IAEA-TECDOC-932

Pilot study on the management of ageing of instrumentation and control cables

Results of a co-ordinated research programme 1993–1995

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The originating Section of this publication in the IAEA was:

Engineering Safety Section
International Atomic Energy Agency
Wagramerstrasse 5
P.O. Box 100
A-1400 Vienna, Austria

PILOT STUDY ON THE MANAGEMENT OF AGEING OF
INSTRUMENTATION AND CONTROL CABLES
IAEA, VIENNA, 1997
IAEA-TECDOC-932
ISSN 1011-4289

Printed by the IAEA in Austria
March 1997

FOREWORD

The IAEA programme on safety aspects of nuclear power plant (NPP) ageing integrates information on the evaluation and management of safety aspects of NPP ageing, generated by Member States, into a common knowledge base, derives guidelines and assists Member States in the application of these guidelines. In this context, pilot studies for representative NPP components have been carried out to assist Member States in applying the Methodology for Management of Ageing of NPP Components Important to Safety, as presented in IAEA Technical Reports Series No. 338.

Results of interim/Phase I studies, which are reported in IAEA-TECDOC-670, provided the basis for in-depth Phase II studies which have been conducted through co-ordinated research programmes (CRPs). This report is the main outcome of the 1993-1995 CRP on Management of Ageing of In-containment Instrumentation and Control (I&C) Cables.

Although few problems have been reported with cables in normal operation of NPPs, there have been some cases where cables which had initially been qualified for a 40 year service life failed a design basis event test after removal from the plant following less than 10 years of normal operation. This report presents recommendations of CRP participants for ongoing qualification and condition monitoring methods that can be used in NPPs to provide additional assurance for the safety of cables inside containment.

The report will be of interest to NPP designers, operators, regulators, technical support organizations and researchers interested in electrical and I&C cable qualification programmes. It was prepared for publication by S.G. Burnay of the United Kingdom, using contributions of the CRP participants. The work of all contributors to drafting and review identified at the end of this publication is greatly appreciated.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

An IAEA programme of pilot studies on management of ageing of nuclear power plant components was initiated in 1989. The overall objective of each pilot study was to identify the dominant ageing mechanisms and develop an effective strategy for managing ageing effects caused by these mechanisms. Four safety significant components were selected for this purpose. These four components, which represent different safety functions and materials susceptible to different types of ageing degradation, were:

- the primary nozzle of a reactor pressure vessel
- motor operated valves
- the concrete containment building
- instrumentation and control (I&C) cables.

The pilot studies were conducted using IAEA's methodology [1], with phase I studies being completed via Technical Committee meetings held in 1990 and 1992 [2]. The phase I studies consisted of assessments of the literature and current state of knowledge on age-related degradation, its detection and mitigation, and recommendations for phase II studies. Separate co-ordinated research programmes (CRPs) were set up for each of the above components to implement the phase II studies.

Cables are vital components of instrumentation and control (I&C) systems in NPPs since they link the system components, such as transducers, with the instrumentation and control equipment used to monitor and control the plant. Safety related I&C cables, therefore, need to be qualified to perform their functions both under their normal operating conditions and under a design basis event (DBE) and post-DBE conditions occurring at the end of their installed life.

The specific objectives of the CRP on in-containment I&C cables were:

- to validate predictive cable ageing models accounting for synergistic effects that take place when radiation and thermal ageing occur over the long time period associated with real plant environments
- to provide practical guidelines and procedures for assessing and managing the ageing of I&C cables in real plant environments.

This report summarizes current experience in the management of cable ageing as developed by CRP participants.

1.2. OBJECTIVE

The objective of this report is to present CRP recommendations for the assessment and management of ageing of I&C cables in real nuclear power plant environments.

1.3. SCOPE

This report is aimed specifically at low voltage (<1 kV) cables used in instrumentation and control circuits inside containment. However, much of the information is also relevant to low and medium voltage power cables used in NPPs, which utilize similar materials and which have similar degradation mechanisms. The examples quoted are primarily for cables based on EPR, EVA and XLPE materials, which are the most commonly used.

1.4. STRUCTURE OF THE REPORT

Various technical issues and concepts of the management of ageing in I&C cables are addressed in this report. Section 2 covers the technical background to the ageing of cables, including a summary of the relevant ageing mechanisms. Additionally, it addresses operating experience for a range of NPP types and an assessment of the current functional capability of cables in typical NPPs.

Section 3 provides an overview of the range of ageing management methods which are currently in use. A more detailed description of the individual sampling and laboratory ageing methods is given in Section 4 and of monitoring and test methods in Section 5. These sections identify both the capabilities and the limitations of the various management methods. Conclusions are presented in Section 6 and recommendations for further work in Section 7.

2. AGEING CONCERNS

2.1. TECHNICAL BACKGROUND

A wide variety of cables is used in NPPs, with different constructions and materials. Cable types can include:

- single or multiconductor
- shielded or unshielded
- coaxial or triaxial
- jacketed or armoured cable.

The insulation and jacket materials most widely used in I&C cables are polymer-based and cover a wide range of materials. Typical materials in use are:

- XLPE (crosslinked polyethylene)
- EVA (ethylene vinyl acetate copolymers)
- EPR and EPDM (ethylene propylene based rubbers)
- SiR (silicone rubber)
- PPO (poly phenylene oxide)
- ETFE (ethylene tetrafluoroethylene copolymers)
- PEEK (poly ether ether ketone)
- PVC (poly vinyl chloride)
- CSPE (chlorosulphonated polyethylene).
- Neoprene (chlorinated rubber).

These are the base polymers for the cables, but each manufacturer will use its own specific formulation for additives and compounds used in the material. For this reason, there can be significant variations in ageing behaviour between cables of the same base polymer type from different manufacturers. Batch to batch variation in cables from the same manufacturer are usually not as large, but can be significant.

In many countries, qualification of safety-related I&C cables is based on compliance with IEEE-323 (1983) and IEEE-383 (1974) standards [3], which detail testing procedures aimed at demonstrating the ability to survive a DBE after a 40 year service life. However, since these standards were written, a better understanding of the degradation behaviour of cable materials has been reached. This has led to a need for improved methods for assessing and mitigating ageing in cables in NPPs since it is now recognized that standard qualification tests may have been inadequate in assessing long term degradation in service, particularly for cables inside containment.

2.2. AGEING MECHANISMS

The main stressors causing age-related degradation of polymer-based cable materials are:

- temperature
- radiation dose rate and total dose
- oxygen
- moisture
- mechanical stress
- ozone
- contaminating chemicals.

Of these, the dominant stressors are temperature, radiation dose rate and the presence of oxygen for the majority of reactor systems, but for BWR systems moisture may also be significant. It should be emphasized that real service conditions usually involve synergistic effects between two or more of the stressors listed. In particular, dose rate effects can be a major factor in the degradation of cables in plants. In many polymers the dose required to reach a specific level of degradation (DED) is significantly lower when the dose is applied at low dose rates (e.g. at 1 Gy/h). There is some indication that the other stressors are also important in ageing degradation but, at present, there is insufficient information to assess their significance. For example, it has been noted in irradiation tests on cables wound on mandrels that cracking of the insulation tends to occur on the outer edge of the cable before any cracking is observed on the inner sections. The outer edge would be subject to tensile stresses, dependent on the diameter of the cable relative to that of the mandrel, whereas the inner section is under compressive stress. However, a comprehensive assessment of the effect of stress on the degradation of cable materials does not appear to have been carried out. Ozone effects are only likely to be significant in polymers containing high proportions of double bonds in the molecular chain. Of the polymers commonly used in cables, only some of the EPR materials which are diene-containing terpolymers are likely to show such effects.

Moisture is another potential stressor that has not been adequately studied in its effects on degradation. High humidity and the design of cable trunking and conduits will often expose cables to excessive moisture within NPPs. Its presence within the cable insulation can have a significant effect on the electrical properties of the cables, but little is known of its effects on changes in the mechanical properties.

For many of the polymers of interest in cables, oxidation is the dominant ageing mechanism and is initiated both thermally and by irradiation. In PVC, which was widely used in older NPPs, loss of plasticiser from thermal ageing is also an important degradation mechanism. Both of these mechanisms can result in embrittlement of the cable materials, increasing the probability of cracking of the insulation under mechanical stresses. Such stresses can arise in the plant from handling, vibration, thermal cycling or from the way in which the cable is routed. In practice it is this loss of mechanical integrity which is the prime cause of failure of low voltage cable, resulting in the loss of electrical integrity.

Since embrittlement is a major result of ageing degradation, the elongation at break of a cable material is an indicator of the state of degradation. Conventionally, the reduction in elongation to 50% absolute is taken as the failure criterion for a cable insulation material. It is generally accepted that 50% elongation after a DBE test represents a material that is still in a functional state electrically with a satisfactory degree of margin before failure. In many of the polymers used in cables, there is little change in elongation values in the early stages of ageing degradation. In some cable materials, significant reductions in elongation are only seen in the last quarter of total life. For this reason, although elongation is used as the prime indicator of degradation, other parameters which show changes in the earlier stages of degradation are particularly useful in assessing the state of cables. Examples of these types of degradation parameter are oxidation induction time or temperature, dielectric loss, indentor value (see Section 5.1 for more detail).

Initial qualification of cables includes in-laboratory accelerated ageing using higher temperatures and dose rates than are normally experienced in service. Current standards in some cases allow acceleration factors up to 4000 [4] but these do not give realistic test data. The high temperatures and dose rates used are likely to give unreliable results. Acceleration factors of a few hundred are recommended as being more realistic.

Only a few test laboratories are able to carry out simultaneous radiation and thermal ageing in these accelerated tests. Therefore, in many cases, such tests are carried out by using sequential ageing, either thermal followed by radiation, or vice versa. The use of high acceleration factors and sequential ageing can introduce considerable uncertainties in determining what is an appropriate test sequence for each type of cable material.

It should be noted that the failure criteria normally defined in standards may not be appropriate for DBE tests. Considerably lower values can be accepted for the duration of the test provided that they do not materially affect the safe operation of the circuit. For example, insulation resistance is normally limited to a minimum value of 1 MΩ but during a DBE test, a more appropriate limit could be a maximum leakage current for the whole circuit of 1% of total current, provided that this does not affect the functionality of the circuit.

2.3. OPERATING EXPERIENCE

For the majority of cables in NPPs, there has been little evidence of significant degradation and few instances of cable failure as a result of normal operations. Degradation of PVC and low density PE cables in the Savannah River reactor after 12 years of operation prompted much of the early work aimed at understanding the effects of radiation on cable materials [5]. The procedures used for qualification of cables utilize high dose rate irradiations in short term tests which may not adequately simulate the behaviour of the cable in long term operational conditions at low dose rates. An example of this has been seen in some types of ETFE insulated cables which failed DBE tests after low dose rate exposure to a dose one tenth of that survived in qualification tests [6].

Qualification procedures are aimed primarily at radiation and thermal degradation of cable materials but do not take into account other degradation mechanisms. For example, in one type of CSPE insulated cable, significant cable failures were observed in the first few years of operation [7], specifically linked to the effects of moisture on this particular type of CSPE cable insulation, which contained MgO. The hygroscopic nature of the MgO made this particular cable type susceptible to the effects of long term exposure to high humidity. Degradation of the cable materials may also cause variation in electrical resistivity arising from plasticiser migration between the shield and insulation in PVC insulated cables [8].

Changes in plant design during service can also significantly affect cable lifetime. For example, changes in fire-fighting sectionalisation can cause localised increases in the operating temperature and result in accelerated ageing of the cables [9].

Other examples of cable degradation requiring replacement of the affected cables has mainly been through abnormal operating conditions. For example, loss of thermal insulation from steam pipes caused local cable degradation from thermal degradation effects [10].

In the radiation environment of high energy particle accelerators such as at CERN, the cables have to be regularly replaced in some areas where radiation levels are high. In some injection sections the annual radiation doses absorbed by the cables can be of the order of 10 kGy, and in some target areas up to 30 kGy. Under these operational conditions, I&C cables with PVC or polyolefin sheaths have to be replaced after a few years of operation [12].

3. AGEING MANAGEMENT METHODS

3.1. INITIAL QUALIFICATION

Selection of cables for NPPs is generally preceded by a qualification programme which includes accelerated ageing and DBE simulation. In many countries the testing is based on the general principles spelled out in IEEE-323 (1983) and specific principles for cable qualification in IEEE-383 (1974). These standards aim to demonstrate the ability to survive a 40 year service life combined with a DBE [3].

According to the standards used, an initial qualification test programme would normally include accelerated ageing at high temperature to simulate 40 year service life, followed by environmental tests simulating harsh environmental conditions (high temperature, seismic vibration, etc.) during DBE and, if required, post-DBE.

The most controversial part of this programme is the suitability of accelerated ageing procedures used to limit the time needed for the qualification, especially the use of large acceleration factors requiring high dose rates and excessive temperatures. The present status regarding application of acceleration factors varies from country to country [4]. As an example, the dose rate used for accelerated testing varies from 500 Gy/h to 10 kGy/h and the total dose applied, including accident dose, varies from 250 kGy to 2 MGy.

Since the promulgation of the above-mentioned standards, a better understanding of the degradation behaviour of cable materials has been reached. Based on the results of both laboratory studies and operational experience of the type described in Section 2.3, the opinion of the participants in the CRP is that initial qualification is not necessarily guaranteed to predict survivability of a DBE after a 40 year installed life. An additional programme is recommended, including ongoing qualification, in order to ensure long term safe operation of in-containment I&C cables.

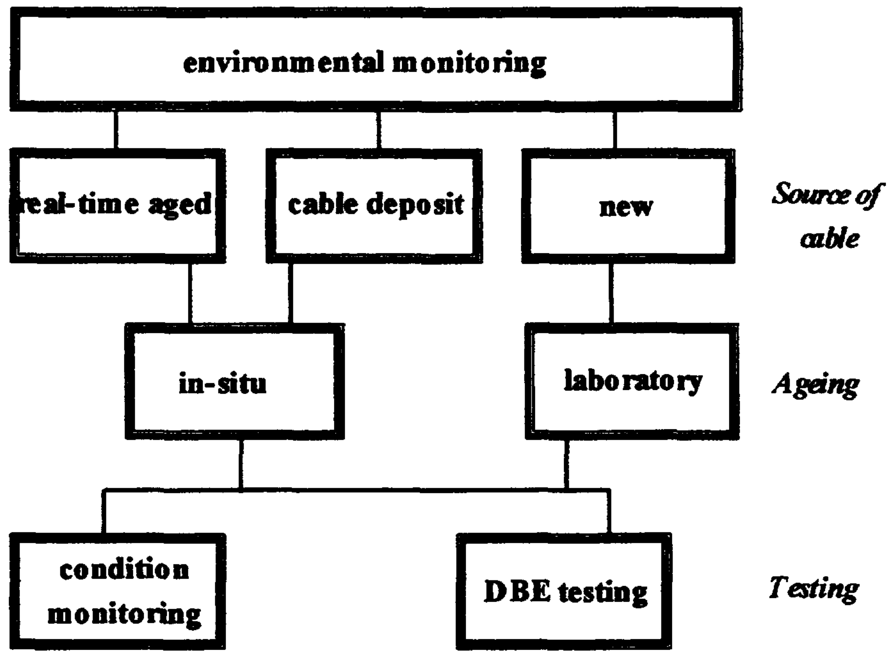


FIG. 1. The concept of ongoing qualification of cables.

3.2. ONGOING QUALIFICATION

Ongoing qualification is a repetitive procedure intended to overcome the concerns with using high acceleration factors and of qualifying for a long life. The principle is to start repetitive testing after a certain installed time, e.g. 10 to 15 years, and subsequently demonstrate continued qualification by repeated ageing and testing (with or without DBE). The procedure, if successful, is repeated until the cables are replaced, whatever the reason may be. Representative samples which have been submitted to realistic environmental conditions need to be obtained and condition-monitoring methods need to be defined.

The basic principles of ongoing qualification are shown in Figure 1. Underpinning all of the procedures is the requirement for environmental monitoring in the plant to obtain a detailed knowledge of temperature, radiation dose rate, humidity etc. in areas of the plant where safety related cables are positioned. Environmental monitoring is discussed in more detail in Section 3.2.2.

Cable samples used for ongoing qualification programmes can come from a number of sources. They may be unaged new cable, from a cable deposit in the plant or from real-time aged cables. The ageing of cables in such programmes is dependent on the source of sample and can be in-situ or in the laboratory. Suitable ageing methods for ongoing qualification are described in more detail in Section 4 and methods for cable condition monitoring are explained in Section 5.

3.2.1. Ongoing qualification procedures

The principle of ongoing qualification is to establish qualification for a relatively short qualified life (typically 10 to 15 years) at the initial qualification, and to extend the qualification by repeated accelerated ageing and DBE testing at the end of the initially established qualified life. By limiting the qualified life, lower acceleration factors can be used in the ageing tests, giving a more realistic simulation of service conditions [19].

Before the end of the initially established qualified life, representative samples of the installed cables are taken out of containment and subjected to accelerated ageing followed by a DBE test. The ageing is again designed to qualify for a limited life , e.g. 7 to 10 years. The cable samples can be from a cable deposit, from installed cables or possibly from long term laboratory tests. If the results of the testing are successful, then the qualified life of the cables is extended.

This procedure is repeated at the end of the extended qualified life and, if successful, the qualified life is again extended. This procedure is repeated until the tests show that the qualified life cannot be extended, or the installed cables are replaced for other reasons, or the power plant is shut down.

Testing of cables during ongoing qualification should include a range of monitoring methods for assessing cable degradation, as well as the DBE testing. The main techniques which can be used for assessing cable degradation are described in Section 5.

3.2.2. Environmental monitoring in the nuclear power plant

A major prerequisite for the implementation of all methods (including those described in Section 4) is specific knowledge of the environmental conditions within the plant. In particular, the radiation dose and temperature distribution at the relevant cable positions inside the containment needs to be known. For some plants, it is also necessary to assess the humidity levels.

Radiation dose distribution inside the containment based on existing calculations may be used for initial assessment. However, it is not advisable to use calculated doses for evaluation of the long term cable resistance. Because of the complex geometric arrangement of the various radiation sources and the wide variety of cable routing systems employed in the containment, calculations can only be performed for a few real positions. In order to obtain as much specific information as possible about the actual radiation dose and its distribution at real cable positions, dosimetry should be given preference over calculations.

Alanine dosimeters have proven to be particularly suitable for long term dose measurements in plant for the following reasons:

- they are not significantly affected by temperature (0.2%/K)
- their fading at moderate temperatures is limited to 1% per year
- the influence of humidity can be overcome by hermetic sealing of the dosimeter
- the neutron dose to cable materials can be neglected during normal plant operation.

Detailed recommendations for dosimetry can be found in Ref. [12] and details about alanine dosimeters and their temperature dependence can be found in Ref. [13]. A sufficiently detailed knowledge of the dose rate distribution in the plant can be made with the aid of dosimeters installed at the most exposed and other representative cable positions. In order to improve the validity of such measurements, it is recommended that the measurement period should be extended to cover at least two operating cycles.

For ambient temperature measurements it may be important to protect the temperature sensor from thermal radiation. In positions where thermal radiation can be expected from surrounding heat sources, it may also be important to measure the surface temperature of cables. The surface temperature measurement elements then need to be shielded from the heat source. Surface temperatures can also be established by the use of IR measurement techniques, including thermal imaging.

3.2.3. Limitations of ongoing qualification methodology

Ongoing qualification can be applied to all types of cable materials. The main requirement is to ensure that the cable samples used for re-qualification are representative of the most severe conditions in the plant. The methodology is mainly suitable for new power plants or for new cable installations in older power plants. It can also be applied to older plants, provided installed cables can be removed for testing and replaced by identical, unaged cables.

Ongoing qualification need not affect plant operation since samples are required for testing at relatively long time intervals which can be scheduled into normal maintenance periods. The timing should be such that the qualified life of the cables being tested covers the next planned maintenance so that any cables which fail the extended test can be replaced within their qualified life.

4. SAMPLING AND LABORATORY AGEING METHODS FOR ONGOING QUALIFICATION

In the course of long term research programmes and the commercial testing of cables in various countries, a number of methods have been developed and tested for examination of the long term degradation behaviour and accident resistance of cables. These methods include:

- cable deposits in nuclear power plants
- sampling from in-service cables in nuclear power plants
- laboratory methods based on accelerated testing.

The following sections cover the methods of assessing the ageing of polymer-based cable materials which are in current use in different countries. Each section discusses the basic methodology, the range of application of the technique, the degree of reliability, limitations, the effect on plant operation, regulatory aspects and relative cost of implementation.

4.1. CABLE DEPOSITS

The basic idea of analyzing the long term properties of in-containment cables by means of ongoing tests is not new. One of the advantages of cable deposits is that the cables age under real plant conditions but can, nevertheless, be checked and monitored.

4.1.1. Selection and installation of a deposit

It is important that the dose rate distribution in the NPP is known so that it can be used to select a position within the plant that is exposed to a higher dose rate than the real cable positions. It may even be possible to find a location where the ambient temperature is also similar to the design temperature (generally of the order of 50°C). Experience has shown that the loop line between the reactor pressure vessel and the steam generator is suitable for this purpose in pressurized water reactors and the reactor water cleanup system is suitable in boiling water reactors. In pressurized water reactors, the dose rate at this position is 1.3 to 1.5 times higher than the values prevailing at the most exposed cable positions.

If the cable samples are carefully arranged (e.g. if they are kept at a constant distance from the loop line as radiation source), the samples in the deposit are exposed to a homogeneous radiation field (Figure 2). The design of the deposit can easily be adapted to the local conditions in the power plant.

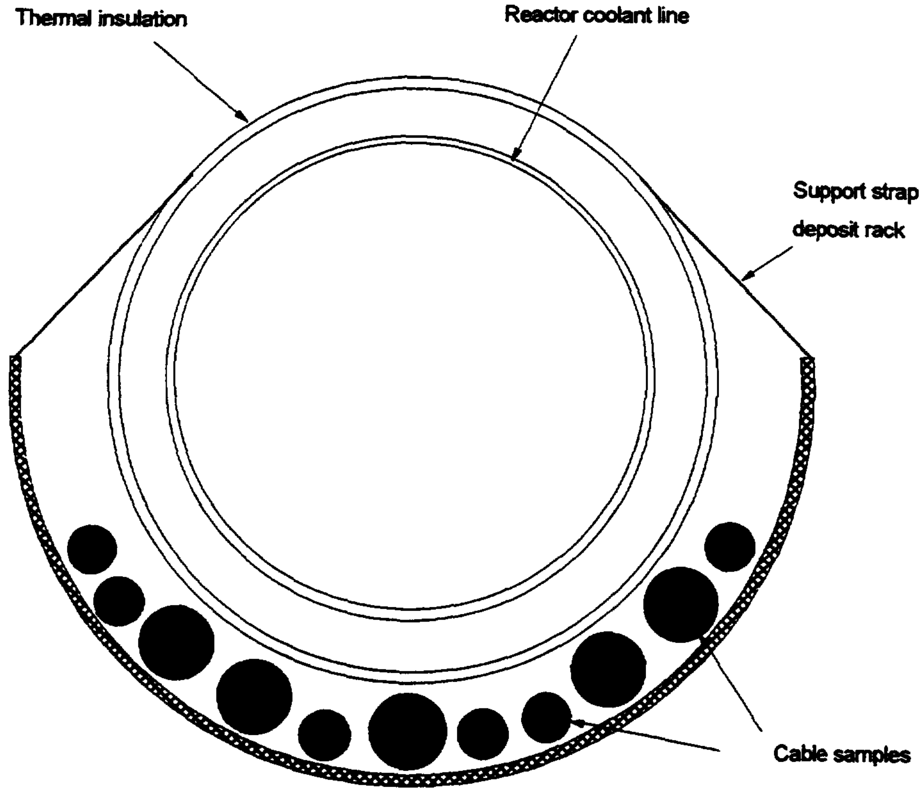


FIG. 2. Schematic cross-section of cable deposit layout around PWR coolant line.

The deposit should be equipped with a comprehensive selection of cables which are typical representatives of the types used in containment. The number of samples and their total length must also be analyzed in detail to ensure that enough material is available for the scheduled and unscheduled removal of samples to cover a period of up to 40 years. In this respect, the intervals at which samples are to be removed and the kinds of tests to be performed are of major importance. The following values can be used as standard: Samples of about 30 cm in length are quite satisfactory for measurements of elongation at break and, possibly, tensile strength in an irradiated condition. However, a minimum length of between 2 and 3 m is required for a DBE test with all electrical measurements.

The cable deposit is fitted with dosimeters to record and track the exact profile of the integrated radiation dose in the cable deposit. Care must also be taken to ensure that there is a free flow of oxygen into the deposit. Suitable contamination protection is desirable but must not restrict oxygen access.

4.1.2. Test procedures

First, it is essential to determine the elongation at break using a new (unaged) cable as reference. At intervals, samples are removed from the cable deposit and prepared for examinations and tests in a suitable test laboratory. The tests to be performed always consist of a sequence of the following steps:

(a) First, a measurement is made of the elongation at break of each sample.
(b) Then, the actual DBE resistance of the sample is determined.
(c) On completion of the DBE test, the elongation at break is measured again.

In order to simplify testing and conserve the supply of sample material in the deposit, the actual DBE resistance is initially examined using a modified DBE test which is referred to as the "steam test" in order to distinguish it more clearly. As long as the elongation at break determined in Step (a) is more than half of the elongation at break in the new condition (half-value dose still not reached), an approximately 30 cm long cable sample is exposed to the specified DBE temperature, pressure and moisture conditions. Electrical measurements are not performed during this test. The complete DBE test with all the normal electrical measurements is only performed when the half-value dose is exceeded. The results of Steps (a) to (c) must be recorded.

4.1.3. Determination of the sampling times and the deposit lead time

The determination of the sampling times can best be explained with the aid of the schematic diagram presented in Figure 3. In the upper section, the accelerated dose in the cable deposit (solid line) is compared with the dose at the most exposed real cable position (dotted line) as a function of time. The data for this graph are obtained from the dosimetry results for real positions and the cable deposit.

The results of the elongation at break test obtained from the cable deposit samples are plotted over the same time scale in the lower section of Figure 3 (solid line). Assuming that there is no significant dose rate effect, the elongation values determined from the cable deposit can be shifted by the lead times (t_{v1}, t_{v2} ..., etc.) to determine the variation in elongation values with time for cables in the rest of the plant. The specific test procedures used will be determined by the elongation values measured on the cable samples taken from the deposit, as discussed in Section 4.1.2. Since the acceleration factor for the cable deposit is small relative to installed cables, dose rate effects are likely to be insignificant.

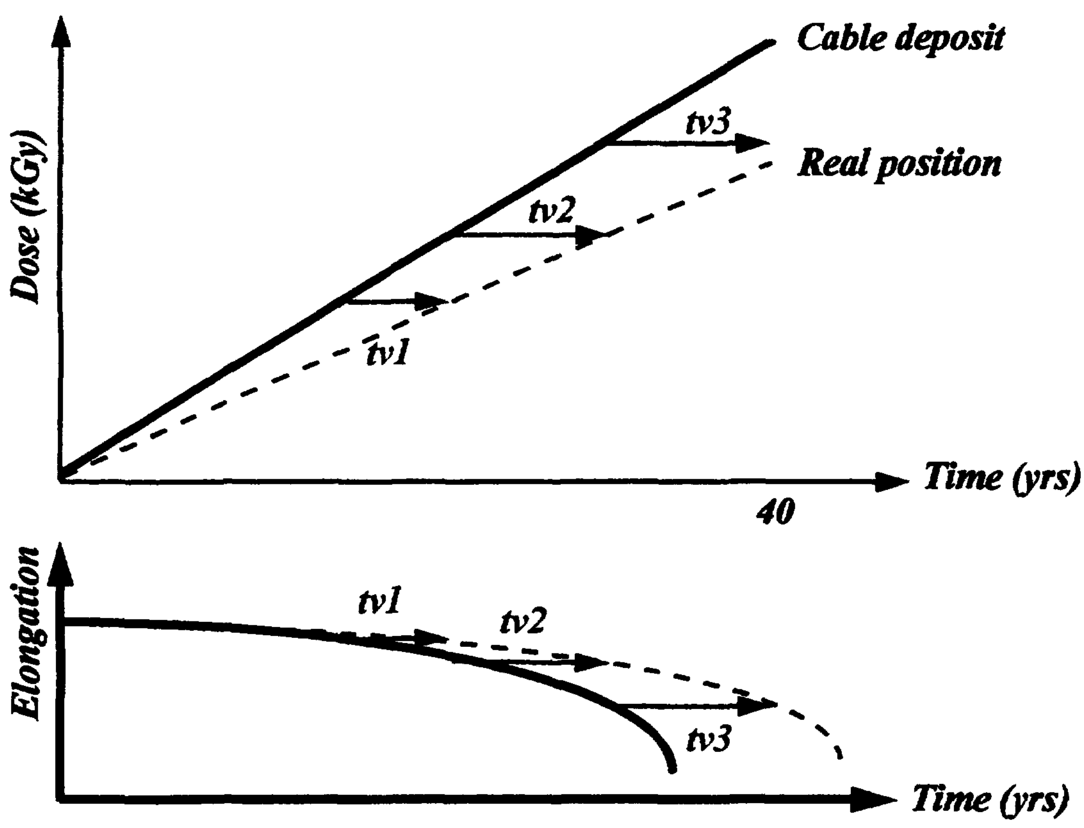


FIG. 3. Cable deposit methodology: determination of lead times for a cable deposit.

For the types of cable currently in use, the first samples from the deposit could be removed five years after the start of plant operation since the type and qualification tests that have already been performed provide an acceptable confidence interval for this period at the least. The determination of further sampling times is dependent on the lead time of the cable deposit, as shown in the upper section of Figure 3, and changes in the test results. As long as the results show little change in elongation, resampling would seem to be sensible after another two to three years. If there is any deterioration in the test results, especially after the DBE test, it may be necessary to shorten the sampling interval accordingly.

4.1.4. Range of application

The above description assumes the most favourable case, namely, the installation of a deposit prior to or within 5 years of commissioning of the power plant. The conditions that are encountered in practice, however, may require modifications. For instance, a deposit can also be installed in a plant that is more than 5 years old. For this purpose, the cable samples to be placed in the deposit must be artificially aged in the laboratory with the lowest possible dose rate in order to attain the necessary lead time. Details of suitable laboratory ageing methods are given in Section 4.3.

The cable deposit methodology is not restricted to particular types of cables or materials. The ongoing nature of a cable deposit programme means that the predictive information is relatively reliable, subject to changes in the environmental conditions in the plant.

A well-designed cable deposit should not affect the operation of the plant, although access to samples in practice would be restricted to normal maintenance outages. The type of cable deposit programme described in this section can be used to satisfy regulatory requirements, e.g. various sections of the German KTA 3706 rule.

4.1.5. Cost of cable deposit methodology

The cost of initially setting up the cable deposit, maintaining unaged material and periodic testing (including DBE) will be relatively high compared with initial qualification testing. The increased reliability of lifetime prediction would, however, be particularly valuable, if the plant operators are aiming for life extension beyond 40 years.

4.2. SAMPLING OF REAL-TIME AGED CABLE

The cable deposit method described in the previous section is primarily suitable for new nuclear power plants. Because of the radiological lead time of a cable deposit, its installation after plant commissioning, is still a viable and acceptable proposition up to about 5 years after commissioning, when it should be possible to catch up with the actual radiation dose of the cables at real positions.

After this time, however, an alternative is to evaluate the actual long term resistance by removing cable samples from the plant. The disadvantages of this sampling procedure are that it constitutes an intervention into the plant and that the samples have to be replaced accordingly. In addition, removal of samples may damage other cables adjacent to the cables sampled. However, it may be necessary to resort to this method if, for special reasons, validated results are required within a short time (e.g. for old plants).

4.2.1. Test procedures

As in the cable deposit method, environmental monitoring of temperature and dose rate within the plant is a prerequisite (see Section 3.2.2). Once the dose distribution is known, a cable position can be selected in the NPP which, on account of its exposure, has a higher dose than most of the other cables. In practice, such positions are usually in the direct vicinity of the loop lines (PWR) or in the reactor water cleanup system (BWR).

Cable samples from real positions (such as, for instance, a cable loop converging on the loop line) are normally irradiated quite inhomogeneously. Before removing the cable from the plant, the local geometry must be observed and the cable sample must be identified clearly in a reproducible manner to allow later test results to be interpreted correctly in terms of the actual radiation dose received.

Performance of the appropriate tests and examinations, determination of the sampling times for further specimens and verification of the test interval are all based on the procedures explained in Section 4.1 for the cable deposit method.

In order to use this method for ongoing qualification, cable samples have to be taken repeatedly from the power plant, a further disadvantage. The problem is whether it will be possible to find additional samples whose ageing behaviour is identical or similar to that of the first sample. In PWR plants, for instance, appropriate identical cable positions are located in the vicinity of the various loop lines. Test programmes of this type have been performed in a number of plants.

4.2.2. Range of application

Sampling of real-time aged cable from plant is most appropriate for older NPPs, where it is not feasible to use a cable deposit and where unaged material is unavailable. The methodology can be applied to any of the cable types or materials. Careful selection of the locations within the plant for sampling will give some lead time over the majority of cables in the plant, but the data are not likely to be as reliable as those obtained from a well-designed cable deposit.

4.2.3. Relative cost

Overall costs will be similar to those of the cable deposit methodology. Replacement of cables which have been removed for testing will require the use of qualified cables, subject to regulatory requirements. Testing of real cable samples will be similar to that of cable deposit samples, eventhough it may not be feasible to sample as frequently.

4.3. LABORATORY AGEING OF NEW CABLES

To be of practical use in assessing the operational behaviour of cables in NPPs, laboratory ageing aims to mimic the type of degradation observed under operational conditions. Conditions of testing therefore need to be carefully chosen to ensure that the degradation mechanisms occurring in the accelerated tests are similar to those which occur in service. In particular, the effect of oxygen on the degradation process must be taken into account. Where service conditions are characterized by low dose rates at moderate temperatures, degradation in most of the polymers of interest to cables will be dominated by homogeneous oxidation through the thickness of the material. Therefore, accelerated test conditions must ensure that the dose rates used are low enough for homogeneous oxidation to occur also in the test samples. Similarly, excessively high temperatures in accelerated testing can also significantly affect degradation mechanisms and render such testing unrepresentative of service conditions. Test temperatures must therefore be chosen at such levels so as not to cause significant melting of the crystalline fraction of semi-crystalline polymers, such as PE, and checks made that the temperature is below that at which rapid degradation occurs in unaged material. DSC (differential scanning calorimetry) can be used to assess suitable temperature regimes for accelerated testing.

4.3.1. Basic methodology

Several methods are used for the prediction of thermal and radiation ageing behaviour of polymeric materials through accelerated laboratory testing. The most commonly used method for accelerated thermal ageing is the application of the Arrhenius equation, describing the relationship between rate of degradation, the ageing temperature and the duration of exposure. There is a large body of experience in the use of the Arrhenius relationship for thermal degradation in cable materials.

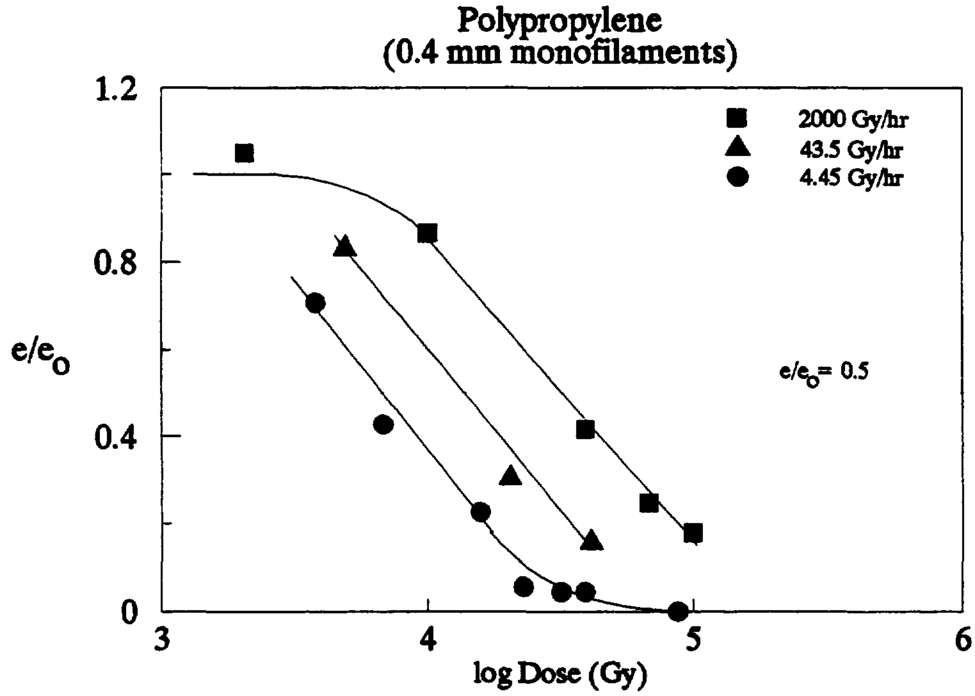
Turning to ageing by radiation, four basic methods of predicting the radiation ageing behaviour of cable materials have been developed in recent years, based on laboratory ageing test. These are:

- the power law extrapolation method
- the superposition of time dependent data
- the superposition of dose to equivalent damage (DED) data
- the kinetic model.

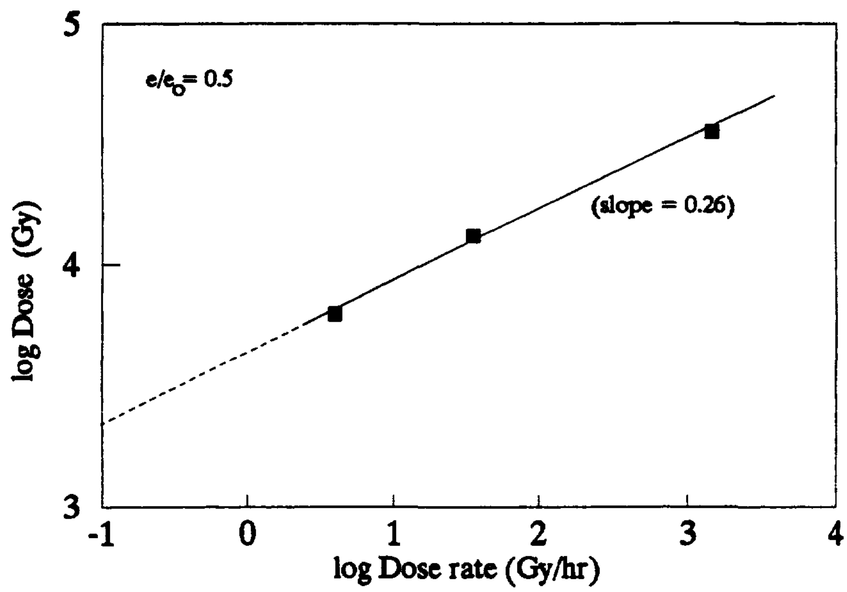
The detailed methodology for using these techniques is described in Refs [14] and [15]. All of the methods utilize data on changes in elongation at break as a function of ageing time under accelerated test conditions, by applying higher dose rates and/or higher temperatures than are normally seen under service conditions. In each of the methods, it is emphasized that care must be taken to ensure homogeneous oxidation conditions when assessing the results. The methods differ mainly in the amount of data required for predicting the behaviour of cable materials and in the way the test data are extrapolated to the service conditions.

The power law extrapolation method utilises data obtained at a single temperature over several dose rates [14]. The DED values are assessed at each of the test conditions and plotted as a function of log DED against log dose rate. Typical DED values for evaluation could be $e/e_0 = 0.5$ or $e = 50\%$ absolute. This plot is linear in a number of polymers, particularly polyolefins, enabling an extrapolation to be made of the predicted DED at lower dose rates. An example of the application of this method on polypropylene is shown in Figure 4 using DED values for $e/e_0 = 0.5$ [14]. Note that the IEC 544 standard for radiation testing [11] recommends the use of $e/e_0 = 0.5$ as the failure criterion.

The method based on superposition of time dependent data uses data on elongation obtained as a function of time in a range of combined temperature/dose rate conditions. The method relies on superposition of the elongation against log time data at each of the test conditions to yield a master curve [14]. The shift parameters required to form this master curve are found to be related to the test temperature and dose rate by a semi-empirical equation which has been verified for a number of cable materials. The equation can then be used to calculate the shift factors for the master curve of elongation against time at temperatures and dose rates appropriate to service conditions. An example of the use of this method is shown in Figure 5 for an EVA material, showing the calculated DED values for $e/e_0 = 0.5$ compared with experimental data [14].



Elongation at break of polypropylene
- irradiated in air



Extrapolation of end-point dose from data above

FIG. 4. Example of use of the power law extrapolation method.

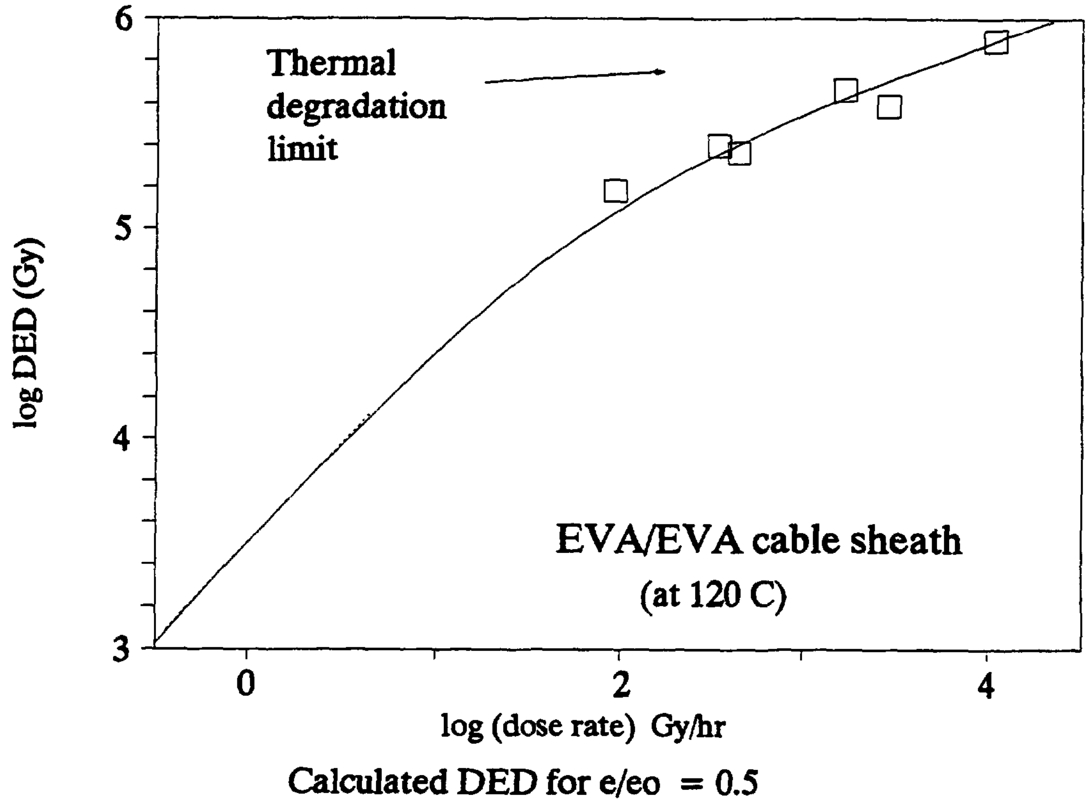


FIG. 5. Example of use of the superposition of time dependent data method.

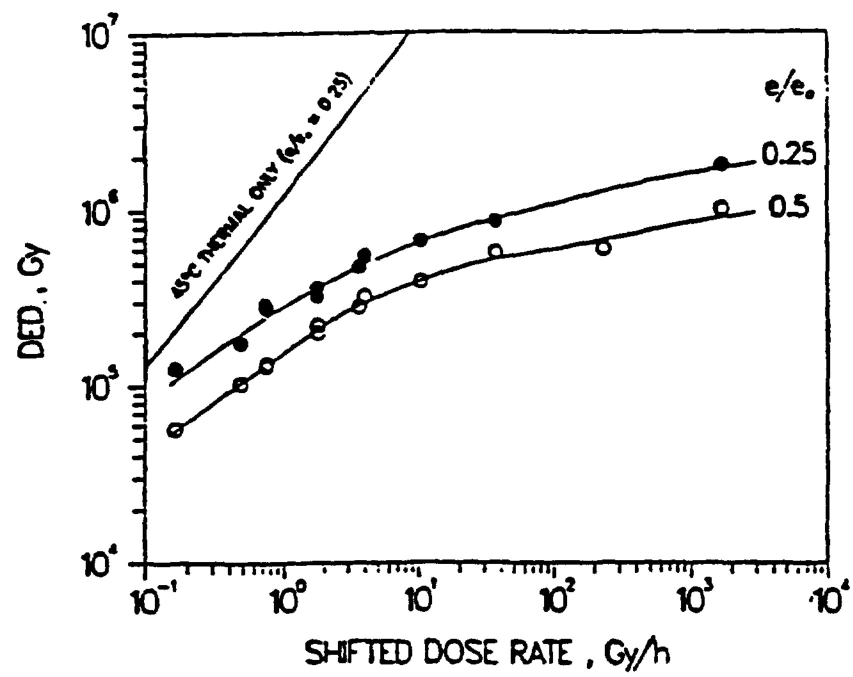


FIG. 6. Example of use of superposition of DED data method.

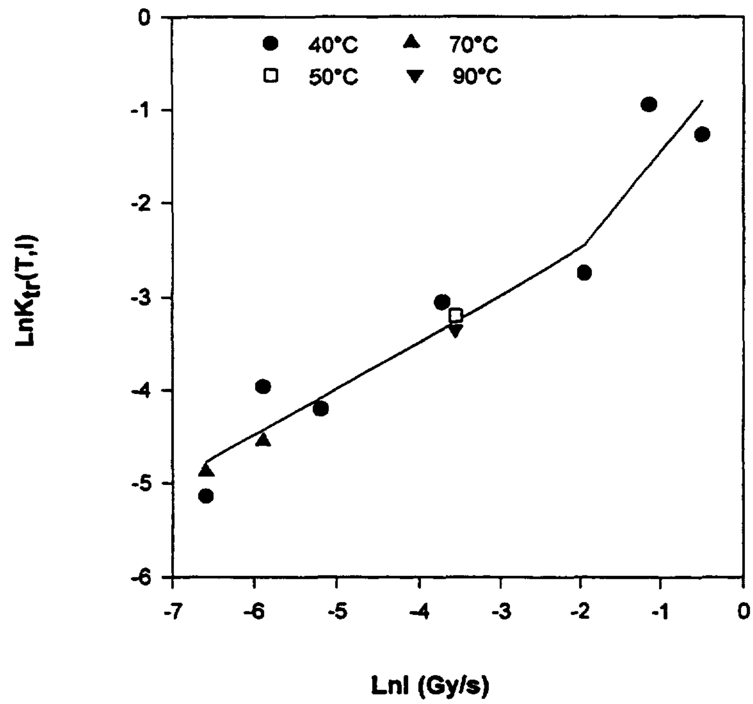


FIG. 7. Example of use of the kinetic modelling method.

The method based on superposition of DED data also utilizes data on elongation obtained at different temperatures and dose rates but calculates the DED values, for e/e_0= 0.5 typically, for each of the test conditions. These DED values are then plotted as log DED against log dose rate and the data superposed by using a shift factor determined by the Arrhenius relationship. In many cable materials, a single value of activation energy can be used in the Arrhenius equation to superpose all of the DED data. A practical example of this method is illustrated in Figure 6 for CSPE involving DED values of e/e_0 = 0.25 and 0.5 [14].

The kinetic modelling method based on Dakin's law also utilizes elongation data obtained in a range of temperature and dose rate conditions. Superposition of the data is obtained using equations based on the chemical kinetics of the degradation [15]. The analysis of the different rate constants (radiation, thermal, pressure etc.) allows to draw up a predominance diagram for the material. The combination of these approaches is useful in defining accelerated test procedures. Figure 7 shows an application of this method on an EPDM material, where the change in reaction rate for radiation ageing is plotted as a function of the radiation dose rate, demonstrating a change in the degradation mechanism at high dose rates [15].

4.3.2. Limitations of the methods

All of the methods are dependent on data being obtained at dose rates low enough for homogeneous oxidation to occur in the test samples and assume that the temperatures used do not span any physical transitions of the polymer, such as crystalline melting or glass transition. This means that the time-scales for carrying out testing are typically in the range of 6 to 18 months. Extrapolation to service time-scales of the order of decades is therefore likely to introduce significant errors in the prediction of lifetimes. However, such errors will be reduced if longer term testing programmes, which can verify the data trends, extend over a period of several years.

The power law extrapolation method can only be safely used for those service conditions where thermal degradation is insignificant compared with radiation-induced degradation. In practice, this limits the method to temperatures up to approximately 40°C, dependent on the polymer. The method has so far only been demonstrated to work satisfactorily on some polyolefins, but it may well have a wider application [14].

The superposition of time dependent data is only possible where the general shape of the elongation versus log time curve does not vary with changes in temperature and dose rate. This implies that all of the degradation mechanisms are equally accelerated by an increase in temperature or dose rate. This is generally the case when the degradation is dominated by a single mechanism (e.g. oxidation), as is the case with many of the commonly used cable materials. If more than one degradation process is significant in the temperature and dose rate range tested, then the curve shapes will not be the same and the data cannot be superposed. The method has been successfully applied to a range of polymers, including EVA, XLPE and EPR [14].

The superposition of DED data can be used even for those polymers which do not have one dominant degradation mechanism. The method does however require a large data set to obtain sufficient DED values for superposition to be carried out. It is not very successful in those materials which show little or no dose rate effect, but can generally be used on a wide range of materials [14].

The kinetic model can be applied to a range of materials, including EPR and EVA. The main limitation in its wider application is the extensive matrix of test data required [16].

At present, the laboratory ageing methods are aimed at predicting age-related degradation of cables arising from their normal operating conditions. These test programmes are not aimed at predicting the ability of the cables to survive a DBE test. Survivability in a DBE would need to be demonstrated by additional specific DBE testing after laboratory ageing.

4.3.3. Reliability and validation

The extrapolation techniques described above have been found to be valid when compared with real-time ageing of cables under service conditions up to approximately 12 years of service. Up to the present, no direct comparisons have been drawn between model predictions and real-time ageing over longer time spans, primarily because of the difficulty of obtaining identical unaged material for the accelerated tests in older NPPs.

4.3.4. Regulatory aspects

Cable life assessment using laboratory ageing does not affect plant operation since all measurements are conducted outside of the plant. As yet, regulatory bodies have not adequately assessed the potential of the various accelerated testing methods. In particular, the upper limit to the dose rate used in any form of accelerated testing needs to be more rigorously defined.

4.3.5. Relative costs

Accelerated testing of cables tends to be expensive because of the quantity of data required to apply the different methods. Of the methods outlined in Section 4.3.1, the power law extrapolation method requires the least data and is therefore the cheapest. The other methods based on superposition and kinetic modelling use data obtained under combined thermal/radiation ageing, which tends to be more expensive to obtain than data for irradiation at ambient temperature. The superposition of DED data tends to require slightly more data than that needed for the superposition of time dependent data. If DBE tests on aged cable are included in the test programmes, costs will be considerably higher.

4.4. COMBINATION OF METHODS

The methods described in Sections 4.1 to 4.3 all have a number of specific advantages and disadvantages. Which method is most suitable will be determined by the specific application in the plant. It is also possible to combine elements of these methods in different ways to offer flexible solutions which can be adapted to specific plant conditions. Figure 8 provides an indication of some of the types of combinations possible in practice.

The most common combinations of methods which are currently in use are:

- use of laboratory ageing to extend the lead time of cables from deposits or real samples
- use of laboratory ageing to provide the initial ageing to enable a cable deposit to be set up in an older NPP (>5 years operation)
- use of in-plant condition monitoring combined with predictive laboratory ageing data to obtain the correlation between degradation and monitoring parameters in real-time aged samples.

All of these are underpinned by a knowledge of the environmental conditions (temperature, radiation dose rate, humidity) within the plant.

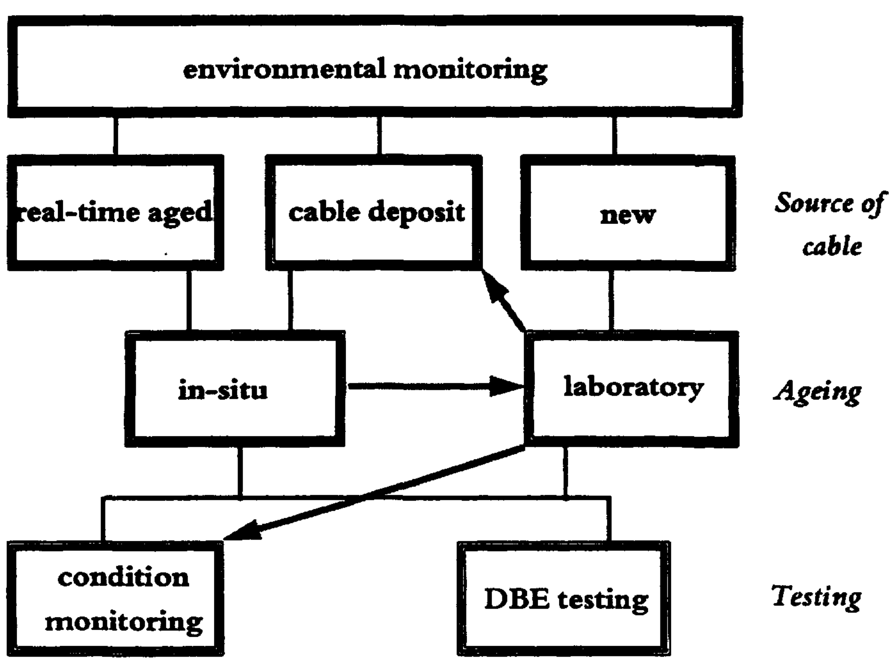


FIG. 8. Some of the combination of methods used in practical ongoing qualification programmes.

5. MONITORING AND TEST METHODS FOR ONGOING QUALIFICATION

5.1. CONDITION MONITORING METHODS

5.1.1. Condition monitoring requirements

There is a general consensus that there are as yet no definitive condition monitoring (CM) techniques available that can assess insulation degradation or predict remaining life, but there are a number of potentially useful CM methods. No one technique can measure degradation. A combination of tests would be required to provide an indication of degradation. For all the current CM techniques, baseline data are needed to make full use of the technique. As insulation embrittlement is the most definitive characteristic of low voltage insulation degradation, the baseline data and subsequent measurements should be related to elongation at break and electrical characteristics.

The desirable attributes of a condition monitoring technique can be broken down as follows:

1. non-destructive and non-intrusive
2. simple to use under field conditions
3. capable of being used during normal operation
4. does not require disconnection of equipment
5. property measured can be correlated with an identifiable failure criterion, such as elongation at break applicable to commonly used cable materials and configurations
6. capable of identifying "hot-spot" degradation
7. reproducible and capable of compensation for environmental conditions such as temperature and humidity
8. less expensive to implement than cable replacement.

In practice, no techniques are available which satisfy all of these requirements. Nonetheless, some of the most useful techniques currently available satisfy a majority of them.

5.1.2. Techniques available

Currently, there are only a few techniques applicable in-plant that have been or are being used for cable monitoring. Several techniques have shown promise in laboratory testing, but have not been reported as viable in-service techniques. Other strictly experimental methods are currently being evaluated in a laboratory setting. The methods can be grouped together under generic types and degree of development, as shown in Table I. This list is not exhaustive and new techniques are under development.

The most widely used CM techniques are:

- Indenter,
- Oxidation induction time (OIT),
- Dielectric loss,
- Time domain reflectometry (TDR),
- Paced test.

TABLE I. CABLE INSULATION CONDITION MONITORING METHODS

Method type	Condition indicator/ instrument	NPP tested	Remarks	Attributes (as defined in Section 5.1.1)
Pass / Fail tests	- dielectric strength - insulation resistance	yes yes	These tests do not indicate the gradual degradation of material. If proper ground is used, cracks in the insulation may be detected.	2, 6, 8, 9
"Local" test without sampling	- indenter	yes	Compressive modulus measured, correlation should be established to relate to elongation.	1, 2, 3, 4, 5[a], 6, 8[a], 9
	- near infrared spectrometer (NIR)	no	Procedure not developed for field use.	
	- torque testing	no	A Japanese technique. No laboratory or field data available.	
"Local" test with micro-sampling	- oxidation induction time/temperature (OIT)	yes	Not applicable to all materials. Useful for XLPE and EPR.	3, 4, 5, 6[a], 8, 9
	- Fourier transform infrared spectroscopy (FTIR)	yes	Not applicable to all materials. Useful for XLPE and EPR	3, 4, 5, 6[a], 8, 9
	- density	yes	Detailed correlation between density and elongation must be established.	3, 4, 6, 8, 9
	- plasticiser content	yes	Primarily used for PVC to assess thermal degradation.	3, 4, 5[b], 8 9
"Global" test with spatial resolution	- time domain reflectometry (TDR)	yes	Sensitive to damaged cables (cracks). Does not measure degradation due to ageing.	2, 5[a], 6, 7[a], 8, 9
	- partial discharge	no	Not useful for unshielded low voltage cables. Gradual degradation not detected.	
"Global" test without spatial resolution	- dielectric loss	yes	UK-AEA evaluating technique. Not proven to measure gradual degradation by other testing laboratories.	2, 5[a], 6, 9
	- time domain spectrometry (TDS)	no	Requires sophisticated equipment, at present limited to laboratory use.	
"Paced" test	- elongation at break	yes	Spare cables installed at hot-spot locations. Used by various organizations. Cables must be installed early in the plant's life.	5, 6, 8 ,9

[a] needs further R&D. [b] only for thermal ageing.

These tests are being used to a limited extent by the various utilities to assess cable degradation or detect potential cable faults (dielectric loss and TDR). None of these tests meet all of the desirable criteria listed in Section 5.1.1 (as indicated in the right-hand column of the table) and the CM area is wide open to further research and improvement. All of the CM methods listed in Table I are described in further detail in the literature mentioned in Ref. [17].

5.2. RANGE OF APPLICATION

Currently, there is no universal CM technique applicable to in-service cables. Utilities that are involved with CM use a variety of techniques, as no single technique can evaluate the different materials, cable configurations and provide accessibility to the cables. However, development work on practical CM techniques is in progress in several countries and considerable improvement is expected within the next few years.

The most widely used technique is the indenter, a portable device which is not excessively expensive. At present, two units are available in Canada and several units are in use in the USA and Europe. However, some serious difficulties arise with the indenter. In the majority of cables, only the jacket properties can be measured and the results must be related to the insulation. Some materials such as the polyolefins do not provide a good ageing trend as the compressive modulus does not change significantly with ageing. However, where there is a relationship between the indenter values and other tests (e.g. elongation, plasticiser content) the technique has proved useful [18].

The other fairly extensively used technique is the oxidation induction time (OIT). This technique requires access to the cable insulation and requires the physical removal of a small specimen. Practical methods have been developed for removal of samples in-plant without compromising cable integrity. The OIT technique has been demonstrated to be useful for a range of polymers, particularly for XLPE and EPR.

Equipment to perform time domain reflectometry (TDR) is commercially available and has been used in power plants as a troubleshooting technique to identify defective splices, connections, and damaged cables. However, there is no definitive data to show that TDR can monitor ageing degradation of long cables, especially, long unshielded cables.

The dielectric loss technique appears promising for a range of polymers used in cable insulation. The equipment is portable and fairly simple to use, compared with other electrical CM techniques. However, at present, very little data is available in the public domain to determine whether the technique can detect ageing degradation in-plant.

The paced test (or cable deposit) can be one of the most useful CM techniques. However, sacrificial cables must be installed early in the plant's life at locations where the service conditions are harsher than those which prevail around the majority of the plant's safety related cables. Under this procedure, periodic removal of cable samples is carried out over the lifetime of the plant, and test data are compared with the test results obtained for the new cables originally installed.

6. CONCLUSIONS

Few problems have been reported to date with cables in normal operations of nuclear power plants. Where problems have been reported, they have generally been limited to local degradation related to higher than average temperatures or dose rates. For this reason, environmental monitoring of temperatures and dose rates is important, as it allows to pinpoint these localised areas.

However, relatively few plants have yet initiated assessment of cable degradation in terms of DBE and post-DBE survival. Where such work has been carried out, there have been instances where cables which had initially been qualified for a 40 year life failed a DBE test after removal from the plant after less than 10 years of normal operation. This experience has raised questions as to the validity of qualification procedures. Currently, no method of conducting short term tests has been demonstrated to be capable of definitively predicting a 40 year lifetime and survivability in a DBE.

The CRP suggests that initial qualification should be supplemented by ongoing qualification procedures and environmental monitoring to provide additional assurance of the safety state of cables inside containment. This report has highlighted various practical ongoing qualification and condition monitoring procedures that can be applied in-plant. Work is still required in this area, and specifically to correlate condition monitoring techniques with survivability in a DBE.

7. RECOMMENDATIONS FOR FURTHER WORK

The current CRP has highlighted some of the uncertainties concerning qualification of I&C cables used in containment. Resolution of these uncertainties would be an appropriate task for a Phase II CRP. The following outline of such a programme is suggested.

7.1. OBJECTIVES OF PHASE 2 CRP

To resolve the uncertainties in the relationship between cable monitoring techniques and DBE survivability and improve existing initial qualification procedures, and thus to provide a technical basis for the assessment and management of ageing of in-containment cables based on the concepts developed in Phase 1 CRP.

7.2. SCOPE OF PHASE 2 CRP

The following topics need to be addressed:

- review and improvement of initial qualification procedures,
- collection of practical experience in the use of in-plant CM techniques,
- validation and correlation of the most promising CM techniques with survivability of a DBE,
- application of additional practical experience in ongoing qualification to make specific recommendations on optimum procedures.

7.3. OUTLINE OF WORK FOR PHASE 2 CRP

The following tasks are linked and not entirely separate:

a. Review initial qualification methods and make recommendations to adapt them to be used as the first step in an ongoing qualification programme. It is essential that the CM parameters used for ongoing qualification are identified and measured during initial qualification procedures.

b. Select practical CM techniques for use in ongoing qualification programmes, based on in-plant experience, validation of techniques against degradation, and correlation with survivability in a DBE.

c. Document results of Phase 2 CRP in a report providing a technical basis for the assessment and management of ageing of in-containment cables though an environmental qualification programme consisting of initial qualification supplemented, as appropriate, by environmental and condition monitoring to ensure required functional capability of cables throughout their installed life.

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Research Co-ordinating Meetings

Vienna, Austria, 6–8 December 1993

Erlangen, Germany, 7–10 November 1994

Bariloche, Argentina, 16–20 October 1995