposed to solar radiation. Thermal ageing can be neglected in these cases.

Investigations reported in SKI Report 97:40 [7.3] indicate that intermittent vibration can reduce the insulation resistance in thermally aged cables under accident conditions. Components outside the containment may be subjected to vibration. This is the case for components mounted to the same structure as vibrating machinery (engines, pumps, etc.), components mounted to structures to which steam-lines are mounted, components mounted on steam-lines, etc. The functional performance of components containing thermally aged organic materials may also be reduced if they are subjected to hits and occasional shocks.

Qualification programs for management of ageing should be performed for safety-related components in areas subjected to essential influences of accident environments. For safety-related components in areas not significantly influenced by accident environments it should be sufficient to perform regular controls of the components' function.

7.2 References

[7.1] Westin, L. "Miljökvalificering av komponenter i kärnkraftverk. Del 2: Komponenter utanför reaktorinneslutningen", IFM Akustikbyrån TR 5.125.01, December 1980 (in Swedish)

[7.2] TBE 101E "Technical requirements for electrical equipment. Environmental specification for normal operation", 1996-12-12

[7.3] Spång, K. "Ageing of electrical components in nuclear power plants; Relationships between mechanical and chemical degradation after artificial ageing and dielectric behaviour during LOCA", SKI Report 97:40, October 1997.

8 Methodology for measurement of the environments of components during normal plant operation

8.1 Background

Prediction of a component's qualified life is built on prediction of the environmental conditions for the component during normal plant operation. Limited knowledge and limited control of the environment must be compensated by margins on predicted environmental severity, resulting in a conservative value on the qualified life. Measurement and control of the operational environment is therefore an important instrument that can be used to limit the degree of conservatism without reducing the confidence in the predicted qualified life. The measured and controlled environment is normally milder than used in the prediction and the life verified by the type rest can often be extended as a result of the measurement data obtained.

Temperature and ionising radiation are the primary contributors to the ageing of components. It is therefore important to control these environments. In certain locations and/or under certain conditions it can be of interest also to control other factors, e.g. relative humidity, pollutants and vibration. This chapter describes methods and technique for environmental measurements with application to control of the environment of components in NPPs.

A satisfactory information on distribution of temperature and ionising radiation in the containment can be achieved if temperature sensors and dosimeters are placed in the most exposed component locations and in places with an environment representative of the majority of the component locations. The measurements should include at least two full periods between revision shutdowns so that normal short-term fluctuations as well as the influence of seasonal influences are covered.

8.2 Temperature, measurement requirements

The temperature of a passive (not self-heated) component is completely determined by the surrounding. Two factors dominate: the temperature of the surrounding air and the heat radiation from surrounding surfaces. Only knowledge of the surrounding air temperature is not sufficient for determination of the temperature environment of a component if there are important heat sources in the vicinity from which the component is not shielded.

The temperature of an active (self-heated) component is, in addition, determined by the self-heating and the flow of heat from the component to the surrounding through convection, radiation and heat conduction.

8.2.1 Air temperature

Measurement of air temperature should be made with sensors shielded against heat radiation from surrounding surfaces. If the air is rather calm, that is the air movements are mainly determined by convection, the local variation of the air temperature can be significant, depending on closeness to heat-sources. Several sensors may therefore be needed in an area in order to achieve values on the air temperature that are suitable for determination of the temperatures to which the components are exposed during normal plant operation.

8.2.2 Radiation from surrounding surfaces

If the component is directly exposed to surfaces in the vicinity that are warmer than the air temperature, the component temperature will be higher than what is caused by the air temperature alone. The extent to which the heat radiation influences the component temperature depends primarily on the air circulation around the component (the higher the air circulation, the less the influence by the radiation) and by the heat absorption coefficients of radiating and receiving surfaces. If radiating and receiving surfaces are not polished, the absorption coefficient can be conservatively assumed to be close to 1. Theoretical calculations of resulting component temperature from knowledge of air temperature, air flow, absorption coefficients and geometry of heat radiating and receiving surfaces are feasible but rather complicated and built on data which are often not completely known or insecure.

Measurement of the component's temperature is often a simpler and more reliable way but it requires attachment of sensors to representative surfaces of all components of interest that are subjected to heat radiation. It is also possible to use some form of globe thermometer that measures an equivalent temperature, combining air temperature and heat radiation influence.

In order to attain a long life of ageing sensitive components, the best way is to place them in such a way that that they are protected from heat radiation from surrounding surfaces.

8.2.3 Measurement of temperature of self-heated components

The acceleration factor according to Arrhenius formula for thermal ageing is usually based on the difference between the surrounding air temperature under normal operation and the test chamber air temperature used in the accelerated thermal ageing. For a self-heated component this results in an overestimation of the acceleration factor for two reasons:

- The acceleration factor is lower for a given temperature difference in a higher temperature interval than in a lower temperature interval.
- A self-heated component dissipates heat to the surrounding through convection, radiation and conduction. The effect of the self-heating on the component temperature decreases with increasing surrounding temperature. This has the consequence that the difference between the surrounding air temperature and the component temperature is smaller at testing than in operating conditions.

This means that the value of the acceleration factor that has been actually used in testing is lower than the value calculated by the Arrhenius formula if test temperature and operational temperature are used in the calculation. If artificial ageing is performed at a certain surrounding air temperature higher than the operational temperature and the acceleration factor is established by means of Arrhenius formula, compensation must therefore be introduced in order not to underestimate the ageing in actual operational condition. This is illustrated by the example below.

Example:
A component has the surface temperature 70°C at the surrounding air temperature 40°C (the surrounding air is not subjected to forced circulation, only self-convection occurs). If it is

exposed to the surrounding air temperature 100°C in a chamber without forced air circulation the surface temperature reaches 124°C (obtained by extrapolation of the nomogram in IEC 60068-2-2, Appendix A, [8.1]). So, the difference in the component temperature between the accelerated thermal ageing condition and the operational condition is 54°C whilst the test temperature differs 60°C from the operational temperature.

The simplest way to solve the problem is to measure the component's temperature at a test chamber temperature equal to the operational temperature before the ageing test. The component temperature is then used instead of the air temperature in the calculation of the acceleration factor.

If we use the component temperatures for calculation of the acceleration factor in the example above, we get the following result at presumed activation energy equal to 0,8 eV:

$$F = e^{\frac{E}{k}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]}$$

where T_1 is 343 and T_2 is 397, E = 0,8 and k = 0,86*10^{-4}, which gives F = 40

If, instead, the chamber air temperature at testing (T_2 equal to 373) is compared with the surrounding air temperature in operating conditions (T_1 equal to 313), the acceleration factor becomes F = 119,2. Thus, the qualified life is overestimated by a factor of three.

8.3 Measurement of ionising radiation

Since the irradiation field can vary considerably in the containment measurements are needed in the vicinity of ageing sensitive components and not only in general areas. Irradiation doses of importance to ageing are found only in a few component locations, normally in a sector of maximum a few meters distance from primary circuits and steam generators and in the upper part of the containment. It should therefore be sufficient to measure irradiation doses in such locations.

The influence on the ageing of organic materials from actual doses of thermal and fast neutrons is negligible compared to the influence from the gamma radiation.

8.4 Other environmental factors

Vibration occurs only exceptionally during normal operation. The relative humidity is low during normal operation, typically below 20%,. (safety-related components are not installed in wet-well in our BWR's). Also the occurrence of air pollution is low.

8.5 Localisation of hot-spots

Locally, environmental severity can occur (temperature, radiation, humidity, chemical pollutants, vibration) that are higher than those of normal positions. Intervention of possible hot-spots plays an important role in management of the ageing problem. Guidance for detection and handling of hot-spots can be found in EPRI TR-109619, [8.2]. Visual inspection of components and visible cables in connection with revision shutdowns is most important for detection of hot-spots (see clause 5.4).

8.6 References

[8.1] IEC 60068-2-2 Environmental Testing – Part 2: Tests. Tests B: Dry Heat

[8.2] Electric Power Research Institute EPRI Report TR-109619 (1999) "Weinacht, R. "Guideline for the management of adverse localised equipment"

9 Methodology for determination of ageing related properties (condition indicators) of polymers

9.1 General

Measurement of condition indicators is useful as an element in management of ageing of components, under the condition that component parts of importance to ageing are accessible. In case of destructive measurements, condition monitoring can be appropriate also for rather complex components. Non-destructive measurement are to a large extent limited to components for which the ageing can be attributed to for measurement or micro-sampling accessible parts, normally the surface (e.g. cables).

9.2 Non-destructive condition monitoring

Identification and measurement of condition indicators related to components' ageing form a very essential part of the qualification activities according to earlier chapters. Non-destructive measurements, i.e. measurements that do not pose a risk of damaging the component, are especially interesting. They can be used in the initial qualification to follow the changes in the condition indicator's value as function of time in accelerated ageing of one and the same component and can be used on installed components without having to exchange them.

One problem with non-destructive measurements is that they can only be performed on the surface of the specimen. Only the conditions of external parts, e.g. the cable jacket, are measured. However, of primary importance for a cable's function in an accident is the dielectric property of the conductor insulation. The condition of the jacket is not necessarily representative of the condition of the conductor insulation. The reason is that the jacket and conductor insulation materials are not always the same and the jacket surface is directly exposed to the surrounding atmosphere, often resulting in a more rapid degradation due to oxidation for the jacket than for the conductor insulation.

There are, however, good reasons to assume that there is a positive correlation between the jacket's and the conductor insulation's degradation due to ageing. If the jacket at a certain time shows a value of the condition indicator indicating less degradation than the degradation at which the cable has been DBE-qualified, also the conductor insulation can be assumed to be in a better condition than when the cable was DBE-qualified.

This is true as long as dose-rate effects and analogue effects in thermal ageing cause a problem in artificial ageing. If this is the case, elevated temperature and dose-rate result in a oxidation gradient from the surface to the inner parts which is larger than in operation conditions. The internal parts of the cable, i.e. the conductor insulation, has then degraded more in the field than in the test at a certain value of the condition indicator measured on the jacket. This emphasises the importance of avoiding high acceleration factors in the type testing.

9.3 Destructive condition monitoring

Use of destructive condition monitoring allows a larger selection of methods and a possibility to manage the gradient problem described above. It is possible to make measurements in internal parts, e.g. on the conductor insulations of cables. The disadvantage is that it is more complicated to establish the degradation due to ageing as function of exposure time in connection with initial qualification and that spare components (in store or installed) are required for the condition monitoring in field.

At the measurement of the condition as function of exposure time in artificial ageing a number of spare samples subjected to the ageing but not DBE-testing can be added. One spare sample is taken out and measured at each point in time that shall correspond to a point in the degradation-time curve. The last spare sample is taken out and measured when the ageing has been finished before the DBE-test. The condition measured on that sample is representative of the condition for which the component type is qualified (assuming that the component samples subjected to the full ageing plus DBE-simulation are accepted).

High temperatures can cause a problem also due to a reaction of the material that is different over a certain temperature. This cannot be solved solely with condition monitoring of internal parts during initial testing and operation. It should, however, be possible to get around the problems with dose-rate effects if monitoring is made on internal parts and qualified life is substituted by qualified condition.

9.4 Relationship between values of condition indicators before DBE and function during DBE

There are very few systematic studies available on the relationship between degree of degradation, measured with a condition indicator, and behaviour (e.g. insulation resistance) in DBE. Our own investigations, reported in SKI Report 97:40 [9.1] are the only published results we are aware of. They show a scattered picture, but there is a positive correlation, at least for a few of the methods described below.

It is of considerable value that such a correlation exists, since it enables an extrapolation of the results. It is, however, not a prerequisite for using condition monitoring as a method to control that the component at a certain time has not aged above the condition it has been qualified to in the DBE-test. It is sufficient that the value of the condition indicator is correlated to the degree of ageing. This can be assumed to be the case for the condition indicators reviewed below.

An important characteristic of a useful condition indicator is that it shows a trend of degradation that changes gradually. Indication of trends that don't change for a long time and then suddenly undergo drastic changes is not useful for field measurements. Such trends don't make it possible from a measurement at one occasion to show that the components will function properly in an accident occurring before the next measurement occasion (e.g. before the next revision shutdown).

9.5 Condition monitoring indicators that can be used in connection with ageing management

Comprehensive studies and practical tests with a broad range of condition indicators have been performed by us and others in recent years. The indicators we have found to be of greatest interest are described below. The condition indicators can be classified as follows.

- Chemical indicators – microcalorimetry, DSC-OIT (Differential Scanning – Oxidation Induction Time), TGA-OIT (Thermogravimetric – Oxidation Induction Time)
- Mechanical indicators – elongation-at-break, indenter, micro-hardness
- Electrical (dielectric) indicators – insulation resistance, dielectric loss factor, etc.

9.6 Summary of the applicability of the methods

Tables 9.1 and 9.2 summarise the most important characteristics of the condition indicators and their applicability.

Table 9.1 Characteristics of condition indicators

Method	Destructive method	Sampling or testing difficulties	Testing with components in operation	Reliability	Suitable for condition monitoring	Note
Micro-calorimetry	Yes 1-2g of the material is needed	Medium	No	Very good	Not suitable -expensive	Can, due to its sensitivity, be used on materials other methods cannot handle
DSC-OIT	No 10mg of the material is sufficient	Simple	No	Very good	Very suitable	Experienced method
Thermo-gravimetry	No 10mg of the material is sufficient	Simple	No	Good	Suitable	DSC-OIT is better
Elongation-at-break	Yes	Medium	No	Very good	Very suitable	Experienced industry standard
Indenter	No	Simple	Yes	Very good	Very suitable	Experienced method. Not Polyolefines. Portable
Micro-hardness	Yes	Medium	No	Very good	Suitable	Good on small or complex components
Dielectric spectroscopy (loss factor).	No	Difficult	Yes	Medium	Not suitable	Portable
Insulation resistance	No	Simple	Yes	Good	Measurement at elevated temperature can be used	If the method is used at elevated temperature the measurement must be made on a dismantled component
Near IR	No	Simple	Yes	Very good	Not suitable - under development	Portable. No experience
Current analysis	No	Difficult	No	Poor	Not suitable	The result is difficult to interprete
Twisting	Yes	Difficult	No	Very poor	Not suitable	
Bobin test	Yes	Simple	No	Poor	Not suitable	Only resuls in acceptable/not acceptable

Table 9.2. Applicability of condition indicators to various materials (correlation between measured values and degree of exposure to ageing influencing environmental factors)

Material	Micro calorimetry	OIT	Elongation-at-break	Micro hardness	Dielectric spectroscopy	Indenter
EPDM	Good correlation	Very good correlation*	Very good correlation*	Unknown	Good correlation	Very good correlation
XLPE	Unknown	Very good correlation*	Weak to good correlation	Low correlation	Good correlation	Weak correlation
CSPE	Very good correlation*	Can be used if the material contains antioxidants or certain other stabilisers	Good correlation	Good correlation	Unknown	Very good correlation
EPR	Unknown	Very good correlation*	Very good correlation	Unknown	Unknown	Very good correlation
EVA	Good correlation	Good correlation	Good correlation	Unknown	Unknown	Very good correlation
SIR	Unknown	Good correlation	Good correlation	Very good correlation. Especially suitable for very small comp. *	Unknown	Very good correlation
PEEK	Unknown	Unknown	Good correlation*	Unknown	Unknown	Unknown
PI	Unknown	Unknown	Good correlation	Good correlation	Unknown	Unknown
Viton	Unknown	Moderate correlation (depends on the type of Viton)	Good correlation	Very good correlation	Unknown	Good correlation
PVC	Unknown	Good correlation	Good correlation	Unknown	Unknown	Good correlation

* Clear results from studies performed within Westinghouse.

In addition to the characteristics reported in the table, it is of interest if a limit value of a condition indicator can be stated, based on experience, below which the component's functionality is not affected. Such limit values are often given for the ratio between elongation-at-break for aged and non-aged materials, e/e_0. For most insulation materials, the functionality is assumed to be acceptable as long as e/e_0 does not exceed 0,5. Some sources indicate 0,2 as an acceptable limit value. There are, however, no broad studies available that connect the limit values to functionality under DBE conditions.

In [9.1] it is shown that a typical value of the ratio between indenter modulus for aged and non-aged materials, M/M_0 corresponding to e/e_0 equal to 0,5 is $M/M_0 = 1,5$. Typical value corresponding to e/e_0 equal to 0,2 is $M/M_0 = 2,5$. These values can be used equally reasonably as limit values. Limit values of this kind can be of interest in a first screening but they should not substitute testing including ageing and DBE-simulation.

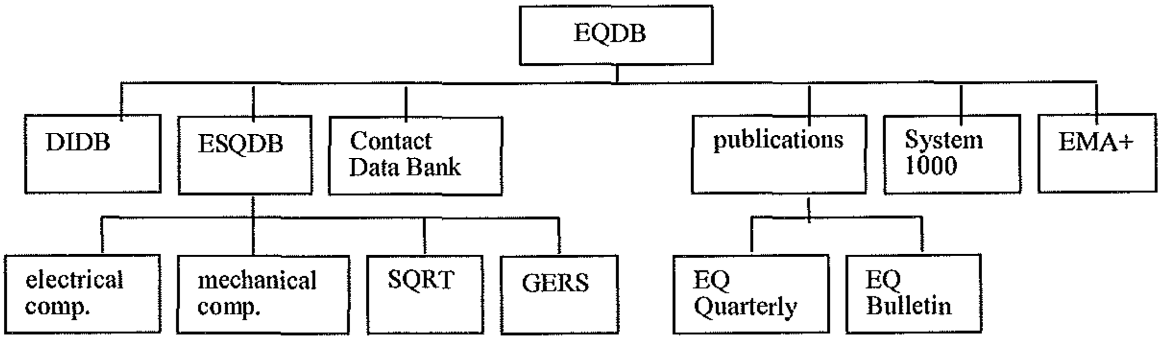
9.7 References

[9.1] Spång, K. "Ageing of electrical components in nuclear power plants; Relationships between mechanical and chemical degradation after artificial ageing and dielectric behaviour during LOCA", SKI Report 97:40, October 1997

10 Data bases

10.1 EQDB

In 1979 EPRI decided to finance the development of a database for component qualification, Equipment Qualification Data Bank (EQDB). It should be provided with information from the utilities on qualification of electrical and mechanical equipment in NPPs, including seismic qualification and effects of ionising radiation and heat on non-metallic materials (ageing effects). It should list equipment that had been qualified by the supplier for use in NPPs. EQDB is managed by NUS Information Services on a license from EPRI. The structure of the data bank is shown by the scheme below.



Document Information Data Bank (DIDB), includes EPRI EQ Reference Manual (information on research and development within the area of component qualification, etc.), summary of all NRC assessments of component qualification, bibliography on test reports, and (since 1989) deviation reports.

In addition to data bases for electrical and mechanical components, Environmental & Seismic Data Bank (ESQDB) includes Seismic Qualification Review Team (SQRT) and Generic Equipment Ruggedness Spectrum Test Data (GERSTD).

The Contact Data Bank includes data bases for contacts with utilities and component producers.

System 1000 Aging and Radiation Library includes more than 1500 records from Arrhenius tests and more than 4100 records from irradiation tests.

Expert Materials Analyst Plus (EMA+) includes more files with ageing information and a data base with chemical designations.

Information on the data base EQDB can be found in ENS proceedings 1986 [10.1], Paper from EPRI/NUS/NUGEQ EQ symposium in Clearwater 1998 [10.2] and EPRI Equipment Qualification Reference Manual 1992 [10.3].

10.2 EQMS (Environmental Qualification Management System)

EQMS is an electronic tool for handling data from environmental qualification, developed by EPRI together with a selection of utilities that are members of EPRI/PSE. It comprises the following:

- EQMS software
- A compilation of test reports (environmental qualification)
- Standardised evaluation from an environmental qualification perspective of a selection of test reports and for a number of common environmental qualified components.

In addition to databases for test reports and methods for evaluation, the software includes databases for documentation of areas with respect to environmental conditions during normal operation, extreme operation and DBE.

10.3 IAEA DATA.DBF

Data on ageing in ionising radiation of cable materials have been collected and fed into a database from the participants of IAEA's co-ordinated research programme (CRP) for management of ageing of I&C cables. The database is limited to three cable materials used in a large number of NPPs around the world:

- XLPE – cross-linked polyethylene
- EPR/EPDM – ethylene propylene based elastomers
- EVA – ethylene vinyl acetate

The database is run on FoxPro software. The database, how it is installed and used and a considerable number of extracts from the content are presented in detail in AEAT-0199 [10.4]. It includes data from condition measurement (e.g. measurement of elongation-at-break) of cable materials that have been aged in ionising radiation at different temperatures.

10.4 References

[10.1] Brett D.A. Sliter G.E. "EPRI equipment qualification data bank" Proceedings ENS symposium "Operability of nuclear power systems in normal and adverse environments", Albuquerque, 1986

[10.2] "EQDB: A comprehensive equipment qualification resource" NUS Information Services. Presented at EQ Technical Conference in Clearwater, Florida, November 1998

[10.3] Holzman P.M., Sliter G.E., Carfagno S.P. "Nuclear power plant equipment qualification reference manual" Electric Power Research Institute, 1992

[10.4] Burnay S.G. "Radiation testing database for XLPE, EPR and EVA cable materials" AEA Technology Report AEAT-0199, March 1996

11 Conclusions

Programmes for qualification of ageing sensitive components in NPPs, which shall be able to function during an accident at the end of its installed life, may require that initial qualification with accelerated ageing followed by DBE testing is combined with follow-up activities after installation. It is an opinion amongst many researchers in the field that initial qualification only can guarantee a rather limited life, often shorter than the desired installed life. Methods for follow-up qualification have been developed and tested in many places and are discussed in the on-going revision of IEEE 323, IEC 60780, and national recommendations. Such methods have been carefully reviewed and described in the report from IAEA's expert group for management of ageing of cables in NPPs.

There is a satisfactory foundation in terms of research results to enable formulation of working strategies and complete programs for consideration of ageing during installed time when new components are purchased and installed. The methods developed for follow-up qualification after installation can also be used for updating and completion of the qualification of components that have been in operation for a long time. The development of such methods has been an important activity behind work on extension of installed life above the original 40 years.

This report provides bases and tools for development of strategies and programs and some data of importance for establishment of qualified life from type testing and for selection of condition indicators for follow-up qualification. Based on this, it has been possible to give concrete recommendations and guidance for program development, issued in Report 02:4A.

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