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Qualification of Electrical Equipment in Nuclear Power Plants

Management of ageing

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Abstract

The purpose of this report is to describe programs and tools for assessment of accomplished and documented qualification with respect to ageing of electrical equipment and for development of complimentary ageing management programs. In addition to description of complete programs for management of ageing, tools for validation of the status with regard to ageing of installed ("old") equipment and, where needed, for complementation of their qualification are also included.

The report is restricted to safety related equipment containing ageing sensitive parts, mainly organic materials. To this category belong cables and cable joints and a number of equipment containing oils, seals (o-rings), etc. For equipment located in the containment, the possibilities of continuous supervision are limited. The accessibility for regular inspections is also limited in many cases. The main part of this report deals with the qualification of such equipment.

Some safety related equipment outside the containment can be located in areas where they are subjected to high temperature and other excessive environmental stresses during normal operation and in areas affected by an accident. Therefore, some material is given also on qualification of equipment located outside containment with better possibilities for frequent inspection and supervision.

Part 1 of the report is an executive summary with a general review of the methodologies and their application. The more detailed description of the programs and underlying material, useful data, etc. is given in Part 2.

The work behind the preceding report SKI 02:4 was financially supported in common by Forsmark Kraftgrupp AB, OKG Aktiebolag, Ringhals AB, Barsebäck Kraft AB and Statens Kärnkraftinspektion (SKI). The project was governed by a steering committee with the following composition:

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Reinhold Delwall, Forsmark Kraftgrupp AB

Karel Fors, Barsebäck Kraft AB

Lars-Olof Ståhle, OKG Aktiebolag

Bo Liwång, Statens Kärnkraftinspektion

The revision has been governed by the steering committee, where the representatives of the utilities now have been

Kenneth Skoglund, Ringhals AB

Sven-Olof Palm, Forsmark Kraftgrupp AB

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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.

Objectives of the project

The purpose of the work has been to produce a background material for planning and management of qualification of equipment inside the containment. The principles are nevertheless applicable also for equipment outside the containment that are exposed to increased environmental effects during events.
The report is divided into two parts; an executive summary and a detailed description of management programs and backgrounds.

Results

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 was published again as a research report by the Swedish Nuclear Power Inspectorate with the reference Rapport 01:17. To be used in the international co-operation in nuclear safety it was also translated into English by the inspectorate. The English translation was published in May 2002 with the reference SKI 02:4.

This report, which supersedes SKI 02:4, takes into account some later experiences and development of condition monitoring methods and their application to management of ageing.

At the time of preparation of the changes to SKI 02:4, resulting in this report, the Swedish Nuclear Inspectorate has become a part of the Swedish Radiation Safety Authority (SSM).

Conclusions

The publication as a report in the authority'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 authority. 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 authority'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

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Part 1. Executive summary

Contents

1 General

This part of the report presents a general review of methods for management of ageing of equipment important to safety in nuclear power plants. It is directed to persons who want to get a general insight in methods enabling control of functionality of equipment important to safety with regard to degradation of ageing sensitive materials. The main focus is on activities after installation for improving and maintaining qualification and extension of qualified life. Detailed programs and underlying material are given in Part 2.

2 Terminology

2.1 Sources from which the definitions are taken

The terms used in part 1 and 2 of this report are explained below. A reference is made within brackets to the sources of the terminology. Where available, IAEA Safety Glossary 2007 has been used. In case the term is not available in this, the terms in IEC and IEEE Standards are used.

2.2 Definitions

accelerated ageing

Accelerated process designed to simulate an advanced life condition in a short period of time. It is the process of subjecting an equipment or a component to stress conditions in accordance with known measurable physical or chemical laws of degradation in order to render its physical and electrical properties similar to those it would have at an advanced age operating under expected operational conditions (From [2.2])

condition indicator

Characteristic of a structure, system or component that can be observed, measured or trended to infer or directly indicate the current and future ability of the structure, system or component to function within acceptance criteria. (From [2.1])

condition monitoring.

Continuous or periodic tests, inspections, measurement or trending of the performance or physical characteristics of structures, systems and components to indicate current or future performance and the potential for failure. (From [2.1])

design basis events, DBE

Postulated events used in the design to establish the acceptable performance requirements for the structure, systems, and components. (From [2.4])

NOTE: In this report, DBE includes post-DBE where this is relevant.

diffusion limited oxidation

Limitation of the ability of oxygen to diffuse into a material, due to formation of a diffusion protective surface layer by exposure to excessive rate of ionising radiation or excessive temperature.

qualified condition

Condition of an equipment, prior to the start of a design basis event, for which the equipment was demonstrated to meet the design requirements for the specified service conditions. (From [2.3])

qualified life

Period for which a structure, system or component has been demonstrated, through testing, analysis or experience, to be capable of functioning within acceptance criteria during specific operating conditions while retaining the ability to perform its safety functions in a design basis accident or earthquake. (From [2.1])

service life

The period from initial operation to final withdrawal from service of a structure, system or component. (From [2.1])

2.3 References

[2.1] IAEA Safety Glossary. Terminology used in nuclear safety and radiation protection. 2007 edition. International Atomic Energy Agency

[2.2] IEC 60780 ”Qualification of electrical equipment of the safety system for nuclear power plants, ed. 2, 1997

[2.3] IEC/IEEE 62582-1 Nuclear power plants – instrumentation and control important for safety – Electrical equipment condition monitoring methods – Part1:General

[2.4] IEEE 323-2003 ”Standard for qualifying class 1E equipment for nuclear power generating stations”, IEEE Power Engineering Society

3 Purpose and basic elements of ageing management

The purpose of ageing management is to establish a qualified life, possibly accomplished with a qualified condition, and to design and implement a program for following and control the ageing after installation. In cases where the desired service life is longer than the initially established qualified life, one of the purposes of the activities after installation can also be to extend the qualified life. The main elements of ageing management include:

- Goals for qualified life
- Prediction of environmental conditions during normal operation in areas where the equipment will be located. Identification of the areas which are

subjected to the highest exposure to environmental conditions, mainly temperature and ionising radiation, during normal operation. The condition of such areas is used for the design of the exposure in the ageing simulation part of the initial qualification.

- Requirements of aged equipment on functionality in DBE.
- Initial qualification testing, including establishment of qualified life by laboratory testing of equipment samples. The influence of environments of importance to ageing is simulated according to some method which accelerates the ageing, after which the test object's ability to perform under a simulated DBE and, if required, post-DBE, is verified. The ageing simulation can be accompanied by intermittent or continuous measurement of the development of one or more condition indicators and establishment of the qualified condition.

  NOTE. For safety related equipment in Swedish nuclear plants, there is a requirement to limit the acceleration factor used in artificial thermal ageing to 250, if it cannot be proved by investigations that higher acceleration factors can be used with acceptable accuracy. Such proof should include a proof that the law (normally Arrhenius equation) can be applied on the temperature span between the test temperature and the temperature in normal operation and an analysis of the effect of diffusion limited oxidation.
- Store of equipment samples in climatic controlled stores for use in future complimentary testing and investigations and/or for substituting installed equipment which are taken out for control of their ageing status at certain time intervals after installation.
- Deposit of a selection of equipment samples in locations representing the areas of installed equipment which are subjected to the highest exposure to environmental conditions during normal operation.
- Use of high acceleration factors involves a number of uncertainties in application of the laws behind the calculation of qualified life. This, combined with limits in time available for the initial qualification, is taken into account in the initial qualification by use of very conservative calculation of qualified life or a design of the initial qualification for a qualified life considerably shorter than the desired service life. Longer qualified life may be established by an additional qualification using long term simulation of the ageing (and condition measurements), also allowing less conservatism in calculation of the qualified life due to use of lower acceleration factors.
- Regular control of ageing status of equipment located in the most exposed areas.

  In the case where the qualification is purely based on establishment of qualified life, repeated testing, including artificial accelerated ageing and DBE simulation, of deposited samples or equipment removed and substituted may be required. Such testing, performed when the installed time approaches qualified life, may be used to extend the qualified life.

In the case where the qualified condition has been established in the initial qualification, the control will mainly be based on regular condition measurements. In a few cases it is possible to apply condition measurements to installed equipment (non-destructive measurements on accessible surfaces). Otherwise, the measurements require access to deposited samples or possibilities to use installed equipment which are substituted by new or stores samples.

The more complex the equipment 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 (e.g. by condition monitoring). Another factor which adds to the importance of follow-up activities after installation can be lack of knowledge of synergetic effects between materials installed near each other. A well-known example is the so called silicone infection due to a surplus of meres in silicone rubber which diffuse in the form of gas and contaminate surrounding equipment.

4 Limitations in qualified life

The initial target for qualified life is limited to what can be verified by laboratory testing before acceptance for installation of the equipment. The life for which the equipment can be regarded safely qualified is limited by the applicability of methods for accelerated artificial ageing and by the time available for this.

The main limitations in calculation of qualified life from laboratory testing are:

- Limited knowledge of the environmental conditions in the equipment locations during normal operation. The temperature of equipment can be affected not only of the surrounding air temperature but also of heat radiation from surrounding surfaces.
- Limitation of applicability of laws used for the application of short term ageing in elevated environmental conditions, primarily elevated temperatures and irradiation dose rates, for simulation of long term exposure in field conditions.
- Effects of diffusion limited oxidation, involving a risk for overestimation of qualified life and qualified conditions.
- Limited knowledge of values of parameters related to the composition of polymeric materials included in the equipment which are essential for the calculation of the acceleration factors, especially the activation energies.
- Complexity of the equipment, especially when it is composed of various ageing sensitive materials, including additives contributing to the lack of well

founded information on parameter values relevant for the calculation of the acceleration factors.

It may not possible to design artificial tests for certain equipment that ascertain a qualified life equal to the desired service life. A gradual extension of qualified life can be achieved after installation through on-going qualification.

5 Condition monitoring as complement or alternative to establishment and control of qualified life

Condition monitoring provides a way to overcome most of the limitations in establishment and control of qualified life. Use of condition monitoring requires that a useful condition indicator for measuring the degradation of the equipment is available. It shall be demonstrated that the equipment at a certain level of degradation measured by this indicator 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 ageing of the equipment after installation is then followed by measurements of the same condition indicator in the field at certain time intervals and comparison with the development of the condition during the simulated ageing in the initial qualification. The condition monitoring is used to assure that the degradation of equipment has not gone so far that their intended function in a DBE is insecure.

Even if the qualified condition determines the ultimate life of the equipment, a calculation of a conservatively established qualified life is needed in order to know before installation that the useful life of the equipment can be expected not to expire within a certain time.

The main advantage of using qualified condition is that it does not depend on a set of parameters of importance for establishment of qualified life which we may have insufficient knowledge of. This includes the prediction of the environmental conditions, applicability of laws on which the acceleration of the simulated ageing is based, parameters of the age sensitive materials in the equipment (e.g. activation energies), etc. It does not, however, take care of the problem of introducing significant diffusion limited oxidation effects when excessive environmental conditions (high temperature, high radiation dose rates) are used in the simulation of the ageing.

The possibility to include condition based qualification depends on the access to useful condition indicators for the actual type of equipment. It also depends on the access in the field to parts of the equipment on which non-destructive condition measurements can be made, or possibilities to make (destructive) measurement in laboratory on equipment samples, either from deposit in representative areas of the plant or installed equipment which are substituted.

The criterion of a useful condition indicator is that it indicates degradation due to ageing accurately and sensitively and that it changes monotonically with the time of exposure.

The most commonly used condition monitoring parameters are:

- Indenter modulus;
- Elongation-at-break (e/e_0);
- OIT and OITP;
- Dielectric loss factor.

Applicability of different types of condition indicators is discussed in detail in Part 2, chapter 7. It is very important for the use of qualified condition that the reproducibility and comparability of the condition measurements are high. This requires detailed description of the methods, including tight tolerances on important measurement parameters, and skilled persons performing and analysing the results of the measurements. If available for the method selected, the standards in the IEC/IEEE 62582 series, issued jointly by IEC and IEEE, should be used.

6 Extension of qualified life

When the installed life of equipment approaches the qualified life, an extension of the qualified life can be achieved in basically two ways:

- By selecting samples of the equipment from the most exposed positions (either ordinary equipment which are replaced or for the purpose especially installed equipment) 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 equipment in the containment, identical to the selected ones, are qualified for the additional life.

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

- By measurement of suitable condition indicator(s) and comparison with the qualified condition. The qualified life can be extended up to the time when the measurements show that the condition(s) approach the qualified condition.

7 Verification and validation of qualified life in connection with purchasing ("new" equipment)

7.1 Environmental prediction and requirements on operation and on qualified life

A prediction of the (ageing influencing) environmental parameters and their severities during normal operation in the most exposed positions is needed for taking ageing into account at purchase of a type of equipment for installation in a nuclear power plant. The prediction should include all environmental parameters that may be present in the actual equipment positions. Part 2, Chapter 6 includes guidance for judgement of which environmental parameters may need to be taken into account.

Note. The term environmental prediction 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.

The desired installed life and functional requirements with acceptance criteria at DBE has to be defined.

7.2 Use of data from experience and knowledge of material

Databases containing equipment and material properties attained from field experience and from testing can be of valuable help in a first assessment of equipment of interest on the market. Material knowledge, especially knowledge of ageing characteristics of polymers, is another important basis for assessment of equipment on the market. The own and other's experiences should be invented and studied.

7.3 Assessment of the qualification documentation provided by the equipment supplier

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

- Equipment data;
  - Parts and materials included
- Environmental test data;
  - Environmental parameters
  - Severities
- Test methods;
- Functional control and acceptance criteria;

- Condition measurements, if available.

7.4 Assessment of environmental parameters of importance to ageing of the equipment

The type testing includes verification of the equipment's life through artificial ageing followed by a DBE simulation including functional control according to the way the equipment is credited in the safety analysis. 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 equipment.

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

7.5 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 supplier should be asked to provide the basis for the acceleration factor applied, e.g.:

- Activation energy selected and the basis for it;
- If available, 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 supplier 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.

Condition monitoring may be used as an essential part of the qualification and management of the ageing after installation. In order to investigate the possibilities of this for the actual equipment, 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 investigate if the composition of the equipment is such that non-destructive condition monitoring can be applied and if ageing sensitive parts are reasonably accessible for condition monitoring.

The data provided by the supplier are needed for the possibility of 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 and 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 this case, it may be necessary to use a more conservative value on the qualified life than the value provided by the supplier.

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

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

Even with conservative assumptions of qualified life, it is recommended that activities for ageing management are performed periodically after installation. As a minimum this should include visual inspection, looking for colour changes of insulation materials etc., if possible accomplished with some condition monitoring.

If the qualified life is shorter than desired service life, activities for extension of qualified life should be included as part of the ageing management program.

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

If the initial qualified life has been established in a not fully reliable way, e.g. by 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.

Periodic condition monitoring is a very valuable tool for ascertaining a qualified status throughout the service life. If the initial simulated ageing performed and reported by the supplier has been made in a reliable way, e.g. with reasonably moderate temperatures and dose rates, but no condition measurements has been included, a qualified condition can be established by performing an ageing simulation identical to the one made by the supplier and measuring the condition during and at the end of the ageing simulation. The equipment can then be regarded as qualified for the end condition, provided that the condition is measured in the parts of the equipment which are essential for its function at DBE (see note below).

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 equipment 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 supplier'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 equipment samples which are stored in controlled (mild) environment. A need for complementary testing, condition monitoring, or on-going qualification may show up later.

Details about qualification of “new” equipment are given in Part 2, chapter 3.

8 Updating of the qualification of an installed equipment ("old equipment")

Installed equipment 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). If not, a qualified condition can be achieved in the way described in clause 7.6, depending on availability of new or stored identical equipment.

An extension of the qualified life can be established in the same way as for new equipment if new or stored identical equipment are available.

Details about qualification of "old" equipment are given in Part 2, chapter 4.

Qualification of electrical equipment in nuclear power plants.

Management of ageing.

Part 2. Programs and underlying materials.

Contents

1 Introduction

1.1 General

This report deals with management of ageing of safety related electrical equipment in nuclear power plants. It describes activities, programs, and tools for management of ageing in connection with initial environmental qualification (type testing) and after installation. Tools are also given for supplementary testing and control with regard to ageing of already installed equipment.

Whilst part 1 of the report summarise methods for management of ageing this part of the report describes the methods in more detail and includes some background material.

Condition monitoring is an important tool for management of ageing. Methods for condition monitoring are essentially useful for equipment for which it is possible to identify and make measurements on age sensitive parts. The type of equipment on which non-destructive condition monitoring on installed equipment in the field is possible is mainly limited to accessible cables. A broader range of equipment can be measured in laboratory (destructive), possibly after demounting in order to access the parts sensitive to ageing. For equipment where the materials sensitive to ageing are not accessible for condition monitoring, activities after installation are normally limited to complementary initial qualification, control of the actual environmental conditions and extension of qualified life through on-going qualification.

This report is limited to age related issues, but also environmental conditions of short duration can affect sensitivity to ageing. Thermally aged equipment can be more sensitive to impact than un-aged equipment. 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 equipment. Environmental data for short duration environments can be found in Akustikbyrån TR 5.082.01 [1.1] (equipment in the containment) and TR 5.125.01 [1.2] (equipment outside containment). Test methods for short-term environments are given in IEC Publication 60068 (Environmental Testing Procedures), [1.3].

1.2 References

[1.1] 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)

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

[1.3] International Electrotechnical Commission IEC Publication 60068 ”Environmental testing procedures”

2 Strategies and programs for qualification of equipment with regard to ageing

2.1 Aims of programs for management of ageing

The aims of programs for management of ageing of safety related equipment are to ensure that the equipment is capable of functioning during normal operation, extreme operation, and DBE at any time after installation. Equipment containing for their function essential organic materials (polymers, lubricants, etc.) are sensitive to ageing caused by thermal influence and influence of ionising radiation. For such equipment, management of ageing is a very essential part of the qualification program. Subjection to humid atmosphere and to mechanical stresses (e.g. vibration) can accelerate the ageing.

2.2 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 the content of additives used in the polymer. Table 2.1 summarises positive and negative influences on ageing of various factors.

Table 2.1. Factors affecting the ageing of equipment

Heat	Humidity	Inert gas1)	Radiation	Catalyst	Antioxidant
strongly negative	strongly negative	positive	strongly negative	negative	strongly positive

1) Investigations, presented in SKI 97:40 [2.1], show that use of nitrogen gas in the containment reduces the oxidative ageing substantially.

Although an increase of temperature and radiation dose rate result in a faster degradation of the polymeric materials, application of laws for comparison of the degrees of ageing at high and low severities must take into account the effect of diffusion limited oxidation at high temperatures and dose rates. This is well-known for high radiation dose rates, but the same effects appear in the application of high temperatures, which is reported in a study at Sandia [2.2].

2.3 Strategy for qualification

The ability of equipment to function in an accident environment at the end of its life cannot be assessed from experience because of lack of practical experience of the use of the equipment in severe accidents. Initial laboratory testing and follow-up of the equipment’s conditions in field is used to ensure its capability to perform during a DBE.

In order to verify that the equipment performs in an accident at any time after installation, it is artificially aged before it is subjected to DBE testing. If the ability of the artificially aged equipment to perform its safety function during the DBE exposure is demonstrated, it can be regarded as qualified for the aged condition it had when it was subjected to the DBE testing. There are two ways of defining the qualified status of the equipment:

a) To calculate a time period in normal operation conditions corresponding to the time for the artificial ageing applied. This is then regarded as the qualified life (in years)

b) To apply condition monitoring during the artificial ageing. The condition measured at the end of the artificial ageing is regarded as the qualified condition (in terms of the value of the condition indicator measured).

Regardless of which of the definitions is used, it is recommended to include condition monitoring in the artificial ageing in order to establish the development of the value of a suitable condition indicator during the ageing and allow follow up activities after installation to ensure that the equipment at no time has aged more than to the condition it had when it was subjected to DBE-testing.

DBE-testing is normally performed by exposing the equipment 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 which simulates the ambient environment in a DBE. In some cases, also sprinkling is included as part of the DBE simulation. Equipment that shall be qualified to earthquake is 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 equipment that shall be installed ("new equipment") as well as already installed equipment ("old equipment").

2.4 References

[2.1] 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

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

3 Management of ageing of new equipment.

3.1 Activities included in the management of ageing

The management of ageing includes the following activities:

- Prediction of environmental conditions during normal operation;
- Establishment of target for service life;
- Description of functional requirements in DBE and/or post-DBE and their measurements:
- Program for artificial ageing as part of initial qualification;
- Program for activities after installation for control and improvement of the basis for the qualified life established in the initial qualification;
- Program for activities after installation for periodic control of the status of the equipment in relation to its qualified status;
- In case of qualified life shorter than service life: Program for activities to extend the qualified life.

3.2 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 equipment 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 equipment 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 equipment includes future measurements.

It is especially important to identify positions of the equipment with the most severe environmental conditions (e.g. hot-spots).

In chapter 7 is stated what should be taken into account in determination of environmental severity for equipment located in the containment.

In cases where there are important heat sources in the vicinity from which the equipment is not shielded, or if the equipment is self-heated, knowledge of the surrounding air temperature is not sufficient for determination of the thermal environment. See clause 7.2.2 and 7.2.3, describing how to determine a suitable test temperature that takes heat radiation from surrounding surfaces and self-heating into account.

A prediction of the dose-rate of the ionising radiation during normal operation is needed as basis for qualification to a certain life. In Swedish nuclear power plants, 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 [3.1]).

A generalised environmental specification for normal operating conditions, mainly based on IEC 60721-3-3 [3.2], can be found in TBE 101 [3.3].

3.3 Establishing target for qualified life

In order to establish a realistic target that can be verified with a sufficiently high degree of confidence at the initial qualification, a study is required of the equipment, 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. Although operating experience from long term use of the equipment in other than nuclear power applications can give some indication of the robustness of the equipment to long term ageing, it normally does not answer if the equipment will operate safely in a DBE after long term ageing. For example, the degradation of the insulation of a cable after long term ageing will normally not result in reduction of the insulation resistance when measured in normal field conditions but still make it fail to keep an acceptable insulation resistance during LOCA.

Examples of material depending parameters of interest are:

- For thermal ageing: the activation energies of the materials;
- For thermal ageing: the range of temperatures in which the laws used in calculation of qualified life from artificial accelerated ageing are applicable;

- For thermal ageing and ageing in ionising radiation: the effects of diffusion-limited oxidation which can make the calculation overestimating the qualified life and the qualified condition.

It may not be feasible to set a target for the qualified life which fulfils the desired installed life of the equipment and can be verified in the initial qualification with sufficiently high degree of confidence. It may then be useful to define one level of qualified life which can be verified with high confidence in the initial qualification before installation, together with a target based on the desired service life which cannot be verified with sufficiently high degree of confidence in the initial qualification but can be successively verified by an ageing management procedure implemented after installation.

3.4 Establishment of functional requirements at normal operation and at DBE

The equipment's functional requirements are defined by the system it is part of and by its task, for safety related equipment especially its task in DBE. 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 conductors or between conductors and earth. For cables, it is important that it is clearly stated for what cable length the minimum insulation value prescribed is defined.

As shown in Figure 3.1 below from measurements, reported in SKI Report 97:40 [3.4], 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 equipment for type testing permits, it may therefore be important, in parallel to subjecting artificially aged equipment samples to simulated DBE, also to include non-aged samples in order to get information on whether the equipment's dielectric characteristics are affected by the ageing or only by the DBE.

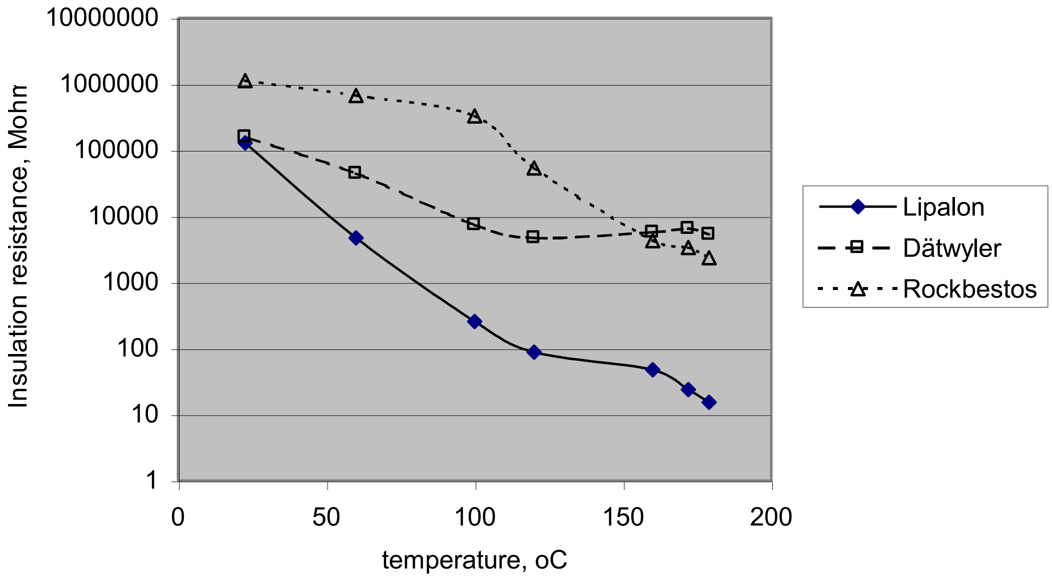

Figure 3.1. The temperature influence on the insulation resistance, measured between conductor and earth on a 1m cable, from [3.4]

A careful analysis before stating the acceptance criteria for required dielectric characteristics during DBE is recommended. Use of generic requirements may involve over- or underestimation of the risk of malfunction. The common requirement on a minimum insulation resistance of 1 MΩm for cables is often over-conservative but may also in certain cases be too low, depending on functional requirements and type of equipment involved. Over-conservative requirements can result in unnecessary rejection of equipment at the initial qualification (type testing) or delay of acceptance due to performance of circuit analysis and change of criterion afterwards.

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 Ωm or MΩkm.

3.5 Program for initial qualification (Type testing)

3.5.1 General

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

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

Type testing is often performed on the basis of rather general grounds and methods. Equipment important to safety that is offered by the suppliers is often environmentally qualified according to IEEE 323-1974 [3.5], IEEE 323-1983 [3.6], IEEE 323-2003 [3.7], or IEC 60780 [3.8]. Reference is also made to specific equipment standards, e.g. IEEE 383 [3.9] for cables.

The Swedish utilities have established guidelines for type testing of equipment, e.g. KBE EP-154 (1996) [3.10].

Reference can also be made to other national standards and rules, e.g. KTA 3706 [3.11].

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 [3.12].

3.5.2 Artificial ageing in type testing

3.5.2.1 General

Initial qualification of safety related electrical equipment which contains organic or polymeric materials includes artificial ageing before subjection to simulated DBE. The aims of the artificial ageing are to bring the organic or polymeric materials in a condition equivalent to their condition at the end of the desired qualified life of the equipment. In order to achieve this in a short time, the artificial ageing is performed at higher severities of factors which the equipment is subjected to during normal operation and which are important for the rate of degradation due to ageing. For equipment installed in the containment, the most important factors are normally heat and ionising radiation, but also some other factors can be important for the ageing, e.g. high humidity, intermittent or continuous vibration, chemical factors, although most equipment in the containment is not subjected to this in normal operation.

3.5.2.2 Limitation of acceleration factors used in artificial ageing

Time available for type testing normally does not permit the accelerated ageing before DBE testing to last longer than one or two months. Therefore, extreme levels of temperatures and radiation dose rates are often used in the artificial ageing in order to achieve high acceleration factors. However, use of excessive temperatures and radiation dose rates involves a risk of significant errors in determination of qualified life and qualified condition, primarily for the following reasons:

- The laws used for calculation of acceleration factors are based on certain conditions which can be invalid at high levels of the environmental parameter used for the acceleration, primarily high temperature (thermal ageing) and high dose rates (ageing in ionising atmosphere). In calculation of qualified life from thermal accelerated ageing, Arrhenius behaviour is assumed in the full range from the temperature in the position of the equipment during normal operation to the temperature used in the artificial ageing. This is only valid in a limited range, depending on the materials involved.
- The outer part of a polymer sample, e.g. a cable jacket, is exposed to oxygen before the gas can diffuse to the center parts of the sample. A diffusion limited oxidation occurs when the rate of oxygen consumption within the material is greater than the rate at which it can be resupplied by diffusion from the oxygen permeating into the polymer. This occurs when a high acceleration factor is used. The oxygen penetration in the sample material is limited due to the high rate of oxygen consumption at high temperatures and radiation dose rates. In the field conditions where the temperature is much more moderate, there will be a balance between the oxygen consumption and the resupply of oxygen. Application of a high acceleration factor can then result in a severe underestimation of the degradation of the internal parts of the sample. This means an overestimation of qualified life as well as of qualified condition.
- Due to desorption and diffusion of stabilisers like antioxidants in a polymer the properties and the concentration of the active additive will have a strong influence of the thermo oxidative degradation of the material. The useful life of the material (i.e. when it is not degraded to an extent which makes the equipment malfunction in DBE) depends on the remaining concentration of the active additives throughout the material. If a short test time is used in artificial accelerated ageing, only the stabilizer at the surface will be consumed leaving the inner layers unaffected. This has a similar effect on overestimation of qualified life and qualified condition as discussed above for diffusion limited oxidation.

3.5.2.3 Artificial thermal ageing

3.5.2.3.1 Model for accelerated thermal ageing

The acceleration is achieved through elevated temperature. It is assumed that the relationship between temperature and rate of degradation follows the Arrhenius relationship

$$r = Ae^{-\frac{E}{kT}} \qquad (3.1)$$

where

A is a constant for the material tested

E is the activation energy for the process (in eV);

k is Bolzmann's constant ($0{,}86 \cdot 10^{-4}$ eV/K),

T is the temperature (in K);

The acceleration factor F is the ratio between the rate of degradation at the elevated temperature and the rate of degradation at the field temperature at normal operation. It is calculated from the Arrhenius formula as follows:

$$F = \frac{r_2}{r_1} = e^{\frac{E}{k}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]} \qquad (3.2)$$

where

r_1 = rate of degradation in exposure to the temperature at normal operation;

r_2 = rate of degradation at the test temperature;

T_1 = temperature (in K) at normal operation;

T_2 = test temperature.

The qualified life t_{qual} is then equal to $F*t_{test}$, where t_{test} is the time of exposure at the 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 equipment's temperature during normal operation. The margin can be reduced if the temperature is controlled (and measured).
- Knowledge of the characteristics of organic materials involved, 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 equipment samples tested.

3.5.2.3.2 Reliability of verification of qualified life using Arrhenius equation

The reliability of the verification of qualified life is limited by the factors above but also by uncertainties related to the application of the Arrhenius formula to complex equipment, e.g. to equipment 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. Different chemical processes may take place at higher temperatures than at lower temperatures which means that the accelerated ageing process in a high temperature interval and natural ageing process in a moderate operating temperature interval are not parallel. This puts a limit to the acceleration factor that can be applied with a reasonable degree of confidence in accelerated ageing.

Studies performed on cable insulation materials used in Swedish nuclear power plants indicate that for those materials Arrhenius behaviour is a valid assumption at moderate acceleration factors. Based on the studies and in order to limit the effects of diffusion limited oxidation and diffusion of stabilisers, it has been recommended to restrict the acceleration factor in calculation of qualified life to 250 if it is not shown that higher acceleration factors can be applied with acceptable confidence for the accelerated thermal ageing of the specific equipment. To show that high acceleration factors can be credited, the interval over which the Arrhenius behaviour is shown must stretch from temperatures not very far from the normal operating temperatures up to rather extreme temperatures. A margin still has to be included in order to compensate for diffusion limited oxidation effects.

The limitation of the acceleration factor to 250 means that if the target for qualified life is 40 year the artificial accelerated ageing must last for almost 60 days. In cases where a temperature resulting in an acceleration factor above 250 is used in order to estimate service life, only a factor of 250 should be credited in the establishment of the qualified life.

The choice of the limitation to 250 does not mean that use of an acceleration factor below 250 is “safe” and above 250 is “unsafe”. The exact limit between “safe” and “unsafe” application of Arrhenius law varies with material, temperature range, etc. It is not feasible to require a full investigation of the appropriate limit in each individual case. The limit 250 is assumed to be reasonable for most materials, but there may still be materials and conditions where a limitation to 250 is still too high, especially for avoiding overestimating the qualified life or qualified condition due to diffusion limited oxidation effects.

It is of course in any case not acceptable to use an artificial ageing temperature that results in completely different behaviour of the material than at operating temperatures, e.g. by reaching the crystalline melting phase.

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

Example:

A certain equipment 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 equipment is limited. No tests are available showing the activation energy of the polymer and the dose-rate effects on the degradation of the material.

Since the information on temperature during normal operation at the position of the equipment is limited, a conservative value of +55 C is selected, based on measurement in other similar positions and the variation of temperatures within the containment.

If no measurements of activation energy of the specific composition of the insulation material used in the equipment are available, the value to be used is collected from a survey of reports available on measured activation energies for similar polymers. This survey shows a range of measured values 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.

The range of temperature in which an Arrhenius behaviour has been proven for the insulation material with the composition used in the equipment is not known and therefore also the temperature used for the ageing is selected in a conservative manner, say at +110 ^{o}C. By this, the effect of oxygen diffusion limitation is assumed to be small.

Thus, lack of better knowledge about the parameters of the insulation material with the actual composition, the environment during operational conditions, etc., is compensated for by use of very conservative values, which may result in a qualified life which significantly underestimate the possible service life.

With the assumptions made, the acceleration factor is then 35, which means that the accelerated thermal ageing must continue for 7 months in order to reach a qualified life of 20 years.

Influence of the assumption of operating temperature and temperature used for the artificial ageing: Figure 3.2 shows the variation of the acceleration factor with the assumed operating temperature and the temperature used for the artificial ageing.

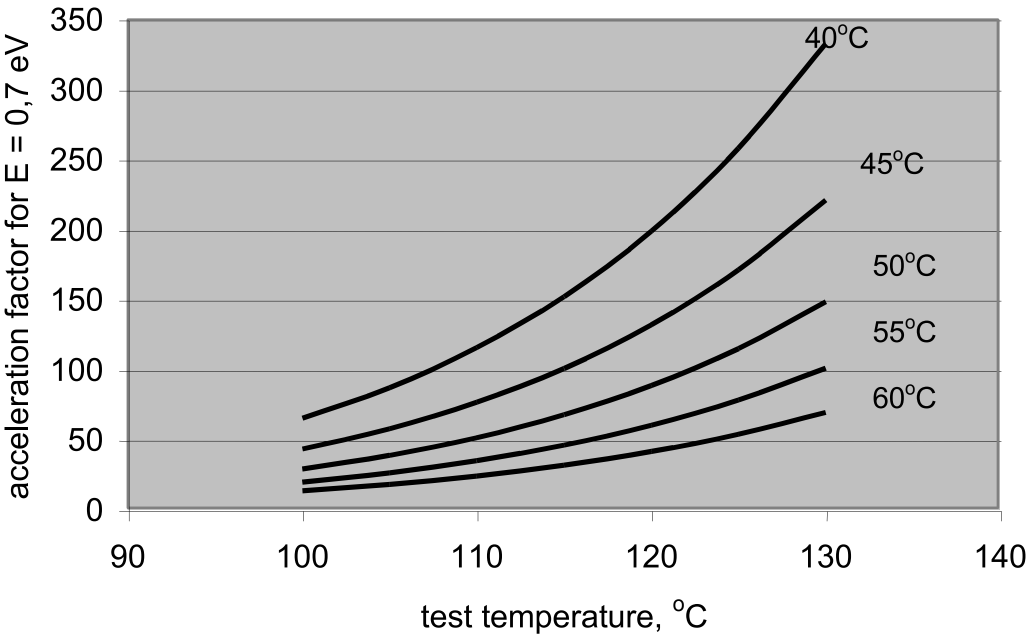

Figure 3.2. Influence of thermal ageing test temperature (from 100 °C to 130 °C) and operating temperature (from 40 °C to 60 °C) on acceleration factor at thermal ageing of a material with activation energy E=0,7 eV.

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 allowing a higher test temperature. An increase of the test temperature must be based on an assurance that no mechanisms occur that will affect the equipment in any other way than at normal operating temperature and knowledge of the sensitivity to oxygen diffused limitation.

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 in the example is increased to 77.

If further careful studies of the material show that the temperature during the accelerated thermal ageing can be increased to 120 °C, the acceleration factor increases to 132. This means that the goal of a qualified life of 20 years can be achieved by duration of the thermal ageing of 55 days.

Influence of the assumption of activation energy: Measurement of the activation energy within the actual temperature interval is a further step towards reduction of necessary conservatism. Figure 3.3 shows how an increase of the acceleration energy value influences the acceleration factor.

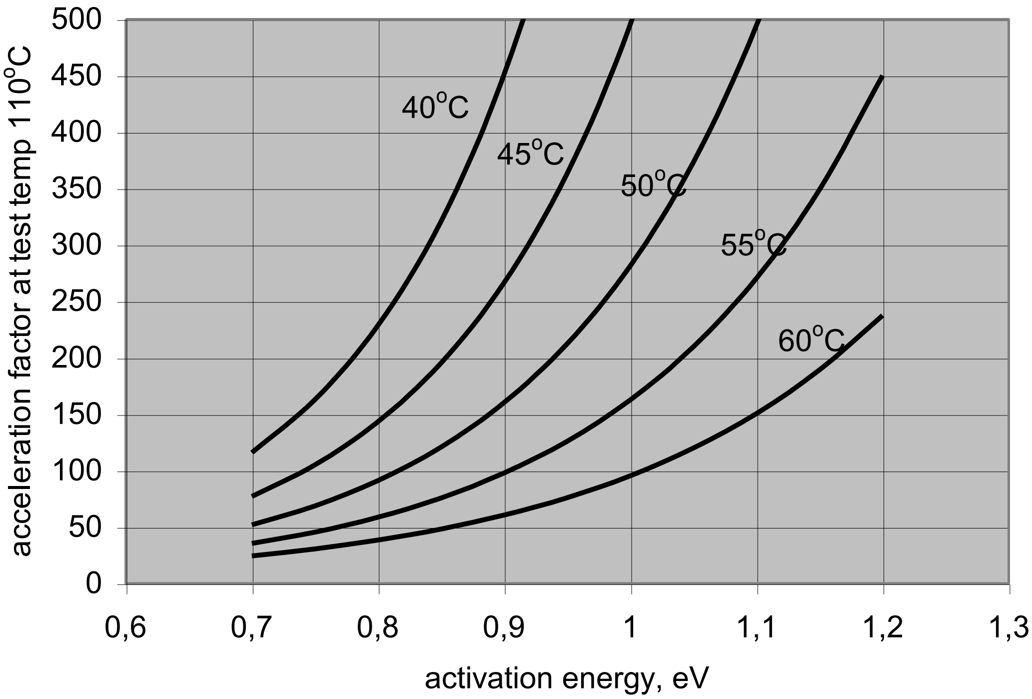

Figure 3.3. Influence of activation energy at different operating temperatures (from 40 ^{o}C to 60 ^{o}C) on the acceleration factor at thermal ageing performed at +110 ^{o}C.

Assume that a value on the acceleration energy close to 1 eV has been established in the example by 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 ^{o}C during one month then qualifies for a life of 20 years.

The example illustrates how a combination of a high degree of safety in the determination of qualified life and poor knowledge of the operational conditions and the important characteristics of the ageing sensitive materials involved result in unrealistic test requirements. In addition to the conservatism needed in the use of the test parameters and calculations, also the use of a small number of test items and test tolerances call for margins.

As a conclusion, application of qualified life as the basic (and only) criterion for management of ageing is only realistic if it is based on good knowledge of the various parameters involved. For some of the parameters involved, e.g. the environmental conditions during normal operation, rather exact figures may be attained but for other parameters of importance for the calculation of the qualified life it may not be possible to get a more exact figure. Examples of the latter are activation energies and effects of diffusion limited oxidation. Inclusion of condition based qualification offers a possibility to manage the ageing without knowledge of some of the parameters, e.g. environmental conditions during normal operation and activation energies. It should be kept in mind, however, that it does not handle the problem of diffusion limited oxidation effects of using excessive temperature and irradiation dose rates in the artificial ageing.

3.5.2.3.3 Selection of activation energy in calculation of qualified life

As illustrated in Figure 3.3, 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 [3.10] 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 [3.4], 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 equipment 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 equipment and thereafter age the assembled equipment. A typical example is shown below.

<u>Example:</u>

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 ^{o}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 spare 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 even more complicated to install spare 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.

A limitation of the acceleration factor to 250, results 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^{o}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 ^{o}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, before mounting in the complete penetration (which is then aged for 60 days at +105 ^{o}C before DBE-testing). In order to attain this, the o-rings from EPR and silicon rubber are pre-aged for 38 days at +120 ^{o}C and 45 days at +130 ^{o}C, respectively.

For some equipment, only certain polymers involved are of interest to the integrity. For instance, for a cable it is primarily the integrity of the conductor insulation that is important for the functionality, whilst the jacket is a mechanical protection. It should, however, be observed that in certain applications, e.g. where the tightness of the cable parts between dry-well and wet-well of a BWR power plant is important, the condition of the jacket is a safety issue.

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.

3.5.2.3.4 Assessment of activation energies provided by the equipment supplier

Suppliers of equipment normally provide activation energy values of the polymeric 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 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 equipment production, drilling, milling, punching of the equipment, etc. The values provided by the supplier can normally be used as guidance for identification of the material that limits the equipment's life. The material or materials that limit 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 equipment 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.

3.5.2.4 Artificial ageing in ionising radiation

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 highly 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, especially the sensitivity to diffusion limited oxidation;
- 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 [3.13]. An exception is equipment containing Teflon (sensitivity threshold down to a few kGy) or ordinary micro-processors (sensitivity threshold a few Gy). [3.13] gives the following threshold levels for polymers, below which the effects of ionising radiation are negligible.

Table 3.1. Threshold values for ionising radiation (from [3.13])

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				

The threshold values vary with the composition of the material, including additives like types of anti-oxidants, fire inhibitors, colour pigments, etc.

Westinghouse Sweden 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 indicates threshold levels of 10 kGy and 100 kGy, respectively. In addition, Westinghouse 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 [3.11] prescribes 0,5 kGy/h (100 h) for simulation of ageing dose. In Japan 1 kGy/h is prescribed. KBE EP-154 [3.10] prescribes1 kGy/h. 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 3.2 shows a compilation of available data on dose-rate dependence for materials used as insulators in cables and other equipment and in o-rings used in NPPs.

Table 3.2 Dose-rate dependencies

Material	***Dose-rate dependence at comparison between high and medium 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 equipment in the containment of Swedish nuclear power plants does not cause any significant degradation to the majority of the equipment also when dose-rate effects are taken into account. For equipment 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 equipment 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 equipment 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 margins to take dose-rate effects into account.

3.5.2.5 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 [3.14]. Our safety related equipments 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 [3.4] 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 equipment placed in vibrating structures and equipment which for other reasons have been subjected to excessive vibration.

3.5.2.6 Sequence and combination of environments in artificial ageing

During normal operation, equipment in the containment is 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 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 conservative results. When the radiation simulates the exposure in DBE, the radiation exposure shall in any case be performed after the thermal ageing.

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 [3.15].

3.5.2.7 Establishment of qualified condition as an alternative or complement to qualified life

3.5.2.7.1 Methodology

As illustrated above, lack of knowledge, uncertainty and limitation of applicability of laws for calculating qualified life from artificial accelerated ageing results in large uncertainty in the time which the artificial ageing in the initial qualification correspond to in field conditions. This leads to use of excessive conservatism and margins in determination of qualified life. The equipment will therefore normally be able to function in a DBE at a time which is considerably longer than its qualified life. In exceptional cases, it may still be shorter. In any case, there is a demand for following the actual ageing of the equipment by regular activities after installation. Methods for this are described in chapter 4.

Application of the concept of condition based qualification allows a direct follow-up of the degradation of the equipment in the field due to ageing and comparison with the level of degradation for which the initial qualification has verified that it will still meet its design requirements in a DBE. By this method, it may be possible to extend the qualified life beyond the value originally calculated from the initial qualification.

The qualified condition is established in the initial qualification by measuring one or more selected condition indicators during the artificial ageing. The value measured at the end of the artificial ageing is the qualified condition, provided that the ability of the artificially aged equipment to function according to its specification during DBE (and post-DBE if required) has been demonstrated. The establishment of qualified condition and relationship to qualified life is illustrated in Figure 3.4.

The value measured shall include a margin for measurement tolerances.

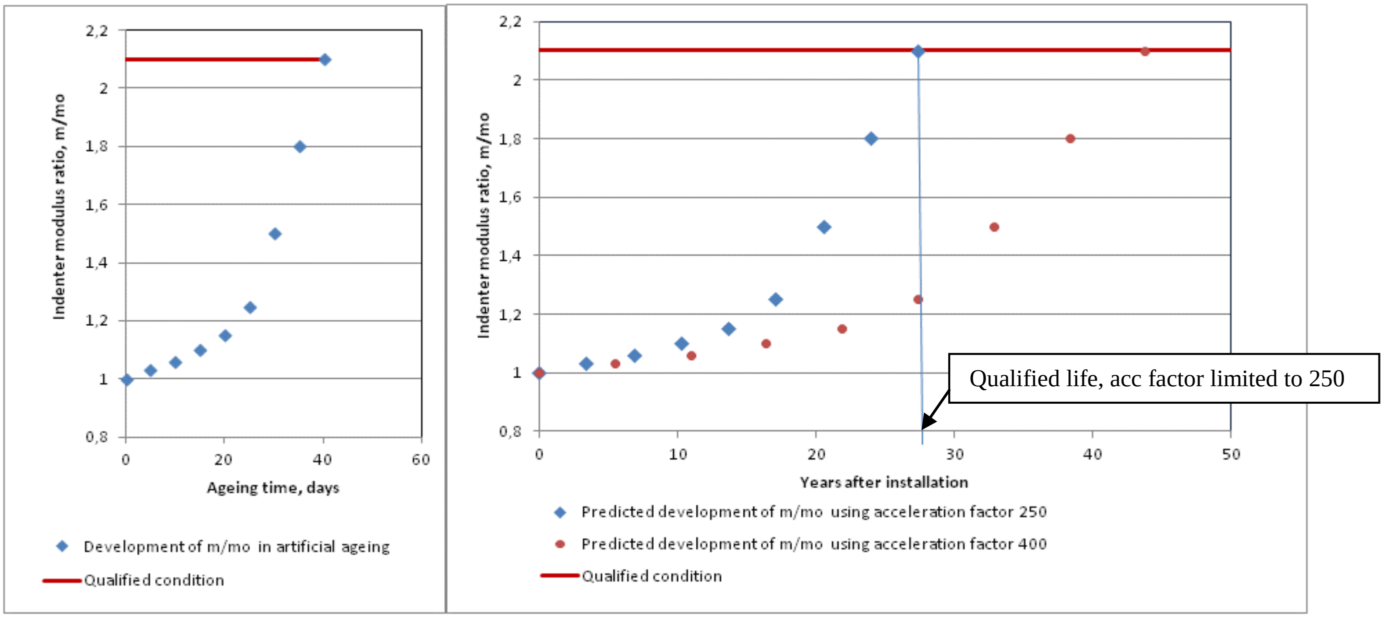

Figure 3.4. Establishment of qualified condition. The left diagram shows the development of the indenter modulus during the artificial accelerated ageing before DBE testing. The right diagram shows the predicted development in field for different acceleration factors. In the example, 400 is the acceleration factor achieved with the assumptions of activation energy and temperature during normal operation. In the calculation of qualified life only an acceleration factor of 250 is credited.

3.5.2.7.2 Selection of condition indicators

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

- identify condition indicators applicable to the equipment;
- 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 condition indicator selected for the qualified condition shall have a uniform trend with ageing time and be related to degradation of parameters of importance to the operability of the equipment.

It is of some advantage if monitoring can be performed without affecting the equipment (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.

Selection of condition monitoring indicators is discussed more in detail in Annex A.

3.5.2.7.3 Benefits of use of qualified condition

Use of qualified condition solves the problem of depending on the laws for calculation of acceleration factors in artificial accelerated ageing and their parameter values, e.g. the activation energies, prediction of environmental conditions in the field (temperature, radiation dose rate, humidity, etc.), as well as synergism of combined environments. This means very substantial advantages for the management of ageing.

However, use of qualified condition does not solve the issue of the effects of diffusion limited oxidation. This still has to be handled by collecting information on the materials involved and by applying moderate levels of the environmental parameters used for the artificial ageing.

Vibration of polymers that have been subjected to thermal ageing or ageing in ionising radiation can result in development of micro-cracks which <u>can influence the dielectric behaviour in DBE</u>. Equipments in the reactor containment are normally not subjected to significant vibration. It should be noted, however, that <u>condition monitoring methods do not normally react to micro-cracks in the polymers.</u> Degradation of dielectric properties from having been subjected to vibration as part of the ageing only shows up at measurement in humid atmosphere, especially in DBE-conditions. It is therefore important to be aware of the risk of reduction of the ability of equipment which have been subjected to vibration, e.g. from external or internal events, at any time during its service life.

3.5.3 DBE-test

Equipment 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, possibly including the total dose expected in normal operational conditions during the service life, 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, [3.16] and the corresponding profiles for DBE testing are given in KBE EP-154, [3.10].

The dose-rate can be made equal to what is expected during DBE. Possible synergism of the combination of ionising radiation and the thermodynamic conditions in DBE is normally taken care of by applying a margin when prescribing the radiation dose for the DBE-simulation.

Requirements on function during 30 days of post-DBE are prescribed for certain equipment in Swedish NPPs of type BWR. It is not recommended to use accelerated ageing in simulation of DBE in qualification of equipment for application in BWRs since it is possible to allow the full time needed (30 days). For PWRs where the requirements on function in post-DBE may be up to a year, it is necessary to accept accelerated ageing, which includes a combination of elevated temperature and high humidity. Methods for acceleration of humidity effects are given in [3.14]. They are, however, equipment specific and not generally applicable.

3.5.4 Test tolerances

IEC 60068-2-2 Tests B: Dry heat [3.17] is applied in heat testing of equipment 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^{o}C of specified value. The margins needed for compensating the test tolerances are small and can normally be neglected in relation to other uncertainties.

3.5.5 Number of samples tested

Few investigations are available of the variation in degradation due to ageing of different equipment 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.

It is economically and in practice feasible to include a sufficient number of samples in the initial qualification for a few types of equipment, e.g. cables, to allow a statistical treatment of the variation in functional parameter values of aged samples during DBE and calculation of the risk of a single specimen to fall outside the required functionality.

For more complex equipment it is normally not realistic to require a sufficient number of samples in initial qualification to allow a statistical treatment. It is still important to use at least three samples in order to get an indication if a significant variation in degradation due to ageing and in functional characteristics in DBE of the aged equipment can be expected. If this is the case, an analysis of the risk of aged equipment falling outside functional requirements in DBE, possibly including test of more samples, has to be made.

SKI report 93:39 [3.15] 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 ^{o}C. The results show that the differences in degradation related to functionality of the samples tested are not negligible even when the samples have been selected from the same batch.

3.6 Installation and storage of equipment for application of condition based qualification and for on-going qualification

The various methods available for assuring that the equipment is within the qualified condition and for extension of qualified life normally require storage of samples in areas representative for the most exposed equipment positions or, as a minimum, storage of samples in climatically controlled stores, mainly ensuring that they are not subjective to other than normal laboratory temperature and humidity and protected from other significant ageing factors, such as aggressive air pollutants, excessive vibration, rough handling. The purpose of the latter is to have access to replacement units in case of using ordinary installed units for on-going qualification or destructive condition monitoring. It also makes it possible to go back to original equipment, which is less aged than installed equipment, for possible complimentary future studies applying new knowledge, etc.

It is important that the samples stored are well documented regarding identity with the equipment that have been subjected to initial qualification (type test) and with the equipment that have been installed.

It shall be possible to trace the environmental history of the samples, preferably from measurement of the environmental condition in the location where they are stored.
As shown below, artificial ageing as an element in repeated testing for on-going qualification can be substituted by using equipment samples that have been subjected to more severe environmental conditions in normal operation (in hot-spots) than the equipment that shall be qualified. If equipment samples are installed specifically for this purpose, it is important that the environment for the samples is kept under control.

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

3.7.1 General

Type testing of equipment before installation provides a certain degree of confidence that the equipment manage to function satisfactorily in various situations including in a DBE. Lack of detailed knowledge of the important parameters and limitations in the applicability of laws for calculation of acceleration factors in the individual case is compensated for by use of a high degree of conservatism and extensive margins in the establishment of qualified life. The qualified life is also limited by limitation in time available for artificial ageing in the initial qualification.

The methods available after installation for improving the reliability of initially established qualified life and possibly to extend the qualified life 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 equipment for which an assessment of the initial qualification points to a need for complementary qualification

The goals for the management and testing of equipment important to safety after installation is to ascertain that they do not degrade to an extent that falls outside the status for which they have been verified to fulfil their design criteria 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 equipment etc. determine the extent and design of complementary programs for maintaining qualified life.

3.7.2 Activities after installation for reducing the uncertainty in the calculation of qualified life and justifying less conservative assumptions

After installation, a basis for recalculation of qualified life through use of more precise data may be attained as follows.

a. Measure the field environmental conditions (mainly temperature and radiation) which the equipment are subjected to. Measurement of the environment of equipment in the field is dealt with in Chapter 7.
b. Investigate characteristics of the ageing sensitive materials of the equipment. Examples are activation energies, influence of diffusion limited oxidation, synergistic effects of combination of temperature and ionizing radiation.
c. Repeat the initial qualification, using longer artificial ageing times, possibly with less extreme temperatures and dose rates in order to extend the qualified life and reduce the demand for margins due to possible non-Arrhenius behaviour and effects of diffusion limited oxidation.

These activities can justify a recalculation of qualified life with less conservative assumptions, still maintaining the required high degree of security that the equipment will meet its operational requirements in a DBE at any time during its qualified life.

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 equipment after installation (e.g. to apply condition based qualification), the investigations needed for establishment of condition indicators and their change with time can instead be made in connection with the repetition of the initial qualification or in connection with just a repetition of the ageing which was used in the initial qualification.

3.7.3 Extension of qualified life through repeated qualification testing (on-going qualification)

As indicated above, the conservatism in the establishment of qualified life implies that the equipment can normally function as required during DBE significantly later than at the end of the qualified life. In addition to recalculation of qualified life through activities according to 3.7.2, the qualified life can be extended through a procedure where equipment samples in locations representative of the environmentally most exposed equipment are removed at a time t_1 before expiration of qualified life and subjected to the following testing:

- Artificial aging in laboratory at a severity of the environment (temperature, radiation dose rate) and duration corresponding to the desired extension of qualified life Δt, followed by
- DBE simulation including functional control

If this procedure verifies that the samples after the artificial ageing function in DBE in accordance with the requirements, the qualified life of the equipment is extended by Δt.

This procedure is performed first time when the equipment approaches the qualified life and is then repeated at prescribed time intervals until it no longer succeeds extended qualification or is exchanged for other reasons.

In case samples which have been stored in hot-spot areas are used the artificial ageing as part of the life extension can be substituted by regarding the exposure of the samples in the hot-spot area as an acceleration of the ageing. The difference between the environmental severities in the hot-spot area and the corresponding environmental severities in the most exposed areas where equipment are installed is used as basis for the calculation of the extended qualified life. In this case, Δt is calculated as follows:

A. If temperature is the important long term ageing factor (normal case in Swedish nuclear power plants), calculate the thermal acceleration factor $F_{thermal}$ caused by the temperature in the hot spot, compared to the highest temperature in any area where the equipment is installed

$$F_{thermal} = e^{\frac{E}{k}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]} \qquad (3.3)$$

where

T_2 is the temperature to which the sample in the hot spot area has been subjected during normal operation

T_1 is the highest temperature during normal operation, representative of any area where the equipment is installed

Δt is then calculated as

$$\Delta t = (F_{thermal} - 1) * t_1 \qquad (3.4)$$

where

t_1 is the time from installation to removal of the sample in the hot spot area

B. If irradiation is the important long term ageing factor, the same principle is used with

$$F_{radiation} = \frac{d_2}{d_1} \qquad (3.5)$$

Δt is then calculated as

$$\Delta t = (F_{radistion} - 1) * t_1 \qquad (3.6)$$

where

d_1 is the dose rate in the area representative for the most exposed equipment

d_2 is the dose rate in the hot spot from which the sample has been taken

The methods for extension of qualified life are illustrated in Figure 3.5.

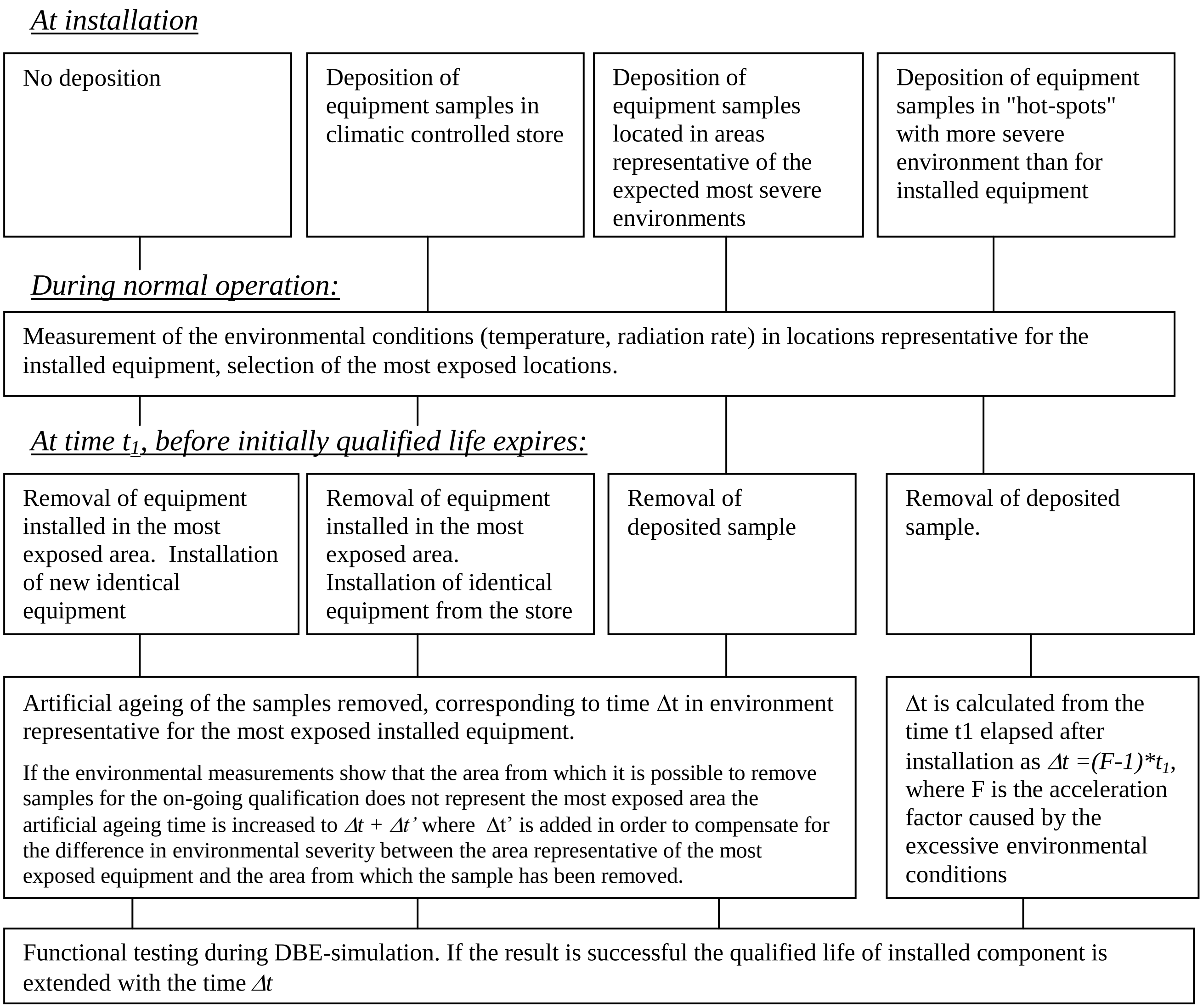

Figure 3.5. Scheme illustrating the methods for extension of qualified life.

SKI Report 93:39 [3.15] compares tests with low acceleration factor and a test time shorter than required for a certain service life 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.

It is necessary to know the environmental history of the equipment removed for on-going qualification and for typical locations, especially the most severe environmentally exposed locations, of the installed equipment that shall be qualified.

3.7.4 Use of condition monitoring in the management of ageing

3.7.4.1 General

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 equipment 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 are tools to confirm that the ageing after a longer installed time has not proceeded at a higher rate than expected. Condition monitoring can be used to maintain and possibly extend qualified life and to ascertain that the equipment is not degraded to an extent above its qualified condition.

When condition monitoring has been included in the qualification program, the initial qualification includes (see 3.5.2.6.1 above) the following steps:

- Identification, selection and measurement of condition indicators applicable to the equipment;
- Recording the changes with time of the values of the condition indicators during the artificial ageing in the initial qualification;
- Establishing the values of the condition indicators at the end of the artificial ageing before the function in DBE is verified.

After installation, identical measurements of the selected condition indicators are carried out regularly on representative samples and the values are compared with the qualified condition.

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 equipment, 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.

Figure 3.6 illustrates the results of the measurement of the selected condition indicator at certain time intervals after installation and comparison with the predicted development of the indicator value from the results of the measurements during the artificial ageing in the initial qualification.

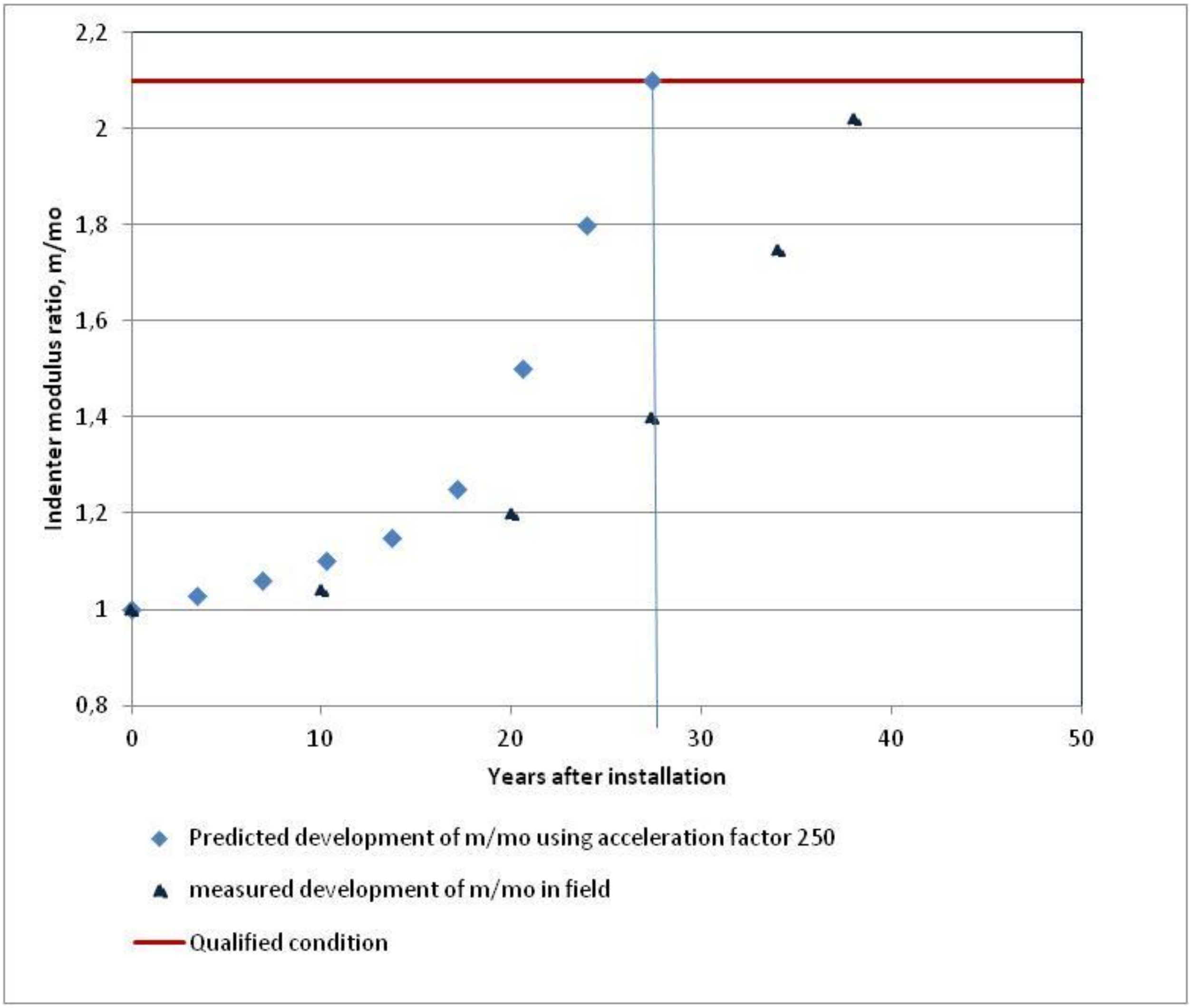

Figure 3.6. Use of qualified condition.

In the (hypothetic) example illustrated in Figure 3.4 the qualified life was calculated to 28 years. The first measurement of the indenter modulus is in our example (see Figure 3.5) made after 10 years and shows a value lower than the expected value. The next measurement is made after 20 years and confirms a trend which points to a useful life longer than the qualified life. The third measurement is made after 28 years, i.e. at the expiration of the qualified life and the trend continues to show that an extension of the qualified life is justified. It is extended to 40 years, corresponding to the service life, under the condition that the next measurement is made within 6 years and a reconsideration of the extended qualified life is made, based on the result. The next measurement is then made 34 years after installation. Since an extrapolation of the trend now shows that there is a risk that the qualified condition is reached before 40 years after installation, it is decided to make a new measurement within 4 years. The result is rather close to the qualified condition and the equipment is either substituted or a decision is taken to follow the development during the remaining years of the service life with more close measurements.

3.7.4.2 Intervals between performance of condition monitoring after installation

When condition based qualification is applied, a decision has to be taken on the intervals between the condition measurements in the field.

In case of doing the measurements in the field, using methods which are accepted as non-destructive, rather frequent measurements of the development of the condition indicator value can normally be made. In case of doing the measurements on samples removed from representative positions in the field, the number of measurement occasions is limited by the access of samples.

In any case, the first measurement should be made significantly earlier than at the expiration of the qualified life. If the development with time of the value of the condition indicator has been established in the initial qualification, this curve can be used to establish the time of the next measurement by matching.

In case of doing the measurements on samples removed from the field in laboratory, one way to establish the time interval to the next measurement Δt is to make an artificial ageing of the sample removed corresponding to a time equivalent to Δt plus margin before the condition measurement is made.

3.7.4.3 Control of qualified condition when non-destructive measurements can be used

The main advantage of using non-destructive condition monitoring is that more frequent measurements are feasible since we are not dependant on access to deposited samples or new or stored samples for substitution of removed equipment. The method of establishing the time to the next measurement by artificial ageing before the measurements are made cannot be used, but we can afford more conservatism in the choice of the time to the next measurement by affording shorter intervals.

Figure 3.7 illustrates the method for control of qualified condition in this case

At artificial accelerated ageing as part of initial qualification (or at complimentary measurements after the initial qualification)

Establishment of the qualified condition in addition to qualified life by the value of the condition indicator versus time *c(t)* in the initial artificial exposure. The end value before successful subjection to simulated DBE, c_{end}, is the qualified condition

During normal operation:

Measurement of the environmental conditions (temperature, radiation rate) in locations representative for the installed component, selection of the most exposed locations. Selection of the location in which condition measurements will be made

At time t_1 after installation:

Non-destructive condition measurement in the field at time t_1, measured indicator value = c_1

Decision of the time interval Δt_1 within which the next measurement shall be made, based on comparison of c_1 with $c(t)$ and its distance to c_{end}.

At time $t_n = t_{n-1} + \Delta t_n$:

The procedure is repeated until the results show that there is a risk that the qualified condition is exceeded before the next time when measurements can be made. The equipment has then reached its end of life and must be substituted.

Even if the qualified life is exceeded, the equipment can remain in the plant until the measurements show that there is a risk that the qualified condition is exceeded before the next time where measurements can be made.

Figure 3.7. Scheme illustrating the various steps in control of qualified condition using follow-up condition measurements in the field

3.7.4.4 Control of qualified condition when destructive measurements are used

Condition monitoring in the field can only be applied by use of methods which can be accepted as non-destructive. Although some of the methods for condition monitoring can be applied to installed equipment in a non-destructive way, it is in most cases only feasible or at least more convenient to make the measurements on samples of complete equipment or age sensitive parts of equipment brought to a laboratory, where it is easier to control the measurement of the values of the condition indicators.

Figure 3.8 illustrates the method for control of qualified condition in this case.

At artificial accelerated ageing as part of initial qualification (or at complimentary measurements after the initial qualification)

Establishment of the qualified condition in addition to qualified life by the value of the condition indicator versus time *c(t)* in the initial artificial exposure. The end value before successful subjection to simulated DBE, c_{end}, is the qualified condition

At installation

No deposition	Deposition of equipment samples in climatic controlled store	Deposition of equipment samples located in areas representative of the expected most severe environments	Deposition of equipment samples in "hot-spots" with more severe environment than for ordinary component

During normal operation:

Measurement of the environmental conditions (temperature, radiation rate) in locations representative for the in stalled component. Identification of the area where the equipment exposed to the most severe environmental conditions during normal operation is installed. In case of equipment samples located in “hot-spots” also the environmental conditions of this shall be measured. In this case, the difference Δt_0 in life in the environment to which the component located in ”hot-spot” has been exposed and in the area of the most exposed installed equipment is calculated.

At time t_1, in good time before initially qualified life expires:

Removal of equipment installed in the most exposed area. Installation of new identical equipment	Removal of equipment installed in the most exposed area. Installation of identical equipment from the store	Removal of deposited sample	Removal of deposited sample

Condition measurement in laboratory of the equipment sample removed, measured indicator value = c_1.

Decision of the time interval Δt_1 within which the next measurement shall be made, based on comparison of c_1 with *c(t)* and its distance to c_{end}.

At time $t_n = t_{n-1} + \Delta t_n$:

The procedure is repeated until the results show that there is a risk that the qualified condition is exceeded before the next time when measurements can be made. The equipment has then reached its end of life and must be substituted. In the case of using samples from the “hot spot” deposit, the equipment is qualified for use for the time Δt_0 after the measurements have shown that there is a risk that the qualified condition is exceeded before the next time when measurements can be made.

Figure 3.8. Scheme illustrating the various steps in control of qualified condition using follow-up condition measurements in the laboratory

3.7.5 References

[3.1] Krosness A., Spång K. ”Miljökvalificering av komponenter i kärnkraftverk. Del I: Komponenter i reaktorinneslutningen (Environmental qualification of components in nuclear power plants. Part I: Components in the containment)”, IFM Akustikbyrån TR 5.082.01, utgåva 2, September 1980 (in Swedish)

[3.2] IEC 60721-3-3 Classification of environmental conditions – Part 3 Classification of groups of environmental parameters and their severities – Section 3: stationary use at weather-protected locations

[3.3] TBE 101(E) ”Environmental Specification for Normal Operation”, Svenska kärnkraftverken (Swedish NPPs), 1996

[3.4] 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

[3.5] IEEE 323-1974 ”Standard for qualifying class 1E equipment for nuclear power generating stations”, The Institute of Electrical and Electronics Engineers, Inc.

[3.6] IEEE 323-1983 ”Standard for qualifying class 1E equipment for nuclear power generating stations”, The Institute of Electrical and Electronics Engineers, Inc.

[3.7] IEEE 323-2003 ”Standard for qualifying class 1E equipment for nuclear power generating stations”, IEEE Power Engineering Society.

[3.8] IEC 60780 ”Qualification of electrical equipment of the safety system for nuclear power plants, 1997

[3.9] IEEE 383-2003 ” Standard for qualifying class 1E electric cables and field splices for nuclear power generating stations”, IEEE Power Engineering Society.

[3.10] KBE EP-154 (E) ”Environmental Qualification for Accident Conditions”, Svenska kärnkraftverken (Swedish NPPs), 1996.

[3.11] KTA 3706 ”Wiederkehrender Nachweis der Kühlmittelverlust-Störfallfestigkeit von elektro- und leittechnischen Komponenten des Sicherheitssystems”, Kerntechnischer Aussuss (KTA).

[3.12] IAEA-TECDOC-1188 Assessment and management of ageing of major nuclear power plant components important to safety: In-containment instrumentation and control cables. Volume I and II. International Atomic Energy Agency, December 2000

[3.13] Aging Management Guidelines for Commercial Nuclear Power plants – Electical cable and Terminations. Contractor Report SAND96-0344, September 1996 (Specified dissemination)

[3.14] Spång, K. ”Långtidsverkan av miljöpåkänningar på säkerhetsrelaterade elkomponenter i kärnkraftverk. State-of-the-art (Long term effects of environmental stresses on safety-related electrical components in nuclear power plants. State-of-the-art)”, IFM Akustikbyrån TR 5.299.03, September 1984 (in Swedish)

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

[3.16] TBE 102:1(E) ” Environmental Specification for Accident Conditions”, Svenska kärnkraftverken (Swedish NPPs), 1996

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

Other reports of interest to chapter 3, not directly referred to in the text:

[3.18] NUREG/CR-4301, SAND85-1309 ”Status Report on Equipment Qualification Issues Research and Resolution”, Sandia National Laboratories, November 1986

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

[3.20] ”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

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

[3.22] 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)

4 Management of ageing of “old” equipment

4.1 General

Complete programs for management of the ageing problem, built from applicable elements of available methodologies describe above, can be developed in connection with purchase and qualification of new equipment for installation in NPPs. Also in the cases of already installed equipment (referred to as old equipment), for which it is desired to follow up and complement existing qualification or to extend qualified life, include methods for establishment of qualified condition, etc., applicable elements from the above described methodologies can be used. A survey of the possibilities is made below.

Most of the methods described above can be applied to old equipment if identical new equipment from the manufacturer or in store is available and can be used for complementary testing or exchange of installed equipment.

4.2 Recalculation of qualified life

A basis for recalculation of qualified life through use of more precise data may be attained as described in chapter 3.7.2, including one or more of the following elements:

- Measurement of the field environmental conditions;
- Investigation of characteristics of the ageing sensitive materials of the equipment, e.g. activation energies, influence of diffusion limited oxidation, etc.

These activities can be used to strengthen the confidence in the qualified life, reduce some margins used initially in the calculation of qualified life and possibly justify an extension of the qualified life.

4.3 Complementary testing in laboratory

In cases where the qualification of the old equipment has been based on artificial accelerated ageing at temperatures and dose rates involving a substantial uncertainty in the qualified life, repetition of the initial qualification, using artificial ageing with longer times and less extreme environmental conditions can be used to allow a more reliable re-calculation of the qualified life. This requires access to identical new equipment or identical equipment which has been stored in climatic controlled stores.

The uncertainties due to use of excessive environmental conditions in the initial qualification has normally been compensated for by a very significant conservatism in the calculation of the qualified life. The complementary testing can be used to investigate the possibility to extend the qualified life by allowing less conservatism in the calculation.

If the initial qualification is repeated, it is recommended to include, if possible, condition monitoring and establishment of qualified life as described in 3.5.2.6.

4.4 Extension of qualified life through on-going qualification

On-going qualification for extension of qualified life of "old" equipment requires access to stored identical equipment or new equipment that can replace equipment removed for tests for extension of qualified life.

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

4.4.1 Use of installed equipment which is removed, qualified for extended life, and substituted

If removal of installed equipment and replacing them with equipment from the store or new equipment can be made, on-going qualification can be performed in the same way as for "new" equipment as described in chapter 3.7.3. Removed samples are aged artificially (at elevated temperature) corresponding to the time Δt in real conditions and subjected to functional testing during DBE-simulation. If the result is approved, the qualified life of the installed equipment is extended by the time Δt.

4.4.2 Qualification for extended life without removal of installed equipment

If removal of installed equipment in the most exposed area is not possible but identical stored or new equipment are available, such equipment can be artificially aged to a degree corresponding to at least the ageing of the equipment which have been installed in the most exposed positions. The methods for artificial acceleration ageing described earlier in this report can be used for this. If possible, a check that the degradation of the equipment artificially aged is not less than the degradation due to ageing of the equipment installed in the most exposed areas may be made by making (non-destructive) condition measurements on both and comparing the results.

The procedure is illustrated in Figure 4.1 where the installed equipment is assumed to have been in operation for the time period t_0.

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

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

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

Removal of installed spare samples at time for extended qualification. Artificial ageing of the samples corresponding to the time Δt in real environment	Δt is calculated from the time t_1 elapsed after installation as $\Delta t = (F-1)*(t_1-t_0)$, where F is the acceleration factor caused by the excessive environmental conditions
Functional testing during DBE-simulation. If the result is accepted the qualified life of installed equipment is extended with the time Δt	Functional testing during DBE-simulation. If the result is accepted the qualified life of installed equipment is extended with the time Δt

Figure 4.1. “Old” equipment. Method for extension of qualified life for the case where installed equipment cannot be removed for testing and substituted.

4.5 Application of the concept of qualified condition to "old" equipment

If identical equipment has been stored in climatic controlled stores or new identical equipment is available, it is possible to apply the concept of qualified condition also to old equipment for which the qualified condition has not been established in the initial qualification. Two methods are available, depending on the information from the artificial ageing used in the original initial qualification.

a) Method where only the artificial ageing part of the initial qualification is repeated. The most expensive and complicated part of the initial qualification is normally the DBE testing. Data for using condition based qualification as basis for the on-going qualification after installation, possibly including extension of qualified life, can be achieved with an exact repetition of the exposure used in the original initial qualification. It is then not necessary to include DBE testing since the equipment is already qualified for DBE at its condition at the end of the artificial ageing.

b) Method including complete initial qualification. If information on the environmental condition used in the artificial ageing in the original initial qualification is not documented well enough for use in the procedure described in a) or is not satisfactory (e.g. due to too high temperatures or radiation dose rates involving a risk of significant diffusion limited oxidation, a complete requalification including reestablishment of qualified life and establishment of qualified condition may be needed.

The methods are described by the schemes in Figure 4.2

Full or partial initial renewed qualification, performed on stored or new identical equipment

The conditions used in artificial ageing in the original initial qualification are satisfactory and well documented.

Exact repetition of the artificial ageing in the original initial qualification, including establishment of the qualified condition by measurement of a suitable condition indicator during and at the end of the artificial ageing (establishment of $c(t)$ and c_{end})

The conditions used in artificial ageing in the original initial qualification are not satisfactory and/or not well documented.

Complete initial qualification, including artificial ageing and simulated DBE testing. Establishment of the qualified condition by measurement of a suitable condition indicator during and at the end of the artificial ageing (establishment of $c(t)$ and c_{end}).

During normal operation:

Measurement of the environmental conditions (temperature, radiation rate) in locations representative for the installed components, selection of the most exposed locations. Selection of the location in which condition measurements will be made

At time t_1 after installation:

Non-destructive condition measurement in the field at time t_1, measured indicator value = c_1

Decision of the time interval Δt_1 within which the next measurement shall be made, based on comparison of c_1 with $c(t)$ and its distance to c_{end}.

At time $t_n = t_{n-1} + \Delta t_n$:

The procedure is repeated until the results show that there is a risk that the qualified condition is exceeded before the next time when measurements can be made. The equipment has then reached its end of life and must be substituted.

Even if the qualified life is exceeded, the equipment can remain in the plant until the measurements show that there is a risk that the qualified condition is exceeded before the next time where measurements can be made.

Figure 4.2. Scheme illustrating the various steps in application of condition qualification to "old" equipment.

5 Equipment outside containment

5.1 Management of ageing

A comprehensive study of the environmental conditions of safety-related equipment located outside containment was performed in 1980 and reported in IFM Akustikbyrån

TR 5.125.01 [5.1]. TBE 101 [5.2] 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 equipment that shall function for a long time, especially equipment located in areas affected by an accident. For equipment 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 equipment is, however, not always sufficient. Introduction of periodic inspection may be needed, where the equipment 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 elastomer (o-ring) has been mounted in "hot" electrical equipment outside critical areas.

For equipment located in areas affected by accident, such controls are not sufficient since they do not indicate if the equipment is able to perform its intended function in connection with an accident. For such equipment, 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.

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 [5.1] 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. Equipment located close to the place of a steam-line break in a primary event room is 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.

According to TR 5.125.01 [5.1], 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 polytetrafluoroethylene (PTFE) and some similar fluoropolymers.

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 equipment in particularly exposed positions.

Equipment 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 equipment’s life through corrosion and chemical effects.

The equipment 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 ^{o}C can be expected in summer, somewhat cooler in winter, assuming that the equipment 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 [5.3] indicate that intermittent vibration can reduce the insulation resistance in thermally aged cables under accident conditions. Equipment outside the containment may be subjected to vibration. This is the case for equipment mounted to the same structure as vibrating machinery (engines, pumps, etc.), equipment mounted to structures to which steam-lines are mounted, equipment mounted on steam-lines, etc. The functional performance of equipment 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 equipment in areas subjected to essential influences of accident environments. For safety-related equipment in areas not significantly influenced by accident environments it should be sufficient to perform regular controls of the equipment's function.

5.2 References

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

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

[5.3] 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.

6 Methodology for measurement of the environments of equipment during normal plant operation

6.1 Background

Prediction of equipment's qualified life is built on prediction of the environmental conditions for the equipment during normal plant operation. Limited knowledge and limited control of the environment must be compensated for 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 equipment. It is therefore particularly 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 equipment in NPPs.

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 equipment locations and in places with an environment representative of the majority of the equipment 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.

6.2 Temperature, measurement requirements

The temperature of passive (not self-heated) equipment 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 equipment if there are important heat sources in the vicinity from which the equipment is not shielded.

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

6.2.1 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 equipment is exposed during normal plant operation.

6.2.2 Radiation from surrounding surfaces

If the equipment is directly exposed to surfaces in the vicinity that are warmer than the air temperature, the equipment temperature will be higher than what is caused by the air temperature alone. The extent to which the heat radiation influences the equipment temperature depends primarily on the air circulation around the equipment (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 equipment 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 equipment's temperature is often a simpler and more reliable way but it requires attachment of sensors to representative surfaces of all equipment 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 equipment, the best way is to place them in such a way that that they are protected from heat radiation from surrounding surfaces.

6.2.3 Measurement of temperature of self-heated equipment

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 self-heated equipment 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;
- Self-heated equipment dissipates heat to the surrounding through convection, radiation and conduction. The effect of the self-heating on the equipment temperature decreases with increasing surrounding temperature. This has the consequence that the difference between the surrounding air temperature and the equipment 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:

An equipment has the surface temperature 70 ^{o}C at the surrounding air temperature 40 ^{o}C (the surrounding air is not subjected to forced circulation, only self-convection occurs). If it is exposed to the surrounding air temperature 100 ^{o}C in a chamber without forced air circulation the surface temperature reaches 124 ^{o}C (obtained by extrapolation of the nomogram in IEC 60068-2-2, Appendix A, [6.1]). Thus, the difference in the equipment temperature between the accelerated thermal ageing condition and the operational condition is 54 ^{o}C whilst the test temperature differ 60 ^{o}C from the operational temperature.

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

If we use the equipment 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:

$$F = e^{\frac{E}{k}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]} \qquad (6.1)$$

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.

6.3 Measurement of ionising radiation

Since the irradiation field can vary considerably in the containment, measurements are needed in the vicinity of ageing sensitive equipment and not only in general areas. Irradiation doses of importance to ageing are found only in a few equipment 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.

6.4 Other environmental factors

Vibration occurs only exceptionally during normal operation. The relative humidity is low during normal operation, typically below 20 %. Safety-related equipment is not installed in wet-well in Swedish BWR's. Also the occurrence of air pollution is low.

6.5 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, [6.2]. Visual inspection of equipment and visible cables in connection with revision shutdowns is most important for detection of hot-spots (see clause 3.7.4.1).

6.6 References

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

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

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

7.1 General

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

7.2 Non-destructive condition monitoring

Identification and measurement of condition indicators related to equipment 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 equipment, 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 equipment and can be used on installed equipment 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 an oxidation gradient from the surface to the inner parts which are 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.

7.3 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 equipment (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 equipment type is qualified (assuming that the equipment 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.

7.4 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 equipment 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 equipment will function properly in an accident occurring before the next measurement occasion (e.g. before the next revision shutdown).

7.5 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 others and us 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), IR (Infrared spectometry);
- Mechanical indicators – elongation-at-break, indenter, micro-hardness;
- Dielectric indicators – insulation resistance, dielectric loss factor, etc.;
- Electrical indictors – TDR (Time Domain Reflectometry), FDR (Frequency Domain Reflectometry), LIRA (Line Resonance Analysis);
- Optical fibre indicators – OTDR (Optical Time Domain Reflectometry).

International joint IEC/IEEE standards are available or under development on some of the methods ([7.2] – [7.6]). Annex B includes descriptions of some of the other methods, especially the electrical indicators.

7.6 Summary of the applicability of the methods

Tables 7.1 and 7.2 summarise the most important characteristics of the condition indicators and their applicability.

Table 7.1 Characteristics of condition indicators

Method	Destructive method	Sampling or testing difficulties	Testing with equipment 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 equipment
Dielectric spectroscopy	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 equipment
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 interpret
Twisting	Yes	Difficult	No	Very poor	Not suitable	
Bobin test	Yes	Simple	No	Poor	Not suitable	Only results in acceptable/not acceptable
LIRA	No	Simple	No	Poor for determination of global degradation	Method still under development	Sensitive for finding hot spots and local deviation
FDR/TDR	No	Simple	No	Poor for determination of global degradation	New analysis tools to old technology open new field of use	Sensitive for finding hot spots and local deviation
IR	Yes	Simple	No	Very Good	Suitable	Experienced method. Requires chemical analysis throughout the artificial ageing.
OTDR	No	Medium	No	Good	Limited to optical cables	Sensitive for finding hot spots and local deviation

Table 7.2. 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 equipment'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 [7.1] 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.

7.7 References

[7.1] 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

[7.2] IEC/IEEE 62582-1, Nuclear Power Plants – Instrumentation and control important to safety – Electrical equipment condition monitoring methods – Part 1: General

[7.3] IEC/IEEE 62582-2, Nuclear Power Plants – Instrumentation and control important to safety – Electrical equipment condition monitoring methods – Part 2: Indenter modulus

[7.4] IEC/IEEE 62582-2, Nuclear Power Plants – Instrumentation and control important to safety – Electrical equipment condition monitoring methods – Part 3: Elongation at break

[7.5] IEC/IEEE 62582-2, Nuclear Power Plants – Instrumentation and control important to safety – Electrical equipment condition monitoring methods – Part 4: Oxidation induction techniques

[7.6] IEC/IEEE 62582-2, Nuclear Power Plants – Instrumentation and control important to safety – Electrical equipment condition monitoring methods – Part 5: Optical time domain reflectometry

8 Conclusions

This part of the 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.

Programs for qualification of ageing sensitive equipment 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 were carefully reviewed and described in a 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 equipment 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 equipment that are installed and in operation, depending on the availability of equipment which can be substitute samples of installed equipment which are removed for testing. The development of such methods has been an important activity behind work on extension of qualified life.

Annex A.

An example showing the relationship between insulation resistance of thermally aged cables before and during LOCA

Figure A1 shows the result of a study of conductor insulation resistance of thermally and radiation aged Lipalon cables (CSPE) before and during LOCA, performed 1996-97. It is part of the study presented in SKI Report 97:40 in October 1997. The cables were subjected to thermal ageing by exposure to 95°C for duration of 48, 96, 192, and 384 days, followed by a ionizing radiation for a duration of 50h at a dose rate of 10 kGy/h, which took into account the expected radiation dose during a LOCA. The blue points show the insulation resistance measured after the thermal ageing and ionizing radiation but before exposure to the LOCA chamber. The red dots show the lowest value of the insulation resistance measured during the exposure in the LOCA chamber.

The results show that the thermal ageing did not have an influence on the insulation resistance measured before the exposure to the LOCA chamber, but it had a very significant effect on the insulation resistance measured during LOCA (from356 kΩ for the cables which had been exposed to 95°C for 48 days to 55 kΩ for the cables which had been exposed to 95°C for 384 days.

The example illustrates the fact that an ageing of cable insulation may have an influence on the ability to function according to its specifications during LOCA also if its operability in normal operational conditions has not been affected by the ageing.

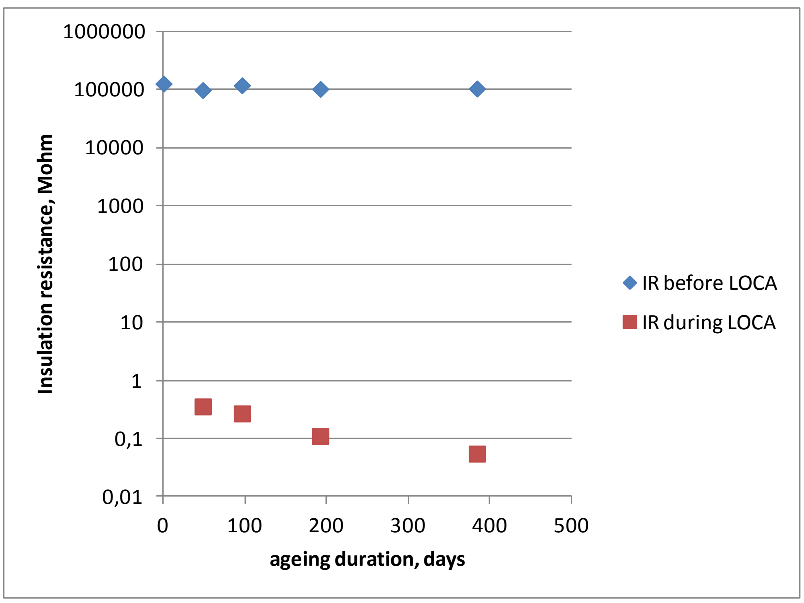

Figure A.1 Insulation resistance of thermally and radiation aged cable conductor insulation before and during exposure in a LOCA chamber.

Annex B

Short description of electrical condition monitoring methods and IR

B.1. Line Resonance Analysis (LIRA)

The method is based on the transmission line theory used for investigation of cable properties. The transmission line is the link between a signal source and a load. The behavior of a transmission line depends by its length in comparison with the wavelength λ of the electric signal traveling into it. When a high frequency noise source is used the resolution over the length of the cable is the better than if a low frequency noise source is used. The typical resolution when using 100 MHz noise source e.g. 2 x 10^8 data pints per second is 3 m. The resolution is also dependant of the signal speed in the cable.

The LIRA software is designed to investigate the behavior of a transmission line at high frequencies. A transmission equivalent circuit is depicted in figure B.1.

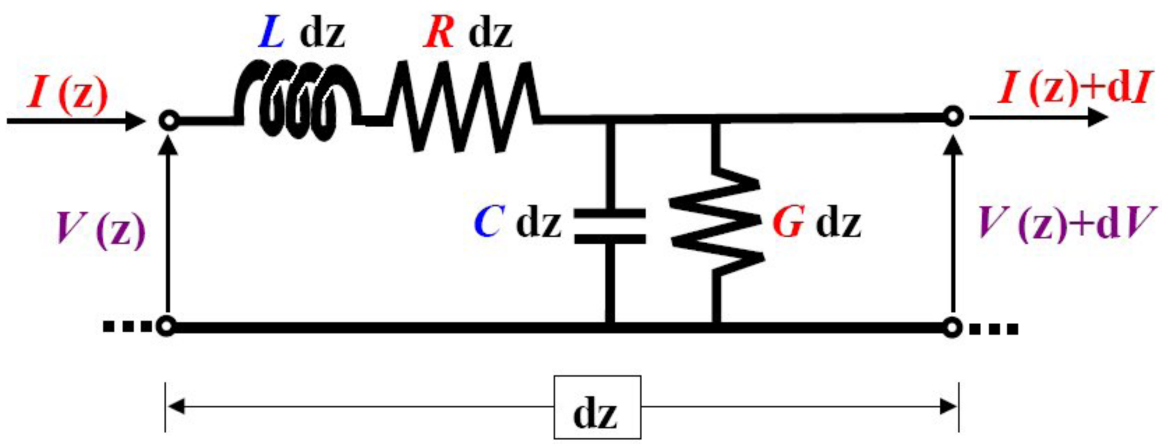

Figure B.1. Transmission equivalent circuit (LIRA)

Changes in the dielectric properties of the insulating materials e.g. wire insulation, fillers and jacket can be detected an after calculation performed by the system software monitored. The system is able to detect degradation in the insulation due to heat, bending, scratches, other mechanical impacts, fatigue, corrosion, water intrusion, water trees etc. Changes at cable joints and in cable splices can also be detected. The sensitivity is rather good for detection of local deviations and influence at hot spot positions. The ability to detect global degradation is highly dependent of base line data collection when determining the qualified lifetime or qualified condition of the cable. Two different equations for calculation of global conditions are used.

A - CBAC2 is calculated through the estimation (using frequency analysis) of:

1. The high frequency attenuation (3rd harmonic analysis)
2. The cable characteristic impedance Z0
3. The signal phase velocity VR

B - CBAC is the Central Band Attenuation for Capacitance

The cable degradation can for some cable design be detected by measuring and calculating the damping of the wideband noise in the cable. The equation is

$$\alpha(dB/km) = Kf^{a}\sqrt{\frac{C}{L}}$$

Where K is a constant for each cable design and geometry and is based on the DC-resistance. F is the frequency of the signal and the exponent α is a skin effect value between 0.5 and 1.

B.2. Time Domain Reflectometry (TDR)

The method is based on an impulse signal injected into a cable. The time for getting reflections of the pulse or parts of the pulse is measured. The magnitude of the reflections is dependant of the local impedance and small changes can be detected. Properties like standing wave ratio, impedance ration, return loss, reflection coefficients, impedance conformity structural return loss, and position of fault can be measured and calculated. This makes the method suitable for finding changes or discontinuities in the cable from baseline conditions at qualification or installation to characteristics measured after time in operation.

By comparing a baseline plot (fingerprint) with actual plots changes in characteristics can be identified. The method requires two or more conductors or one or more conductor and a shield. The test object must be disconnected at one end and de-energized before connecting the TDR-instrument. The method is usable for troubleshooting of cables and localization of defects. Corroded connectors, loose connectors, splices and cable glands.

The method has not been successful for measuring degradation of long installed cables. The method can however be considered as a complementary method for condition monitoring of cable systems, especially when signature data or fingerprints are established when qualifying the cable with connectors etc.

B.3. Frequency Domain Reflectometry (FDR)

The method is based on a wideband noise or swept sine (chirp) signal injected into a cable. The method is very similar to TDR and the test object must have at least two conductors or one conductor and a screen. The cable must be disconnected and de-energized when performing the measurement. Instead of injecting pulses into the cable white wideband noise, or swept sine (chirp) signals are used. The response (impedance) is presented in the frequency domain after signal processing such as Fourier transform.

The measurement can be realized with assistance of a VNA (Vector Network Analyzer). The FDR method has been modified and developed. Methods like STDR (Sequence Time Domain Reflectometry) are based on injection of pseudo random noise in a cable and correlation analysis of the signals to locate non conformity in the electric properties of the cable. One similar method is the JTFDR (Joint Time Frequency Domain Reflectometry).

All variants of the method can be used to identify the location of deviating spots of the cable impedance. Basic consideration regarding sampling, anti aliasing and filtering must be taken when analyzing the response signal. The method has similar to the TDR method not been successful for measuring degradation of installed cables. The method is in general more accurate to identify distance to fault. The fault or defects are e.g. corroded connectors, loose connectors, splices and cable glands. The method is under development and progress has been reported.

B.4. Infrared spectroscopy (IR)

Infrared spectroscopy is the common term for a number of methods for investigation of the content in polymers. The method can be based on reflection, transmission, absorption etc. The optical properties of base material, the condition of the material and all additives, and the amount of them are analyzed with the method and an IR-spectrum is generated. The shape of the spectrum with peaks and dips is characteristic for the content of the sample analyzed. The method is well established for identifying polymers and can be used for determination of material degradation. The spectrum used for analysis is within the range from about 12000 cm^{-1} to 50 cm^{-1}. Some methods can be performed with very small samples (in the mg range) and may therefore be regarded as non-destructive.

2013:10

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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