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ASSESSING AND MANAGING CABLE AGEING IN NUCLEAR POWER PLANTS

IAEA NUCLEAR ENERGY SERIES No. NP-T-3.6

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property." The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

This report was prepared based on the recommendation of the IAEA Technical Working Group on Nuclear Power Plant Instrumentation and Control (TWG-NPPIC), which recognized the need to update certain existing IAEA publications to reflect the technical advances of the past 25 years and, at the same time, to provide guidelines on establishing cable ageing monitoring programmes in new nuclear power plants.

It is known that instrumentation and control (I&C) cables with safety functions and cables ensuring a power plant's availability can degrade during their installed life due to the ageing effect of environmental stressors such as temperature, radiation, moisture and vibration. The continued ability of I&C cables to fulfil their intended function therefore requires various condition monitoring techniques. Such techniques can potentially be used to estimate the remaining lifetime based on the relationship between condition indicators and ageing stressors, and hence support a preventive and effective ageing management programme.

This report relies on previously developed standardization publications and other relevant literature, which are dedicated to the qualification and ageing management of I&C and other low voltage cables in nuclear power plants. It is aimed at I&C and low voltage power cables (<600 V), but some methods may be applicable to medium voltage cables (up to 1.5 kV). It is intended as a road map for the establishment of a procurement arrangement and subsequent ageing management plan, and hence supports any authority wishing to install, maintain and utilize I&C cables for safety relevant functions in a nuclear power plant. As a stand-alone report, it provides general concepts and guidelines for EQ procedures as part of a procurement process, which is complemented by an ageing management and condition monitoring (CM) programme for a safety oriented, long term operation plan.

Some specific recommendations have been made concerning the pre-ageing and design basis accident phases of a qualification test. These recommendations are aimed at significantly reducing the uncertainties that have been identified. A broad range of CM techniques that could potentially be used in a cable ageing management programme are outlined, including several new techniques that are currently under development.

The intended readership covers all stakeholders in the nuclear field including utilities, licensing and regulatory organizations, design and engineering companies, component manufacturers and test laboratories, as well as countries embarking on nuclear power plant projects.

This report was produced by a committee of international experts and advisors from 18 countries. The chairpersons of the report preparation meetings were T. Koshy (USA) and S. Burnay (United Kingdom). The IAEA wishes to thank all of the participants and their Member States for their valuable contributions. The IAEA officer responsible for this report was O. Glöckler of the Division of Nuclear Power.

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1. INTRODUCTION

1.1. BACKGROUND

Given the growing need for sustainable energy to support current and future energy needs, it is expected that nuclear power plants (NPPs) will operate longer, and that more countries will adopt a nuclear programme in the future since nuclear energy is an acknowledged part of a balanced energy mix.

The current design life of NPPs could potentially be extended to 80 years. During this extended plant life, all safety and operationally relevant instrumentation and control (I&C) systems are required to meet their designed performance requirements to ensure safe and reliable operation of the NPP during both normal operation as well as during and subsequent to design basis accidents (DBAs). This in turn requires an adequate qualification and ageing management programme that also identifies the responsibilities of all stakeholders and is duly documented in a way that can be reviewed and utilized by qualified personnel and decision makers.

The IAEA Technical Working Group on Nuclear Power Plant Instrumentation and Control (TWG-NPPIC) has also recognized that the IAEA reports published earlier need to be updated to reflect the technical advances of the past 15 years while at the same time providing guidelines to establish cable ageing monitoring programmes, particularly at new NPPs.

1.2. OBJECTIVE

The objective of this report is to provide general guidelines for cable qualification and cable ageing management at nuclear facilities. The main focus will be on I&C and low voltage power cables (<600 V), but some methods may be applicable to medium voltage cables (up to 1.5 kV) as well. It builds upon IAEA-TECDOC-1188 [1] and provides guidelines not only for the existing fleets of reactors but also for the new generation of plants and newcomer countries starting to produce nuclear power for the first time. IAEA-TECDOC-1188 was first drafted in the late 1990s through a coordinated research project (CRP) that ran for more than five years. The document was published in the year 2000 with the title "Assessment and Management of Ageing of Major Nuclear Plant Components Important to Safety: In Containment Instrumentation and Control Cables".

Significant research and operating experience has been gathered since the mid 1990s to warrant a new IAEA document in this area. As such, this document reflects all that has come to light with respect to cable qualification, performance monitoring and ageing management. In particular, plant life extension and licensing renewal activities over the last ten years have given rise to concerns in the nuclear industry and regulatory authorities over the performance of cables, especially those that are expected to help mitigate the potential consequences of a design basis accident. Typically, NPPs were licenced to operate for up to 40 years. This is now changing to 60 or possibly even 80 years, raising questions as to whether or not cables can be left in service for longer periods than originally planned. Fortunately, new techniques have been developed to help the nuclear industry determine the condition of cables and verify whether important cables are still reliable or whether they need to be replaced. In addition, much more is now known about the behaviour of cables in both normal and harsh conditions. These developments are reflected in this document in three distinct areas as follows:

— Qualification processes, including pre-installation laboratory qualification testing as well as post-installation measures to verify adequate cable performance while the plant is operating and in case of DBA;
— Cable life extension in support of the current and future licence renewal activities, which call for existing NPPs to operate for up to 80 years or more;
— Cable CM involving methods that can be used to determine the performance of cable insulation material or try to identify problems in cable conductors.

It should be pointed out that the main focus of this report is on the management of ageing of cable insulation material. However, the conductors, connectors, splices, penetrations and end devices that are collectively referred to as the cabling system are also addressed to some extent in this report, and methods that can be used to test them are included in the section on CM techniques. Some of the electrical methods that are available for testing of cabling systems can also offer an indication of the condition of cable insulation material as described in the body of this report.

1.3. SCOPE

This report has been prepared for a general technical audience with an engineering or managerial background who are interested in learning more about ageing of cables in NPPs, as well as for the cable experts who can benefit from the comprehensive collection of the most relevant references and techniques used in the cable ageing field.

The report also contains introductory level materials that present a summary of key issues in cable ageing at NPPs, and it can be used as teaching materials for training courses and workshops.

Newcomer countries embarking on NPP projects can also benefit from the report by learning the necessary conditions and requirements for setting up a cable ageing monitoring and cable qualification programme at an early stage of the NPP operation.

In summary, the primary target audiences are:

— Technical experts at nuclear utilities;
— Decision makers at regulatory authorities and utilities;
— Research and development organizations;
— Manufacturers and vendor companies;
— New users in newcomer countries.

1.4. STRUCTURE

This report is broken down into sections, followed by additional material such as references, a glossary and detailed background material provided in the Annex. Section 2 introduces the basic concepts of testing, monitoring and qualification of cables. Sections 3 and 4 discuss the following areas in detail:

— Condition based qualification of cables;
— Monitoring the condition of cables and their environment;
— Cable testing methods.

The remaining sections cover the areas of quality assurance, cable ageing monitoring programmes in connection with life extension and recommended practices.

2. OVERVIEW OF TECHNICAL ISSUES IMPORTANT IN CABLE AGEING MANAGEMENT

2.1. BACKGROUND

Currently, the nuclear industry depends mostly on manufacturers' qualification data to ensure adequate cable performance, and very little testing is performed to verify that cables remain reliable for long term service, except for cable troubleshooting with the purpose of locating and solving problems in conductors, connectors and end devices. With plant life extension efforts currently under way, cable CM requirements are taking centre stage both at utilities and regulatory agencies.

In connection with plant life management/plant life extension (PLIM/PLEX), considerable research has been done to address the ageing of the reactor vessel and its internals, piping and civil structures. However, although cables are also very important to PLIM/PLEX, their ageing degradation can be monitored to ensure replacement before end-of-life. In the area of I&C, cables are one of the components of most concern for ageing management, especially in plants seeking licence renewal beyond 40 years. Fortunately, experience has shown that qualified cables that are sized properly for the application can typically serve for 40 years or more, provided that they are installed correctly and not exposed to higher than design basis environmental conditions.

2.2. PURPOSE OF QUALIFICATION

The purpose of environmental qualification (EQ) is to demonstrate that cables installed in an area that may be subject to a DBA can perform their expected safety functions throughout their qualified life. It is also necessary to evaluate cables in mild environments to identify whether any corrective action is required to prevent common mode failures that could lead to service interruptions and plant transients.

Cables installed in areas that are not subject to a DBA may not need to be qualified, provided that their serviceability under normal operating conditions is established based on appropriate standards and criteria.

2.3. SCOPE OF QUALIFICATION

The owner of the nuclear station is responsible for identifying the scope of the components and level of qualification required based on specific performance requirements. Typically, these would include equipment required for mitigation of an accident and prevention of radiation release as well as their supporting systems and post-accident monitoring instruments. Section 5.2 specifically discusses equipment located outside harsh environments. The report addresses cables in the 0–1.5 kV AC and 0–250 V DC voltage range with polymeric insulation.

2.4. EQUIPMENT CATEGORIES

The qualification of electrical equipment covers the seven areas listed below, and the electrical cables associated with each of the functions are briefly discussed for each of their respective categories.

Category 1. Equipment relied on for mitigating the effects of an accident (safety systems) that are subjected to the accident environment.

The equipment and associated cables that are relied on for the mitigation of an accident and are also subjected to the accident environment have to demonstrate that they are capable of operating during and after the worst case DBA. This is generally referred to as a harsh environment that significantly increases radiation, temperature, humidity, chemical effects etc. as a consequence of the accident. The performance expectation is significantly higher for these components because they are inaccessible for any corrective or preventive maintenance subsequent to the initiation of an accident.

Category 2. Equipment relied on for mitigating the effects of an accident (safety systems) that are not subjected to the accident environment.

This equipment and associated cables have relatively lesser performance requirements because they remain accessible for servicing subsequent to the DBA. They are safety systems but are not subjected to any significant change in their operating environment.

Category 3. Equipment necessary to prevent the release of radiation.

The third category of equipment and associated cables is generally only required to complete their active function (e.g. isolating the containment boundary or isolation of piping or other openings associated with an accident environment).

Category 4. Equipment that supports the systems necessary for accident mitigation.

The fourth category of equipment and associated cables provides supporting functions necessary for continued operation such as air supply, lubrication systems and service water for cooling, electric and hydraulic power.

Category 5. Post-accident monitoring instruments.

The fifth category of equipment and associated cables supports monitoring and gauging the potential for a containment breach or off-site release and provides necessary information for accident management and evacuation requirements. These instruments may need selective qualification based on their particular service.

Category 6. Equipment necessary for the normal operation of the plant.

The sixth category of equipment and associated cables is necessary for supporting power production, avoiding plant trips or transients.

Category 7. Equipment that can fail and mislead the operator during an accident.

The seventh category of cables and equipment needs to remain functional to prevent the provision of misleading information to the operator.

The EQ programme will address some safety and safety-related equipment in all categories except for equipment in Categories 2 and 6. This document will primarily discuss the qualification of equipment that is exposed to a design basis environment outside of the normal service environment; however, Section 5.2 specifically discusses equipment located outside harsh environments. The programme will address cables in the 0–1.5 kV AC and 0–250 V DC voltage range with polymeric insulation.

2.5. MILD AND HARSH ENVIRONMENTS

A mild environment would never be significantly more severe than the environment during normal plant operation, including anticipated operational events. The operating environment could include high radiation and temperature, exposure to moisture, submergence and various combinations of these environments. Mild environment areas are NPP locations that experience the effects of seismic events but whose environmental conditions do not significantly change as a result of a DBA.

A harsh environment is an environment resulting from a DBA, such as a loss of coolant accident (LOCA), high energy line break or main steam line break. The requirements (in terms of qualification and documentation) for equipment in harsh environments are more rigorous.

2.6. AREAS OF CONCERN

The nuclear industry has taken several approaches to qualifying equipment. The simplistic approach was to choose one sample and subject it to an EQ test. The EQ test on equipment and associated cables should have demonstrated reliability and availability to perform its respective functions. A test programme needs to consider the potential for common cause failures, including the effects of ageing and environmental conditions. The qualification process should clearly identify the duration of qualified life or the qualified condition, coupled with CM intervals and maintenance requirements.

Simulation of the effect of exposure to plant temperature conditions and the post-accident temperature conditions were based on the Arrhenius equation for accelerated ageing for a life of 40 years. The radiation ageing was based on the operational dose plus the accident dose, administered as a total integrated dose. The testing was conducted in sequence with either thermal ageing followed by radiation ageing or vice versa. Based on the successful test results, the equipment was considered qualified for 40 years, and no CM was required. These test results were then used to extrapolate the known margins for extending the life for an additional ten years or more.

As a better understanding of the ageing behaviour of polymeric materials has been developed, concerns have been raised over the original approach to qualification. Annex A–1 gives a brief summary of the ageing mechanisms in polymeric cable materials and the effects of accelerated ageing versus operational ageing that are relevant to the qualification process.

2.6.1. Margins

The margins used in the original test protocol were originally intended for addressing manufacturing and measuring tolerances when using a single specimen or a limited number of specimens. However, the margins have in the past been incorrectly used to account for several of the following concerns:

(1) When sequential testing was found to have non-conservatism, the margins were considered to be a solution.
(2) The activation energy values used in the Arrhenius equation covered a wide range of values that could lead to inaccurate results in thermal ageing.
(3) Degradation of polymeric cable materials is primarily an oxidation process, therefore any restriction on the availability of oxygen will alter the observed ageing degradation. The small LOCA test chambers may become oxygen starved within a few hours of the test, and that in turn can reduce further degradation of the equipment.
(4) The operational and accident radiation dose was administered to the sample as a total integrated dose in a short duration. When radiation doses are given at a high rate, most of the damage is limited to the outer surface of the polymer, preserving the inner area fairly intact. The undamaged inner polymer leads to inaccurate results.

These areas of concern are discussed in more detail in Annex A–2.

2.6.2. Pre-ageing of semi-crystalline polymers

The thermal ageing of most polymers follows an Arrhenius type of behaviour (i.e. ageing increases with rising temperatures), and the rate of ageing is given by the Arrhenius equation (see Annex A–2.3). Non-Arrhenius behaviour has been observed in some semi-crystalline polymers used in cables. Semi-crystalline polymers such as cross-linked polyethylene (XLPE) have a crystalline melting point T_m in the region of 90–120˚C [1]. Such materials are usually used in NPPs at operational temperatures below T_m. The accelerated ageing used to simulate operational ageing in the EQ test has typically been carried out at temperatures $>T_m$. In these circumstances, where a physical transition occurs across the extrapolated range from the test temperature to the operational temperature, the Arrhenius equation cannot be used to predict the operational ageing from accelerated ageing tests carried out above T_m.

The non-Arrhenius behaviour is also often associated with a negative temperature effect at near ambient temperatures (i.e. degradation is worse at lower temperatures in the range <90˚C; see Annex A–2.7). This is because some ‘self-healing’ occurs in the polymer due to the increased chain mobility in the crystalline regions at slightly elevated temperatures [2].

---

[1] Note that T_m is the temperature at which the polymer becomes an amorphous structure but is still solid. It is considerably lower than the physical melting point of the material.

The degradation of XLPE during radiation ageing also tends to show a marked dose rate effect, with dose to equivalent degradation (DED) decreasing with a decreased dose — see Annex A–2.2.

These concerns are limited to polymers with a high crystalline content (e.g. XLPE, for which the worst-case scenario for operational ageing in a NPP is near ambient temperature at a low dose rate). An approach that could be used to carry out accelerated ageing in XLPE for the pre-ageing phase of an EQ test is described in Annex A–2.8.

2.6.3. Ongoing research

Extensive information on cable ageing mechanisms is available, including data on simultaneous versus sequential ageing, oxidative degradation and issues related to the Arrhenius ageing model. However, in light of the concerns regarding the uncertainties in the original test protocol (Section 3.1.2), ongoing research is in progress. This aims to establish the technical basis for assessing the qualified life of electrical cables in light of the uncertainties identified following the initial (early) qualification testing. Furthermore, this research will investigate the adequacy of the margins and their ability to address the uncertainties. This research aims to confirm that EQ requirements for electrical equipment are being met throughout the current and life extension periods of operating reactors.

2.7. RECOMMENDED QUALIFICATION PROGRAMME

The experience gained from the past decades in qualification studies and ageing experiments has prompted the development of a condition-based qualification (CBQ) programme to ensure confidence in the operational readiness of the EQ equipment in an accident environment.

A CBQ programme involves assessing the condition of the test specimens at different stages of the qualification test. This includes measurements made at the beginning of the qualification test (at intervals during the accelerated ageing used to simulate operational ageing) to record the actual equipment condition. This equipment condition is then compared with the actual condition of equipment in the plant during the operational phase to confirm whether the condition of the equipment remains within qualification limits.

A detailed description of the recommended approach to qualification is given in Section 3.

2.8. CABLE CONDITION MONITORING (CM)

CM is an important aspect of cable ageing management for both existing NPPs and new plants. The types of CM methods that are used will be dependent on whether or not the CBQ approach to qualification has been used.

2.8.1. CM for condition-based qualification

For those NPPs that use the CBQ approach, CM is a vital part of confirming that qualification continues to be valid. The methods used for monitoring in CBQ will be closely defined as part of the qualification programme and will only include those methods that have been fully validated as condition indicators. These types of CM techniques may be used in conjunction with cable deposits, where samples are placed in locations in the NPP where the environment is more severe in terms of operating temperature and/or radiation dose rate than the bulk of the cables in the plant.

The samples in a deposit can be tested on a regular basis without affecting operational circuits. Cables in such a deposit, installed in a significantly harsher environment, will generally age more rapidly than most other cables in the plant and thus will provide early warning of the need to replace cables.

2.8.2. CM for ageing management

A broader approach to cable ageing management can make use of a wider range of CM techniques to assess the current status of cables within NPPs. These methods may not be fully validated as condition indicators but can provide an indication of the state of degradation. For example, such methods might be used to determine the extent of cable damage arising from a hot spot or used to locate a problem in a cable system.

Cable deposits are particularly important for new plants but can also be used in existing NPPs, provided that the samples are pre-aged to simulate the ageing that would have occurred from the start of operation until the time at which the deposit is installed.

Periodic CM can address cables in mild environments. For harsh environments, the level of degradation needs to be compared with the qualified condition.

2.8.3. CM techniques

Numerous methods, ideas and procedures have been researched, developed, tested or validated to help provide the nuclear industry with a means to manage the ageing of cables and/or address signal anomalies that arise from cable problems. Some of these methods are well established, while others are still being developed or validated. A summary of each of the currently available techniques is given in Section 4.

3. QUALIFICATION METHODOLOGY

Qualification may be accomplished in several ways: type testing, operating experience and analysis. These may be used individually or in any combination depending upon the particular situation. EQ by analysis alone is not acceptable and must be conducted in combination with type test data or operating experience.

The preferred method of qualification is type testing which is described in various standards, national requirements or recommendations [3–6]. It begins with a detailed qualification test plan, described in standards [3], and continues with pre-ageing, design DBA simulation and functional properties measurement. The results of the tests are described in a final qualification report.

Operating experience on cables that were demonstrated to be capable of performing their expected safety functions under specific operating conditions may be available for EQ. When using operating experience for EQ, it is important to verify that the target cable is capable of performing its expected safety function during and after a DBA, taking into account the operating conditions for the normal operational period in which the target cable will be used.

3.1. CONDITION-BASED QUALIFICATION

The EQ of cables has evolved in the past two decades to provide methods suitable for providing an increasing level of confidence in cable performance.

The early cable qualification tests involved operational ageing and DBA tests (i.e. functional tests during and after the DBA) to verify that the sample successfully completed all the tests. The service life of the component is projected based on the operational ageing and adjustments to that period based on the actual service environment. This approach was considered adequate based on the circumstances speculated at that time. The drawback to this approach to ageing management is the reliance on initial assumptions regarding the normal environment that are not later verified. The actual environment could be more or less severe depending on the period, and the combined effects and impact on cable ageing may remain unknown. Consequently, the service life cannot be accurately predicted.

CBQ is an improved method of EQ that provides improved confidence in equipment performance. The qualification process described in this section differs from the early processes in that it requires CM techniques to be utilized following each step in the qualification process that could cause degradation in any of the cable characteristics. CM activities measure and record the level of cable degradation to keep track of the rate of degradation of the cable being tested. These values are then used to determine the Qualified Level of Degradation

(QLD) that can be applied to installed cable. Figure 3.1 indicates the QLD that a specific type of cable can withstand while retaining its capability to withstand a DBA environment.

The concept of CBQ, as shown in Fig. 3.1, is to perform CM measurements during the qualification process. Figure 3.1 shows a generic curve, which indicates that degradation is occurring during the ageing process, thus decreasing the performance capability. The type(s) of CM measurement should be determined and applicable to the specific material. Initially, a baseline CM measurement (CM_0) on unaged cable is taken, which will be used to compare with subsequent CM measurements. During accelerated ageing, CM measurements (CM_{ageing}) are recorded to provide data on how the condition indicator (CI) tracks during ageing. The quantity of CM_{ageing} measurements should be determined in the qualification plan. At the end of accelerated ageing, which is taken at the expected end of service life, another CM measurement is taken, $CM_{post\text{-}ageing}$. If the samples pass the DBA test, this point ($CM_{post\text{-}ageing}$) with additional margin determines the QLD against which ageing is managed.

Note that in the case of equipment outside a harsh environment (as indicated by the dotted line in Fig. 3.1), the performance capability is not significantly degraded by a DBA, and the lifetime is significantly higher. For equipment located in a harsh environment, a DBA test is performed after accelerated ageing, which dramatically decreases the performance capability of the equipment. A CM measurement made after the functional test that verified that the equipment can function after a DBA, as indicated in Fig. 3.1 as $CM_{post\text{-}DBA}$. For equipment needed after the DBA, the post-accident period is simulated, and a CM measurement is again taken. The CM measurement value after the post-accident period should be above the design specification as defined in the acceptance criteria. Margin is applied to the acceptable performance limit to obtain the design specification. The margins are only meant to account for test measurement inaccuracies and production variations.

If the equipment has passed the required tests, and the QLD is established, this will be the value with which future CM measurements on installed cable are compared.[2]

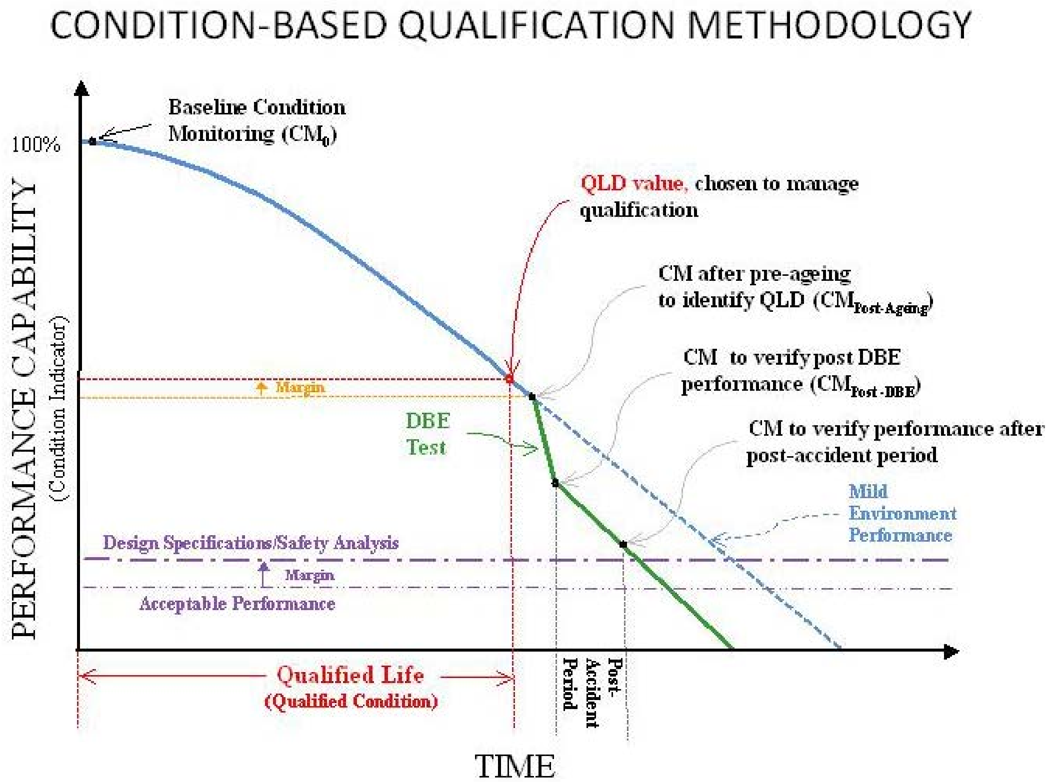

FIG. 3.1. Condition based-qualification methodology.

[2] Note that the QLD established in the EQ test is the maximum degradation that has been demonstrated to pass a DBA test. The material may be capable of passing a DBA test at higher levels of degradation, but unless DBA tests are repeated at higher levels until the cable fails, the QLD established will be the value used for CBQ.

An incremental qualification approach requires performing a DBA test on a variety of aged samples (e.g. equivalent to 25 years, 30 years, 35 years, 40 years, 45 years, etc.) and establishing a QLD value for each sample. The QLD becomes the degradation management limit for actual plant applications. The QLD point is then the performance capability indicator that will closely reflect and account for the historic environmental effects at the plant. Such measurements that are non-destructive could be conducted on deposited samples or on cables in service to confirm that the QLD is not exceeded. Furthermore, an incremental qualification approach, which involves ageing the cable for another ten years or other suitable increments and performing DBA testing, could be used for the life extension of cables.

Furthermore, this approach can be used for equipment in mild environments by determining an acceptable level of degradation and utilizing CM activities to measure and record the level of cable degradation in order to keep track of the rate of degradation. Such management would provide greater confidence in the reliability and availability of the cable.

3.1.1. Overview of the qualification procedure

Figure 3.2 shows the sequential steps involved and provides important notes to consider in the qualification process. The numbers shown in brackets (e.g. [3.xx] in Fig. 3.2) indicate the relevant sections in this document. A brief description of the process is given below; more detailed descriptions can be found in the following subsections.

The first part of the qualification process is the development of a detailed qualification plan, which contains the chosen condition indicator(s) and acceptance criteria, and describes the limiting service environment, the chosen target service life as well as the methodology used.

Once a qualification plan is finalized, the samples are prepared. Pre-test preparation includes (1) a visual inspection of the cables and documenting any anomalies, (2) preparing samples and (3) ensuring that the samples meet the requirements for insulation thickness and length. An initial functional test and baseline inspection are required to verify the functional capability of the equipment per the acceptance criteria. Furthermore, initial condition monitoring measurements should be taken to establish the baseline value of the condition indicator for the new, unaged equipment.

The preferred method for simulating operational ageing is concurrent thermal and radiation ageing. However, if sequential testing is used, the worst-case ageing sequence should be chosen, which is generally radiation ageing followed by thermal ageing. Pre-ageing rates should ensure homogeneous degradation of the samples and, as such, limits for the temperature and dose rate, specifications on the activation energy and ageing time should be properly evaluated. At intervals during pre-ageing, functional tests and CM measurements (depending on the type of technique) will be made to ensure the operability of the cables as well as to document how the condition indicators track degradation/ageing. Following pre-ageing, another functional test should be performed to verify the equipment's functional capability and that the acceptance criteria defined in the qualification plan are met. In addition, a CM measurement is taken after pre-ageing. This value, with a margin, will define the QLD parameter, assuming that the samples pass the DBA testing. The QLD provides the level of degradation that the equipment can withstand while retaining its capability to withstand a DBA environment.

Fire tests may be required on samples subjected to pre-ageing, depending on national requirements. Country-specific requirements will determine the timing of the fire test or whether separate unaged samples can be utilized for the fire test. In addition, country-specific requirements will determine whether seismic tests, vibration tests and/or aircraft impact tests are required. A functional test is necessary following any seismic/vibration/aircraft impact tests to verify the capability of the specimen. Subsequently, the condition indicators shall be measured and evaluated to assess whether the equipment can withstand further testing.

To ensure the cables are able to perform their safety functions under DBA conditions, the cables are subjected to DBA radiation, followed by DBA temperature, pressure and chemical spray. Simultaneously with DBA testing, functional tests and CM measurements should be conducted to assess the equipment's functional capabilities and also to collect information on how the condition indicator(s) vary under the DBA conditions. Post-DBA functional tests are performed to verify the equipment's operability after an accident. In addition, CM after DBA testing could be used to evaluate future increases to service life.

The post-accident period will depend on the application of the equipment, but the minimum post-accident test period for equipment whose service life is less than one hour shall be the required period plus one hour. A

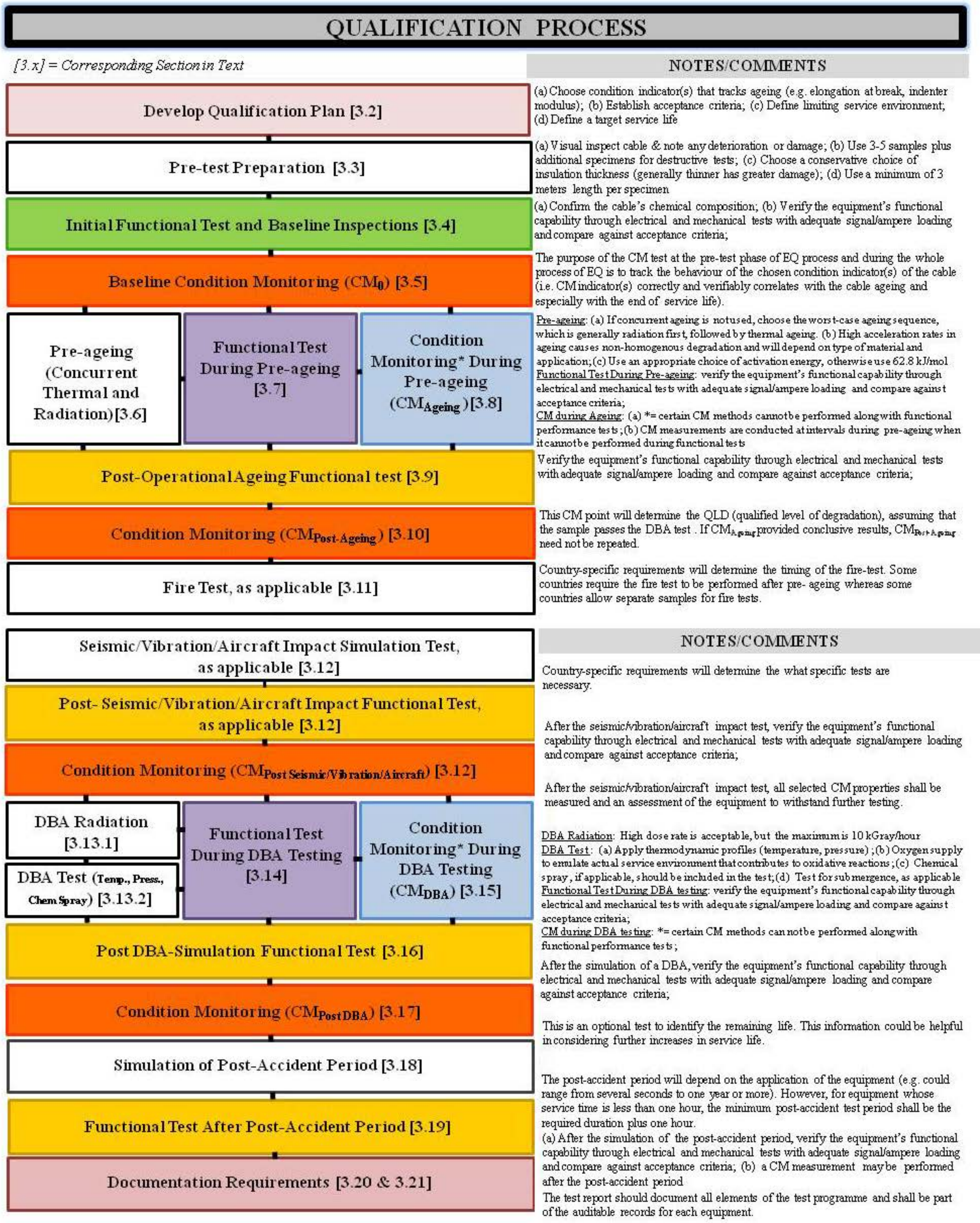

FIG. 3.2. Qualification process.

successful functional test following the post-accident period will ensure that the equipment will be able to function when needed.

The entire qualification process should be documented in detail. An auditable documentation file is required for each piece of equipment and should include the test procedure, acceptance criteria, test data, test report, qualified condition, maintenance requirements and frequency for CM. The documentation file will provide proof of the successful qualification and should therefore include direct responsibility (signature). Section 3.21 details the necessary items in the documentation file.

3.1.2. Uncertainties

The simulation of ageing effects constitutes an important part of qualification, and the uncertainties due to the use of accelerated ageing must be taken into account. The main sources of the uncertainties in EQ cable testing are diffusion limited oxidation, dose rate effects, applying the Arrhenius model, limitations of activation energy values, synergistic effects and the complex problem of the DBA and post-DBA simulations [7]. These areas of uncertainty are discussed below and in more detail in Annex A–1.

Recent data has shown that for most polymers, simultaneous radiation and thermal ageing produce synergistic effects that reduce the qualified life as compared with sequential ageing. The worst-case ageing should be chosen to ensure an accurate and reliable qualification test.

For ageing of cables, a high dose rate for radiation ageing can result in heterogeneous degradation, where the surface layer is fully oxidized but the inner layers have been subjected to lower levels of oxidation. Hence, a lower dose rate would more adequately simulate radiation degradation effects.

The applicability of the Arrhenius model is discussed in Annex A–2.3 but utilizing accurate activation energy is essential. When imprecise activation energy or too high a temperature is used in the Arrhenius equation, the impact on the time needed for thermal ageing can be significant.

An important source of uncertainty in the DBA simulation may be the limited oxygenation of the DBA test chamber. The pressure chamber is usually relatively small, and the oxygen present at the start of the test is rapidly consumed so that the later stages of the testing are performed in the absence of oxygen.

Qualification margins were originally applied to account for the uncertainties associated with type testing of single samples of equipment. However, these margins have subsequently been used to address the uncertainties arising from accelerated ageing and DBA simulation. The margins applied may not be adequate to cover all of these uncertainties, so the predicted service lifetime may not be fully justified. Therefore, additional ongoing condition and environmental monitoring of cable ageing is recommended as discussed in Section 4. CM is performed on in-plant samples (e.g. cable in service) and/or on deposit samples [1].

3.1.3. Test margins

The test margins applied during the qualification process are solely to account for test instrument inaccuracies and production variations. The test margin is NOT to be used to account for any of the uncertainties listed in Section 3.1.2.

The test margin is the difference between the service conditions and the conditions used for cable qualification. In the absence of any detailed specification, suitable margins are suggested in the standards [3–5]. Typical margins are:

- Peak temperature: +8 °C;
- Peak pressure: +/–10% of gauge;
- Radiation: +10% on accident dose;
- Power supply voltage: ±10%, but not exceeding cable design limits;
- Frequency: +5%;
- Vibration: +10% acceleration;
- Time: +10% with minimum of required duration plus one hour.

It is necessary to note that the test margins may be positive or negative to increase the severity of the tests. For example, in containments under negative pressure, the margin added would increase the negative pressure and result in a pressure closer to atmospheric pressure.

Additional margins should be considered for any other factors that influence ageing and performance.

3.2. QUALIFICATION PLAN

The first step of qualification is the preparation of the test plan, which should contain sufficient detail to describe the required tests, including: the limiting service environment, target service life, condition indicators, ageing procedure and acceptance criteria. The information that should be contained in the test plan can be found in national and international standards [3, 5].

3.2.1. Condition indicators

The qualification plan should indicate the condition indicator(s) that will be used to track the ageing of the cables. An important characteristic of a useful condition indicator is that it demonstrates a trend that changes monotonically with degradation and can be correlated with the safety related performance. For example, the parameters used as condition indicators could monitor the change in the chemistry of the material (e.g. polymer chain degradation, side reactions), monitor the physical properties (e.g. tensile elongation, hardness), or monitor electrical properties of the material (e.g. dielectric properties or through the electrical response of systems). A large number of methods are available, but the condition indicators should be sensitive to the effects of ageing for the particular material.

3.2.2. Acceptance criteria

The acceptance criteria shall be thoroughly defined in the qualification plan. The criteria are usually the limiting values of properties beyond which the degree of deterioration is considered to reduce the ability of the cable to withstand stresses encountered in normal service, and during and following accidents. The acceptance criteria shall be, on the one hand, conservative enough to sufficiently cover margins and uncertainties and, on the other hand, they shall not be too demanding to give needlessly negative results. The acceptance criteria shall be defined before the beginning of type testing, and during the qualification all selected criteria shall be met. It is not acceptable to meet only some of the criteria.

During qualification, a number of functional properties are tested. The extent of the measured properties and their acceptance criteria may vary and are generally based on the specific cable application at the NPP. The most frequently tested parameters are insulation resistance, voltage withstand tests and mechanical properties. Other properties (e.g. capacitance, attenuation and/or signal propagation) can also be measured. An engineering analysis should be used to justify the critical characteristics for specific NPP applications.

New cable should meet all requirements described in its technical specification and/or given in the respective design. During operational use, the cable may change some of its properties but shall not be damaged to the extent that would compromise its proper function. Some recommended functional properties, which are typically measured during cable qualification, and their acceptance values are described in Table 3.1. Some critical cable performance characteristics are described in the standards [5, 8]. Some qualification criteria are summarized and compared in Ref. [9].

During the qualification test, cable performance is evaluated for the specified design and structure of the cable. Cables with or without jackets are treated equally in the qualification process. The application will require a cable structure that successfully completed the test.

3.2.2.1. Mechanical properties

In addition to electrical properties, mechanical properties (such as elongation at break or a mandrel bend test) are very important parameters. They have no direct influence on the functionality of the cable but demonstrate the retention of a degree of flexibility and ability to withstand some movement and vibration during normal operation, as well as during postulated accidents. A typical recommended threshold value of elongation at break after pre-ageing is not less than 50% absolute. This value covers some important safety margins such as material inhomogeneity along the cable length, imperfections during the cable installation at the NPP (e.g. cable bending or crushing), differences between individual batches, variations of properties between cable sizes, possible movements during an accident and margins for the cable lengths. However, for some cables, a lower value than 50% absolute may be appropriate as a threshold value.

TABLE 3.1. SOME RECOMMENDED FUNCTIONAL PROPERTIES AND THEIR TYPICAL ACCEPTANCE CRITERIA

Technique	Cable type	Acceptance criterion		
		New cable	After pre-ageing	During and after DBA
Elongation at break	All types	Should meet cable technical specification	>50% absolute[a]	Not measured
Mandrel bend test	All types	No insulator cracks	No insulator cracks	No insulator cracks
Voltage withstand test	All types	Pass the test	Pass the test	Pass the test
Insulation resistance/volume resistivity	All types	Should meet cable technical specification or should meet the values given in the respective design. Volume resistivity $\geq 10^8$ Ωm	Should meet the value in technical specification decreased by one order or should meet the values given in the respective design. Volume resistivity $\geq 10^8$ Ωm	Should meet the value in technical specification decreased by four orders; the functionality must be maintained or should meet the values given in the respective design. Volume resistivity $\geq 10^8$ Ωm
Capacitance	Communication coaxial	No changes relative to the technical specification	No changes relative to the technical specification	No changes relative to the technical specification[b]
Attenuation	Coaxial	No changes relative to the technical specification	No changes relative to the technical specification	No changes relative to the technical specification[b]
Characteristic impedance				
Noise rejection				
Signal propagation				
Other		Depend on the specific cable application (e.g. no fluid or steam inside the cable under the DBA test)		

[a] A lower value than 50% absolute may be appropriate for some cables.
[b] Only changes such as the attenuation increase due to the temperature increase, allowed by the design, NPP design or standards should be allowed.

3.2.2.2. Electrical properties

Electrical properties are the most important functional properties. The parameters most often tested are voltage withstand and insulation resistance. Nevertheless, other properties, such as capacitance, attenuation, and/or signal propagation can be measured as well. Parameters for voltage withstand are found in more detailed standards (e.g. in Ref. [5]). The test is performed on a cable coiled around a mandrel that has a diameter between 9 and 40 times the diameter of the cable (dependent on the standard applied). The insulation resistance (volume resistivity) of a cable after pre-ageing, during and following a DBA needs to be sufficiently high to exclude the possibility of activation of the current protection systems at the NPP for the specific installation. This means that the maximum leakage current for the whole circuit shall not be higher than a specific value. As an example, a specific circuit may have a requirement that for a 100 m cable, the leakage current shall not be higher than 25 mA for cables with a conductor size of 1.5 mm^2. If such a value is known, it shall be recalculated for the tested cable length. If it is not known, other acceptance criteria shall be used. In certain cases, the plant specific application may have more stringent requirements for applications such as radiation monitors or neutron detectors. New cables shall satisfy the cable technical specifications. The pre-aged cable should satisfy the value in the technical specification decreased by one order. During and following a DBA, the cable should satisfy the value in the technical specification decreased by four orders. A minimum value of 10^8 Ωm over the full temperature range (including DBA) should be used for 400/230 V circuits if no other value is specified.

For specialty cables (coaxial, triaxial), it is recommended that parameters such as capacitance, attenuation, characteristic impedance, noise rejection and signal propagation are measured [8, 10]. The measured values shall not change during the testing. The specific acceptance values must be compared against system requirements.

3.2.2.3. Other properties

No fluid from the surrounding environment (water, steam) shall be detected inside the cable or drop from the cable (so-called tears) during the DBA simulation. Even if the cable passes the test, the fluid could induce a short circuit in real circuits when it gets into a switchboard, terminal box or connector.

3.3. PRE-TEST PREPARATION

The essential condition for starting any activity related to the qualification of cables is to have a finalized and approved qualification plan. Once this condition is met, the immediate pre-test activities related to EQ can start.

3.3.1. Type and number of samples

The number, type and length of the cable samples selected for type testing are described in the appropriate standards [5]. The following types of samples should be used for the testing — complete cable, insulated wire, and insulation and sheath materials stripped from the whole cable. The reason is to demonstrate that there is no adverse interaction between individual parts of a cable (e.g. sheath, insulation, tapes) and to establish the ability of the wire insulation to perform its required function independent of the jacket material. However, coaxial cables are tested as a complete cable to establish that the jacket maintains its integrity as a moisture barrier and provides the required dielectric characteristics and to confirm that geometric deformation of the insulation does not unacceptably affect signal propagation. For cables of the same specifications, a multicore cable should be tested unless that type of cable is only used as a single core cable. In the case of cables with the same specifications except for the insulation thickness, a test cable with the thinnest insulation should be tested. For multicore cables, all of the insulation colours should be included in the test sample.

It is recommended that extra samples are kept in case of failure of the testing equipment (e.g. overheating of the thermal oven) so that the test can be repeated.

When CBQ testing is to be carried out, additional samples will be required to enable condition measurements to be made during the test. The usual practice is that the customer (producer, vendor, power plant) provides the cable samples to the testing laboratory based on the requirements of the EQ programme. The number of samples is an issue related to the target qualified lifetime and the minimum time period for which the lifetime is intended to be demonstrated and documented. For example, for a target qualified lifetime of 40 years and a minimum time period for lifetime demonstration of 5 years, then the number of samples required is 8 + 1. The 8 samples are intended for the performance of accelerated ageing and functional tests, and one sample is intended for measuring the baseline functional data for the unaged cable. Additional samples should be added for any planned destructive tests.

To demonstrate and map the changes in the condition indicator as a function of ageing, the higher the number of samples used the better. The number of samples used should be adequate for the EQ programme objectives and should be justified.

3.3.2. Length of cable required

The minimum length of every sample for DBA testing is 3.05 m based on the requirement of standards [5]. This is the effective length which is exposed to the environmental conditions of the DBA simulation and electrically tested, so it is necessary to have samples slightly longer. Additional lengths of cable will also be required to prepare samples for destructive tests carried out as part of the CM tests (e.g. elongation at break).

The procedure used to prepare samples for EQ tests is up to the customer and must be described in the qualification programme. Samples should be long enough at the beginning of the programme to provide samples for both electrical (non-destructive) and mechanical (destructive) tests. For example, a sample 6 m long can be cut into two parts, using 5 m for electrical tests and 1 m for mechanical tests.

Other possibilities are acceptable provided that sets of samples are clearly identified and prepared according to the requirements of the EQ programme.

3.3.3. Marking of samples

Marking cable samples is very important for quality assurance (QA) of the qualification process. The main purpose of marking the samples is to ensure that the testing facility is able to properly identify the samples during the course of the qualification programme and properly refer to them in the qualification documentation (i.e. qualification test, functional test reports and final qualification report). The marking of samples should be clear and durable in order to "survive" all "harsh" qualification tests (i.e. thermal and radiation ageing, submergence, if applicable, and accident condition simulation tests).

3.3.4. Initial inspection of samples

The initial inspection of samples sets up the reference to the initial visual status of samples. During the inspection, the responsible person observes the samples one by one and makes notes regarding any non-conformances found that are significant from the point of view of physical deterioration and/or existence of damage (due to mechanical, electrical or other type of impact) that might possibly influence the functional capability of the cable.

All findings should be recorded carefully in a visual inspection record, analysed and evaluated from the point of view of capability of the sample to proceed in the qualification programme.

It is recommended that analytical tests are performed to confirm the consistency of chemical properties. Variability in the chemical composition could affect the service life. For example, pigments or plasticisers used in the cable can significantly influence the service life of the cable. Cables being EQ tested should have the same material composition as cables to be installed. This should be documented in the qualification file. Acceptable material composition analysis tests should be employed that can guarantee that this requirement can be appropriately met. This is considered to be significant in strengthening the quality assurance of cable supplies to NPPs.

3.4. INITIAL FUNCTIONAL TEST

The initial functional test is an activity aimed at obtaining the baseline performance characteristics that demonstrate the functional capability of the cable at the beginning of the programme. The cable must satisfy the acceptance criteria set up in the EQ programme. Functional tests usually consist of electrical tests and mechanical tests. The choice and scope of techniques used and parameters measured are up to the customer, however they should be in line with the widely adopted practices and should demonstrate the functional capability of the cable for the intended application.

During qualification, the cables will be subjected to a diagnostic measurement procedure to demonstrate functional capability. The extent of the measured properties may vary and, generally, the procedure is based on the specific cable application at the respective NPP. The most important parameters are electrical and mechanical properties. In general, the functional properties to be measured are those that demonstrate the basic properties and behaviour of the cable during its service life and during postulated accidents. Moreover, the extent of the testing shall not be necessarily excessive. An engineering analysis should be used to identify acceptable performance levels for the specific NPP applications. If the cables are located in an area with potential for electromagnetic interference (EMI) or radio frequency interference (RFI), the impact of these should be considered in qualification. A suitable functional test should be included if EMI/RFI is a concern.

The list of tested properties, the frequency of measurements and the acceptance criteria must be described in the test plan before starting the type testing. Some measured characteristics and accepted values are described in Table 3.1. The functional parameters most often tested are insulation resistance (volume resistivity), leakage current, voltage withstand and elongation at break.

3.5. BASELINE CONDITION MONITORING (CM_0)

From the point of view of preserving EQ during the lifetime of a NPP, CBQ is considered more appropriate than the current practice adopted by utilities, which is mainly limited to the monitoring of environmental conditions. The measured values of temperature and radiation dose are used to demonstrate that operational conditions are within the enveloping conditions used for pre-ageing in the original EQ. Using only environmental monitoring does not provide any information on the cable condition or performance. This is considered insufficient to use as a basis for cable qualification preservation or the extension of the qualified lifetime of cable. Utilities are encouraged to adopt a broader approach that includes both environmental and cable CM within the CBQ process.

The purpose of the CM test at the pre-test phase of EQ process and during the whole EQ process is to track the behaviour of the chosen condition indicator (or indicators) of the cable being qualified. This will identify which parameters correctly and verifiably correlate with cable ageing and especially with the end-of-life criterion to give reasonable confidence in performance.

The concept of CM together with monitoring of the environment is based on the fact that conditions that exist in the real operation of a NPP can be different from those applied during the qualification process, causing different rates of cable degradation (positive or negative).

Appropriate CM techniques, as described in Section 4, shall be used so that they can be applied at the NPP during the operational life of the plant. The results of these measurements have no direct effect on whether a cable will be qualified or not. They will only be used in the subsequent cable ageing management programme. Therefore, it is recommended that additional samples are aged together with the qualified sample on which such measurements could be performed.

3.6. OPERATIONAL AGEING (PRE-AGEING)

In the qualification test, normal operational ageing is simulated by pre-ageing, which consists of accelerated thermal and radiation ageing.

3.6.1. Test sequence

Pre-ageing should be performed by simultaneous radiation and thermal ageing (referred to as simultaneous or concurrent ageing), which usually gives the most severe conditions for most polymeric cable materials. Practical considerations (e.g. availability of facilities capable of conducting simultaneous radiation and thermal ageing on the size of cable samples required for DBA tests) may necessitate using sequential ageing if conservatism can be established in relation to simultaneous thermal and radiation ageing.

If simultaneous ageing cannot be applied, the sequence of ageing (i.e. thermal ageing followed by radiation ageing or radiation ageing followed by thermal ageing) that gives the worst degradation to the cable insulation should be chosen. In many cases, radiation ageing first is more severe for polymeric materials [7, 9, 11]. Therefore, it is recommended that radiation ageing followed by thermal ageing is used for sequential accelerated ageing, unless it can be demonstrated that thermal followed by radiation ageing produces more severe degradation.

3.6.2. Simultaneous ageing

The ageing simulation should follow as closely as possible the mechanism of long term degradation of the components of the cable being tested during its lifetime, where the synergistic effect of elevated temperature and ionizing radiation is taken into account. When considering synergistic effects in simultaneous ageing, it should be noted that generally radiation ageing will dominate at high dose rates whereas thermal ageing will dominate at low dose rates (see Annex A–2.5, Fig. A–4).

Several factors need to be considered in simultaneous ageing and are discussed in the following sections.

3.6.2.1. *Radiation dose*

The radiation of simultaneous ageing is usually carried out using gamma rays from a ^{60}Co source. ^{137}Cs is less suitable because of its low gamma ray energy. It is important to take into account not only the total absorbed dose but also the existence of the dose rate effect. Dose rates that are too high (>1 kGy/h) generally cannot be expected to yield predictive information on the degradation behaviour in an operating plant, in which the maximum operating dose rate is about 0.1 Gy/h to 1 Gy/h.

The main reason is the possibility of heterogeneous oxidation throughout the sample. This effect depends on a number of parameters of the polymeric materials in the cable (i.e. on its chemical composition, thickness, cable construction, the value of the oxygen diffusion coefficient and the solubility of oxygen in the given polymer as well as on the environmental parameters, namely temperature and oxygen partial pressure). IEC standards [3, 12] recommend an irradiation procedure where the dose rate does not exceed 108 Gy/h. Moreover, IEEE standards [13] proposed an irradiation procedure where the dose rate does not exceed 110 Gy/h (this value is for insulation with 1 mm thickness, enveloping the representative kinds of insulation material such as XLPE and EPDM). In practice, the dose rates used in pre-ageing should not exceed 100 Gy/h (lower is preferable) to ensure homogeneous oxidation.

3.6.2.2. *Temperature*

For reliable simulation of long term ageing, the temperature of accelerated ageing should not be too far from the service temperature. Some standards [14] recommend using not more than 25°C difference. Actual operating temperatures are about 40–65°C for I&C cables, but for power cables, self-heating may need to be considered. If power cables are normally energized, then operating temperatures may be 80–90°C. To simulate 40 years or more of service ageing with a <25°C difference would lead to a very long testing time. Hence, the test temperature used in thermal ageing is usually higher.

The maximum allowed temperature for simultaneous ageing is limited by the range of chemical stability (the temperature range in which no chemical changes are detected in a specific time) or by any thermodynamic transitions in the material, e.g. glass transition (Tg), or the crystalline melting point [9, 15]. If such a phenomenon occurs between the test and service temperature, it is very difficult if not impossible to extrapolate the data from a higher to a lower temperature. This is of particular concern for XLPE (see Section 2.6.2).

In practice, the temperature used in pre-ageing for most cables should not exceed 120°C (some specialty cables designed for high temperature operation may be aged at temperatures higher than 120°C). It should be noted that this temperature is dependent on the insulation material. Therefore, a lower temperature may need to be considered for certain materials.

3.6.2.3. *Activation energy*

Polymers are degraded by thermal oxidation in the presence of oxygen as a result of chain scission or cross-linking between chains and the accumulation of oxidative products. Generally, the rate of degradation is accelerated by an increase in temperature. An exception is XLPE, which can show a negative temperature effect at temperatures <90˚C (see Section 2.6.2). The relation between the rate constant for degradation (k) and ageing temperature (T) is determined by the Arrhenius equation Eq. (3.1).

Activation energy (E_A) is a very important value that strongly influences the simulation of degradation and is defined as the energy that must be overcome in order for a chemical reaction to occur. The absolute value of the E_A does not give information about thermal endurance. It only enables the calculation of the testing time at the selected test temperature. Generally, the lower the value of E_A that is applied, the longer it will take for thermal ageing.

The absolute value of the E_A can be calculated from the gradient of an Arrhenius plot (Eq. 3.1). E_A is not always constant over a wide range of ageing temperatures, often decreasing at lower temperatures. The reported E_A values for various cable materials such as PE, EPR, CSPE and PVC were 100–130 kJ/mol. These values were typically determined at ageing temperatures of 120–150ºC. However, recently, the lower E_A value of 60–70 kJ/mol has been reported for ageing temperatures at around 100ºC. For SIR cables, a suitable value of E_A may be even lower (41.9 kJ/mol, 0.43 eV, 10 kcal/mol).

Moreover, the acceleration factor for thermal ageing (T_1 versus T_2) can be calculated by Eq. (3.2). This equation cannot be used for extrapolation across a physical transition (e.g. crystalline melting point).

$$k = A\, e^{-\frac{E_A}{RT}} \tag{3.1}$$

$$a = \frac{t_1}{t_2} = e^{\frac{E_A}{R}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} = e^{\frac{E_A(T_2-T_1)}{RT_1T_2}} \tag{3.2}$$

where

k: Rate constant for degradation
A: Material constant, independent of temperature
E_A: Activation energy (J/mole)
R: Gas constant
T: Ageing temperature (Kelvin)
a: Acceleration factor
t_1: Required service life
t_2: Time of accelerated ageing
T_1: Service temperature (Kelvin)
T_2: Temperature of accelerated ageing (Kelvin)

The principles that should be applied to determine the activation energy used for calculating the pre-ageing time in EQ tests shall be as follows [9]:

— The value of activation energy determined from thermal ageing tests is only applicable for temperatures down to the minimum temperature used in such tests. However, when the calculated activation energy is 62.8 kJ/mol (0.65 eV, 15 kcal/mol) or less, the value can be used to calculate the time required to pre-age samples in EQ tests [9].
— The activation energy to be used in the region between the minimum temperature in thermal ageing tests used to determine E_A and the temperature of actual operating plants must be evaluated from the investigation of degradation in actual operating plants (sampling inspection) and the thermal ageing characteristics at the minimum temperature in the thermal ageing tests.
— When the activation energy cannot be evaluated from the investigation of degradation in actual operating plants, a value of 62.8 kJ/mol (0.65 eV, 15 kcal/mol) is recommended to be used as a tentative value for E_A in the region between the minimum temperature used to determine E_A and the temperature of actual operating plants.

A number of studies have shown that the activation energy measured at temperatures <100ºC is significantly less than that determined at higher temperatures. Values in the range 63 to 75 kJ/mol have been measured for several different cable materials [9, 27]. It should be noted that this activation energy is dependent on insulation material. However, the activation energy of silicone rubber may be smaller (41.9 kJ/mol, 0.43 eV, 10 kcal/mol).

3.6.3. Sequential ageing

Sequential ageing should be used for pre-ageing only when simultaneous ageing cannot be applied for a valid technical reason. If sequential ageing is applied to pre-ageing, radiation ageing followed by thermal ageing should be applied, except when thermal ageing followed by radiation ageing is known to give the worst degradation for the materials being tested.

3.6.3.1. Radiation ageing

In practice, the dose rates used in pre-ageing should not exceed 100 Gy/h; lower is preferable for sequential ageing (see Section 3.6.2.1).

The time for accelerated radiation ageing can be calculated by dividing the total absorbed dose (multiply the required service life by the service dose rate) by the dose rate of accelerated ageing.

3.6.3.2. Thermal ageing

In practice, the temperature used in pre-ageing should not exceed 120°C for sequential ageing. It should be noted that this temperature is dependent on insulation material. Therefore lower or higher temperatures may need to be considered in specific cases (see Section 3.6.2.2).

The time of accelerated thermal ageing can be calculated by dividing the required service life by the acceleration factor Eq. (3.2). This equation should not be used for XLPE (see Section 2.6.2).

3.6.3.3. Activation energy

In general, the activation energy to be used for the thermal ageing component of sequential ageing should be based on the concepts outlined in Section 3.6.2.3. It should be noted that this activation energy is dependent on insulation material.

3.7. FUNCTIONAL TEST DURING OPERATIONAL AGEING

At intervals during operational ageing, the samples should be subjected to functional tests, both electrical and mechanical, to verify the functional capability of the equipment at the simulated ageing times (i.e. 10 years, 20 years, 30 years, 40 years). The cables should be adequately loaded, per their application, while conducting the functional tests. The results of these functional tests shall meet the acceptance criteria specified in the qualification plan in order to continue the operational ageing simulation.

3.8. CONDITION MONITORING DURING PRE-AGEING (CM_{ageing})

CM measurements shall be performed at intervals during pre-ageing (e.g. after ageing equivalent to 10 years, 20 years, 30 years, 40 years of operational conditions). The condition indicator(s) will track degradation/ageing of the specimen at several points during pre-ageing. This data will be useful to determine how much life is remaining when compared to the QLD value. These CM_{ageing} measurements along with the baseline CM measurement CM_0 will provide information on how the condition indicator(s) change as the material ages. Note that some CM methods may not be performed along with functional tests during ageing.

3.9. POST-OPERATIONAL AGEING FUNCTIONAL TEST

After the pre-ageing, the functional properties should be measured again. Usually they are the same as in the initial functional test (see Section 3.4). The extent of measurements and the acceptance criteria are described in the qualification plan.

3.10. CONDITION MONITORING AFTER PRE-AGEING ($CM_{post\text{-}ageing}$)

During pre-ageing, intervals of normal cable operation (e.g. 10 years, 20 years, 30 years) are simulated, and selected CM properties are measured. These are the same properties as defined in Section 3.8 and measured at the beginning of the EQ test.

The final condition monitoring measurement at the end of pre-ageing ($CM_{post-ageing}$) will determine the QLD if the sample subsequently passes the DBA test. $CM_{post-ageing}$ is the level of degradation that the equipment can withstand while retaining its capability to withstand a DBA environment. If a CM measurement was conducted at the interval, which was the end of the ageing simulation (CM_{ageing}) and was successful, then a CM measurement after the post-operational functional test is not necessary. Thus, if a CM_{Ageing} is measured at the end of pre-ageing, it can be used for the $CM_{post-ageing}$ measurement, and it is not necessary to repeat the CM after the functional test. However, CM at this point can provide insight into future life extension.

The simulated service lifetime of cable during the qualification type test may not be enough to reach the QLD. It can be established in stages until a point is reached beyond which the sample cannot withstand a DBA test. Hence, it is recommended to age samples designed for CBQ in order to have varying levels of ageing (30 years, 35 years, 40 years or other appropriate intervals) and to measure the samples at the specified CM steps.

3.11. FIRE TESTING AFTER AGEING

All cables designed for new installations should be flame retardant, halogen free and non-corrosive with low smoke density in a cable fire. The requirements that apply to the cables will depend on country specific regulations. Some countries require that a fire test be carried out on pre-aged cables, and others require the fire test to be performed on unaged samples. If fire resistance needs to be evaluated, it may be addressed at this stage of the test and appropriately documented.

3.12. SEISMIC/VIBRATION/AIRCRAFT IMPACT SIMULATION TEST

If seismic or vibration tests and/or aircraft impact simulations are required, as outlined in country-specific requirements, the tests should be carried out on aged samples based on the susceptibility of the material. The results should be appropriately documented.

If during the qualification, vibration and seismic tests and/or aircraft impact simulations are required, the functional properties should be measured during the tests as well as after the tests. The extent of the measured properties will be described in the qualification test specification.

All selected CM properties should be measured after the seismic/vibration/aircraft impact simulation tests if such tests are required in qualification.

3.13. DESIGN BASIS ACCIDENT TEST

Each NPP should develop its worst-case environmental profile to qualify cables in that service area. The DBA test aims to simulate the conditions that would occur in such an accident situation.

The DBA test conditions must be defined for the following qualification parameters:

- Temperature;
- Pressure;
- Time;
- Spray composition, flow rate and duration;
- Radiation;
- Operating conditions (vibration, humidity, submergence, chemicals).

The values of these parameters will be defined by the specific NPP or from industry standards when applicable. The most limiting environmental profile that envelops all of the profiles for different severe environment areas shall be selected in order to conduct one test. The choice of other profiles will provide qualification for a specific environment only.

During a DBA, cables may be exposed to high temperature steam with chemical spray and a high level of radiation, and in certain cases, a high energy line break could be more limiting for temperature. The specific environmental conditions and the time profiles will depend on the type of NPP. The cables must be able to perform all required functions during and after the simulated accident. Because a DBA could happen at any stage of NPP life, both unaged and pre-aged cables have to be subjected to the DBA conditions.

The ideal method for a DBA qualification test would be to follow the LOCA profile of steam temperature with chemical spray simultaneously with radiation. The test cables would be exposed to the DBA environment and the cable performance measured during and after the DBA. This type of qualification was tried in the past in a few countries with the steam temperature profile to simulate a DBA. This used a ^{60}Co gamma radiation source with a high dose rate at the early stage then a low dose rate at the later stage. The testing facility was large scale and was not practical.

For practicality, the DBA qualification test is usually performed in a sequential manner. First the radiation is applied up to the integrated accident dose followed by the simulation of the DBA profile characterized by a steam environment, chemical spray, high temperature and pressure.

3.13.1. DBA radiation exposure

The radiation arises from radioactive fission products released from uranium fuel and would be a mixture of γ and β radiation with a wide range of energy distribution. The dose rate is very high at the initial stage but decreases with time. The total dose is estimated to be up to 1.5 MGy but may rise up to 3.5 MGy in the case of a severe accident. The evaluation of the absorbed dose to insulation materials may be complicated when the cables are exposed to a DBA, but the estimated dose equivalent to ^{60}Co gamma radiation is usually used. The major part of the radiation dose occurs at the initial stage of a DBA at a high dose rate. In the DBA simulation, it is acceptable for the dose rate of ^{60}Co gamma irradiation to be up to 10 kGy/h at room temperature. The total dose applied is the integrated dose during the DBA.

The irradiation conditions for DBA are different from those required for simulating normal operational conditions where much lower dose rates should be used.

3.13.2. DBA profile (temperature, pressure, chemical spray)

Simulation of the DBA profile is carried out in a special pressure chamber. The temperature and pressure used in the test will be defined by the specific accident conditions being simulated. The test temperature and pressure profiles will normally envelop the calculated temperatures and pressures including margins, using either saturated or superheated steam. Typical temperature and pressure profiles for a PWR (WWER-1000) reactor are shown in Fig. 3.3. For the example shown, the total margin provides the desired exposure even though a limited portion of the profile is outside the enveloped profile. The chemical spray occurs with the steam exposure, and the composition and quantity of chemical spray are defined by each DBA. During testing the cables must be energized in order to simulate operational conditions.

The spray solution in the DBA test can be a spray or jet of water, chemical solution or other fluid and may differ depending on the type of reactor and location within the particular NPP. Conditions for the spraying are defined in the plan or can be found in standards [4]. The chemical composition of a spray solution will be defined and may include, for example, hydroboric acid, sodium thiosulfate, hydrazine or sodium hydroxide. The spray flow rate is typically several litres per minute according to the standards. Some equipment may be submerged during the accident. The spray duration should be defined in the test plan. Depending on the application, if the equipment is expected to be submerged as a consequence of a DBA, then the equipment must be qualified for those conditions separately.

DBA test chambers are generally small in order to provide a reasonable cost and schedule for testing. Thus, the oxygen can be depleted rapidly during the initial phases of testing. The lack of oxygen in the test chamber could impact the cable's qualified life since the equipment could have greater degradation through oxidation when in the presence of oxygen. Most materials will experience more degradation in an oxygenated environment. For most polymeric materials, oxygen may need to be supplied in the test chamber during the test profile to ensure an accurate test that is reflective of DBA conditions.

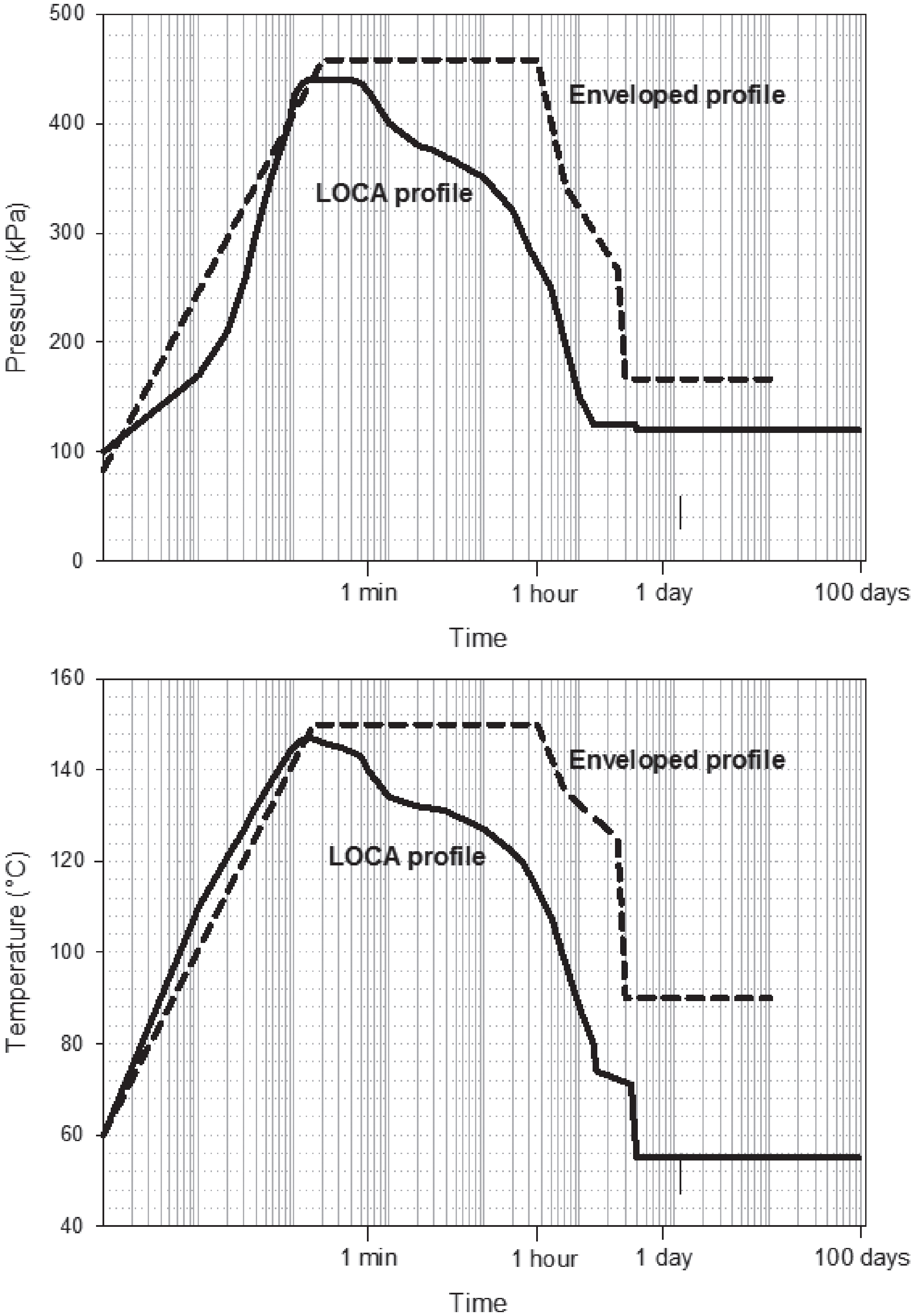

FIG. 3.3. Typical pressure and temperature LOCA profile used for a PWR (WWER-1000) reactor.

3.13.3. EMI/RFI concerns during a DBA test

During DBA conditions, due to the trip of balance-of-plant equipment, EMI/RFI is generally decreased. However, if a plant-specific design includes a higher level of EMI/RFI, then it should be considered in DBA qualification.

3.14. FUNCTIONAL TESTING DURING A DBA TEST

During simulation of the DBA, it must be verified that the cables being tested are able to perform all required safety functions. This is checked by testing the cable functionality during the DBA simulation. Typical measured parameters are leakage current, insulation resistance and impedance [5]. The data can be collected either continuously (preferred) or at specific intervals. The data sampling intervals should be short enough to demonstrate the cable functionality during the test. During the testing of electrical functionality, the electrical loading may be briefly disrupted for making functional measurements such as insulation resistance or tan delta.

3.15. CONDITION MONITORING DURING DBA TESTING (CM_{DBA})

CM testing should be conducted during the DBA testing in order to establish how the condition indicator(s) change when subjected to DBA conditions. This is similar to CM_{ageing}. Note that many of the CM tests cannot be performed during the functional tests.

3.16. POST-DBA SIMULATION FUNCTIONAL TEST

After finishing DBA and post-DBA simulation, final functional properties are measured. The most important are the electrical properties to ensure the equipment can perform its safety function. The post-DBA functional test is not necessarily the same as earlier functional tests (e.g. elongation at break is usually not necessary). The number of tests and acceptance criteria are described in the qualification specification.

3.17. CONDITION MONITORING AFTER DBA SIMULATION ($CM_{post\text{-}DBA}$)

Generally, it is not necessary to use CM techniques for CBQ after the DBA simulation. The reason is that CBQ uses the CM properties for assessing the remaining time to reach the qualified level of degradation QLD, for proof it can survive DBA. However, CM may be useful at this stage when considering an extension of the service life.

3.18. SIMULATION OF THE POST-ACCIDENT PERIOD

In many cases, the DBA continues into a post-accident period, which depends on the specific accident conditions. This period may last up to one year during which the pressure equals atmospheric pressure, and the temperature may vary between 90°C and 50°C. In many cases, the cables are flooded with spray solution. Dependent on the fluid height, hydrostatic pressure may play an important role and should be simulated where appropriate.

The post-accident period is usually simulated by an accelerated test. For equipment whose service times are less than one hour, the post-accident period should be the required duration plus one hour. The cables are held in the desired environment (e.g. spray solution) at a higher temperature. The time of the post-accident simulation may be calculated using the Arrhenius approach. A typical one year post-DBA may be simulated within 30 days. The cables must still be energized and perform all required electrical functions.

3.19. FUNCTIONAL TEST AFTER THE POST-ACCIDENT PERIOD

Functional tests, as described in Section 3.4, should be carried out after the simulation of the post-accident period to show that the equipment can perform its necessary functions when called upon after the accident. A CM measurement is optional but recommended. The data may be helpful when considering further increases in service life.

3.20. TEST REPORT

The purpose of the test report is to document all elements of the test programme. A comprehensive test report should clearly identify the equipment and components tested, state the test objective, define the test procedure, provide a clear statement of test results, list acceptance criteria, provide relevant test data, identify all test anomalies and their resolution, and state conclusions drawn from the test. In addition, the report should include a description of test facilities and provide appropriate documentation of all test instrumentation. The test report should remain available in an auditable condition for the duration during which the equipment is in service. The elements of a typical test report are discussed in the following subsections.

The report should also include CM techniques used as well as results and should propose information on the frequency for CM at the NPP. All CM techniques used in the test programme should be described, including the measuring conditions and results linked to the specific ageing time (degree of degradation). It should also contain recommendations and/or requirements for the ongoing management of cable ageing.

The test report should be prefaced by a summary statement providing the following basic information:

— Report number;
— Report title;
— Testing organization performing and reporting the test;
— Report date;
— Calendar period of the test programme;
— Objective;
— Identification of tested equipment, production code, batch number, product description and environmental condition;
— Identification of test equipment calibration data, make, model, certifications;
— Test programme overview;
— Results;
— Conclusions;
— References and notes;
— Signatories.

3.20.1. Objective

This section of the report should clearly state the fundamental purpose of the test and identify applicable test guidelines and standards. If the safety function of the cable is known, this should be stated.

3.20.2. Acceptance criteria

This section should identify the criteria for satisfactory equipment performance and make reference to all pertinent guidelines and standards.

3.20.3. Environmental conditions

Normal and abnormal environmental conditions should be described.

3.20.4. Identification and description of test specimens

Test specimens should be identified by equipment type, model or product identification number, serial number, batch number and manufacturer. In addition, the description of the test specimens should include all salient features pertinent to the test and provide a statement of all previous specimen conditioning such as radiation and thermal ageing conducted prior to DBE simulations. Any modifications unique to a particular application must also be identified. The selection of test specimens must be justified.

Any identification numbers assigned to test specimens should be clearly stated. Practical identification numbers should be included with the specimens in all photographs used for descriptive purposes. It is also recommended that the polymeric cable materials are identified by an analytical method (e.g. FTIR, elementary chemical analysis, TGA, DSC). It will be useful for future identification and comparison of the tested material and new products.

3.20.5. Description of the test facilities and specimens

A description of the test facilities employed should be included that clearly identifies the salient features of that facility and the manner in which test specimens were processed. The mounting details and orientation of the specimens (photographs, diagrams, etc.) should be documented. For example, salient features of a radiation test facility include the gamma radiation source, the irradiation rate and the physical arrangement of the source with respect to the test specimen. For simulation of a DBE steam environment, salient features would include test vessel arrangements, steam supply, chemical spray supply and distribution, the chamber control system, features for assessing the functionality of the test specimen, and the instrumentation and data collection system. Instruments used for making all measurements should be identified or provided as a test report appendix. Instrument calibration should also be described.

3.20.6. Test requirements, procedures and results

Qualification type test report

The test requirements, procedures and results should be described in sufficient detail to permit a person versed in EQ testing to understand each element of the test programme, evaluate the adequacy of the testing methods and understand the results.

The results should include all pertinent measurements made during the tests, particularly those documenting the performance of the test specimens. Among these measurements are data tabulations, plots of temperature and pressure profiles, and seismic response spectra plots, if applicable. The development of derived data from raw data should be explained. Photographs, as appropriate, should be included to help clarify the information.

CM based report

The CM based report shall include additional information concerning the CBQ. In this report, all CM techniques used shall be described, including techniques applied in the qualification programme as well as measuring conditions and results linked to the specific ageing time (degree of degradation). It should contain recommendations and/or requirements for the maintenance and management of cable ageing. This section states the conclusions drawn from the test programme based on evaluation of the test results in accordance with the acceptance criteria. The documentation shall allow verification by competent personnel other than the qualifier that the equipment is qualified.

3.20.7. Assessment/certification of test results

The test results should be evaluated topic by topic in an orderly, logical manner whereby the progressive effects of the test programme on critical parameters of the test specimen are presented. Significant changes in the parameters or in overall performance should be highlighted and evaluated.

The test report shall describe the quality assurance system of the testing laboratory; certificates should be added in an annex.

3.20.8. Anomalies

All anomalies and changes performed on tested samples formally identified during the test programme must be presented. Where analysis and disposition of the anomalies have been completed, the results must be presented along with any data supporting the conclusion. This section should include photographs illustrating the effects of any equipment failures.

3.20.9. Statement of qualification

The qualification tests are usually done for generic NPPs with enveloping temperature and pressure profiles. A plant-specific evaluation must be performed stating that the cables used for the specific application is qualified.

3.20.10. Annexes

Annexes may be used to document various aspects of the test programme. The following information is often presented in appendices: testing protocols, certificates and written records.

3.21. QUALIFICATION FILE

The qualification file requirements will be specified in country-specific regulations and should contain:

— Identification number. This item is the reference number to identify the particular equipment's qualification file.
— Cable description and application/safety function. Pertinent information related to the cable should be included, such as the type, manufacturer, cable technical specifications, applied materials, location in the NPP, application(s) and safety function. Furthermore, if the equipment is required to function after the DBE, the post-accident duration should be noted.
— Environmental conditions. The normal and DBE environmental conditions should be described (i.e. temperature, pressure, dose rate, humidity, chemical spray, flooding, total integrated dose, EMI/RFI, vibration).
— Fire tests. If applicable, any fire tests that have been carried out as part of qualification should be included.
— Seismic conditions. The seismic conditions, if applicable, should include the expected seismic excitation for the equipment's location as well as response spectra requested and tested.
— Test report. The applicable test report(s) should be included in the qualification file. The elements in the test report are in Section 3.20.
— Specific plant evaluation for equipment (environment, material, location). The qualification file should include an evaluation to show that the test report is relevant and applicable to equipment in the NPP (i.e. same material, enveloping profile). In addition, a plant-specific assessment on where the cable can be installed and any environmental limitations should be discussed. The QLD should be clearly stated. If CBQ is the methodology used for qualification, any deviations from the recommended CM frequency should be evaluated and documented.
— Maintenance. In addition, plant-specific maintenance requirements, frequency of environmental monitoring and any other considerations for the preservation of qualification should be stated. Relevant operating experience may also be included.
— Condition monitoring. The CM programme is a subset of the maintenance programme that will preserve qualification, and as such the frequency and type(s) of CM measurements should be discussed. If CBQ is used, the CM measurements should be compared against the QLD. Changes in CM frequency recommendations (as in the test report) should be noted.
— Review/Approval. The review and/or approval routing should be clearly indicated with the necessary signatures.

The qualification file should remain available in an auditable condition for the entire time that the equipment is in service.

3.22. PRESERVATION OF QUALIFICATION

The preservation of condition based qualification has several elements and is discussed in the following sections.

3.22.1. Periodic CM to confirm cable condition is within the qualified level of degradation

Once the QLD is established, a maintenance programme should be established to ensure that cable degradation never exceeds the QLD. The periodicity of CM could be based on several factors:

— Anticipated environmental conditions;
— Plant events/maintenance activities that temporarily alter the environment;
— Operating experience on similar material;
— Change in the rate of degradation based on CM results.

3.22.2. Monitoring of external environments that affect performance and ageing

During the qualification phase, the worst case environmental conditions in the plant are used. The choice of cable would be based on such plant conditions. For example, cables for control rod drive mechanisms are generally subjected to higher temperatures and additional shielding and cooling is provided to prevent undue damage to cables. Environmental monitoring within the plant would then be used to confirm that temperatures and radiation dose rates are within the design values.

3.22.3. Cable handling considerations

Certain specialty cables have unique requirements in limited bending radius, sensitivity to chemicals, humidity, etc. Such restrictions have to be enforced in the maintenance programme to preserve qualification.

4. QUALIFICATION MONITORING

4.1. INTRODUCTION

In order to fully utilize the concept of a qualified condition in a NPP, it is necessary to carry out qualification monitoring (QM) to confirm that the qualification is still valid. QM covers both environmental monitoring of actual conditions in the plant and CM of the cables. Section 3 discusses the qualification process, and Fig. 3.1 provides a graphical representation of condition based qualification. Environmental monitoring is discussed in Section 4.2, and methods for CM are discussed in Sections 4.3 to 4.7. The overall requirements of a QM programme are summarized in Section 4.8.

4.2. ENVIRONMENTAL MONITORING

This section defines the activities that need to be carried out to identify the environmental and service conditions for electrical cables. The aim is to identify the actual conditions to which these cables are subjected during operation, particularly those that may be less conservative than considered in the original design of the plant. This would include localized areas (hot spots) that could result in significant cable degradation.

4.2.1. Identification of parameters to be monitored

The identification of the environmental conditions to which installed cables are subjected is a basic aspect in QM. Cable degradation is mainly dependent on environmental factors such as temperature, radiation, humidity or contaminants (see Annex A–1). While design conditions are used to establish initial qualification, in the long term, it is necessary to identify the actual environmental conditions in order to obtain data needed to evaluate original qualification and to identify areas with the most conservative environments. The most important environmental parameters to be measured for QM of cables are the temperature, radiation dose and dose rate.

4.2.2. Selection of areas for monitoring

When selecting the areas for environmental monitoring, the following criteria apply:

— All plant areas containing cables with safety functions would initially be selected.
— From these areas, those with the most severe design conditions of temperature and/or radiation dose would be selected. In general, these areas will be in-containment, but other areas with severe conditions may also be considered.
— An initial list of areas to be considered should include those listed in Reference [1], which correspond to typical critical areas at NPPs.
— In areas with similar enveloping conditions, those with a higher number of cables should be chosen.
— Priority areas will be those having piping with high-temperature fluids or high-radiation areas.
— Other priority areas will be those where hot spots have been identified during walkdowns.

4.2.3. Measuring environmental conditions

In general, the parameters to be measured will be temperature and radiation dose as these are the most significant for cable degradation. Nevertheless, other potential localized degradation factors not directly measurable such as the presence of water, steam, flooding and chemical agents should be identified. For most cables in an NPP, temperature will be the most important ageing stressor, with radiation ageing only of concern in specific locations.

Temperature measurement should preferably use sensors that allow for continuous recording during long periods of time, enabling subsequent detailed data analysis. Small self-contained temperature sensors with built-in data-loggers are readily available commercially and are suitable for this purpose. They are usually battery powered and can be used over a logging period of up to two years, if required. Alternatively, melted wax tags will give information on maximum temperatures. Some NPPs have used mercury thermometers to provide maximum and minimum data for the monitored period.

Radiation doses can be measured with dosimeters installed in the areas with the highest doses. Dose measurements should cover long periods of time (i.e. complete cycles between outages) in order to register potential transients or significant deviations in doses. Alanine dosimeters are particularly suitable for this type of measurement, as they are not prone to long term fading [1, 16].

Continuous recording (temperature and radiation) would be more helpful in performing service life assessments.

4.2.4. Identification of hot spot areas

Specific locations (hot spots) can exist within the plant where environmental conditions are more severe than those typical of the area of concern and which also exceed those considered in the plant design and in subsequent qualification. The identification of these hot spots is fundamental in order to avoid significant localized cable degradation and unexpected cable failure.

Typical factors producing hot spots might include:

- High temperature:
  - Proximity to steam piping;
  - Devices that conductively transfer heat to the area of the cable (e.g. thermocouple and RTD pecker heads);
  - Self-heating (power cables);
  - Ineffective ventilation;
  - Steam leaks;
  - Proximity to high temperature equipment (e.g. heaters, energized solenoid valves);
  - Sealing elements, fire barriers or any other element that can reduce heat dissipation of cables.
- Chemical agents:
  - Use of solvents or lubricants not compatible with cable materials;
  - Fluid leaks with chemical agents.
- Radiation:
  - Proximity to high-dose sources (pipes, valves);
  - Primary system areas.
- Electrical conditions:
  - High-leakage currents;
  - Partial discharges;
  - Overvoltages.
- Mechanical conditions:
  - Vibration.

Other additional agents that can produce localized severe conditions include ultraviolet radiation and electrochemicals. Mechanical conditions may be the result of inadequate cable installation.

Section 4.2.6 describes recommended methods to identify hot spots.

4.2.5. Unanticipated operating conditions

Unanticipated operating conditions are caused by defective installation, operation or manipulation of the cable, which can lead to enhanced degradation. These conditions are usually only identified through visual inspection or when degradation has already occurred. Such operating conditions are normally identified through the performance of well prepared and executed plant walkdowns as described in Section 4.2.6.

Unanticipated operating conditions can arise from three main sources: installation, service and maintenance/human error.

Installation

The way a cable is installed can cause significant mechanical stresses that are not evaluated within the design conditions and which can result in cable degradation and failure. When cables are installed through a conduit, they can be damaged through abrasion, cuts and grooves which are produced during the installation process.

When cables are installed in trays, they can be subjected to different stresses, namely:

- The cables installed in the lower part of trays are subjected to mechanical compression stresses.
- If the number of cables is high, cable heat dissipation may be hindered and result in higher than expected temperatures.
- Cables may protrude from the tray and be mechanically damaged.

Other installation problems are associated with inadequate supports, bends and vertical mountings, which may create mechanical stresses on the cables.

When installation does not provide for enough separation, factors already discussed such as water, steam, heat and chemical damage can produce significant cable degradation. An additional factor is the use of fire barrier materials around cables, which may significantly reduce heat dissipation.

Service

Cable loading (voltage and/or current) beyond its design specifications may result in unexpected degradation and a reduction in its established qualified life. Severe overloading may also cause insulation damage by mechanisms other than thermal ageing.

Maintenance/human errors

Defective maintenance practices or human errors may cause localized cable damage and degradation. Examples of these include maintenance personnel standing on cable trays or tools being dropped over installed cables.

4.2.6. Walkdowns for the identification of hot spots and unanticipated service conditions

Several complementary activities can be used to identify hot spots and unanticipated service conditions, namely:

— Interviews with maintenance and operation personnel;
— Analysis of maintenance and operation historical data;
— Plant walkdowns.

Plant walkdowns are a very effective tool for the identification of hot spots and critical service conditions, as well as for local cable degradation, and are therefore discussed in some detail in this section. A useful guide is provided in Ref. [17] with examples of the type of localized conditions that can give rise to hot spots.

4.2.6.1. Areas to be included in the walkdowns

Areas with the most severe environmental conditions should be included in the walkdowns. Typical areas are those listed in IAEA-TECDOC-1188 [1].

As a result of interviews with maintenance and operation personnel and examination of plant design documentation and historical records, areas with a potential for hot spots or unanticipated service conditions can be established and included within the walkdown scope. In general, these areas can be established based on criteria such as:

— The presence of fluids on the floor or other structural elements;
— Signs of damage to the painted surfaces of walls and structures;
— The presence of leaks of any kind;
— Condensation;
— Equipment or structures with high vibration;
— Equipment subjected to frequent maintenance;
— Damaged fire barriers;
— Areas where electrical equipment failure has been identified.

Areas with a large number of cables installed should be selected for walkdowns.

4.2.6.2. Walkdown inspections

The following tables identify the different aspects that should be inspected during the plant walkdowns, indicating the possible origin of the detected symptoms as well as its possible effect on cable condition. Reference [18] includes extensive checklists for visual inspection of electrical components at an NPP, including cables.

Table 4.1 relates to hot spot identification, Table 4.2 to the identification of unanticipated operatory conditions and Table 4.3 to the identification of electrical problems.

TABLE 4.1. HOT SPOT IDENTIFICATION

Aspect to inspect	Origin/effects/actions
Visible spillages or sprays of chemical solutions, oil or fuel	Leakage; clean, locate the origin and repair the leak; check if the ventilation system is causing the exposure of cables to gases from chemical products
An acid/bitter taste or stinging in the eyes	Possible acid leak or other caustic chemical agents; clean, locate the origin and repair the leak
Abnormal smell	Possible use or spillages of chemical solutions, biological activity or abnormal heating of electrical equipment
Abnormally high temperatures	Check for possible faults of the ventilation; possible accelerated degradation process of cables; inspect the cables in detail
Abnormally high radiation dose	Check for possible unexpected sources of radiation; possible accelerated degradation of the insulation
Abnormal or variable sounds	Possible faults on equipment that can affect the cables
Steam leaks	Possible increase of temperature inside the area; cables can be seriously degraded by the direct action of steam; verify the temperature and check that it does not correspond to a radiologically contaminated circuit; inspect the cables in detail
Puddle or leak of water/condensation	Locate and repair; check if the problem proceeds from leaks or steam spray; verify the temperature and check that it does not correspond to a radiologically contaminated circuit; inspect the cables in detail
Deterioration of paint on walls or structures	Possible high temperature or radiation dose
Equipment or structures with high vibrations	Possible damage on cable jackets; check in detail for the existence of cuts or cracks in the jackets
Piping with high temperature	Possible accelerated degradation on nearby cables

TABLE 4.2. IDENTIFICATION OF UNANTICIPATED OPERATING CONDITIONS

Aspect to inspect	Origin/effects/actions
Loss of colour on parts of the cable surface (including appearance of yellowish or whitish marks)	Localized severe environment located
Widespread loss of colour (including the appearance of yellowish or whitish marks)	Widespread severe environment or long term overcurrent
Twisted or excessively bent cable	Possible installation defect, inadequate support, external loads
Abnormally hot cables in localized spots (detected by touch or by thermographic inspection, preferably	Possible localized high temperature environment; possible faulty connections
Abnormally hot cables over its complete length (detected by touch or preferably by thermographic inspection)	Possible long term overcurrent, excessive cable association (groups) or widespread environment with high temperatures
Cracks on jackets or insulations	Thermal, chemical or radiological degradation
Appearance of oil or deposits on the cable surface	Possible migration of plasticiser materials (PVC cables, Butyl rubber or CSPE), biological activity or chemical attack
Trays with high level of filling	Verify temperature of cables

TABLE 4.2. IDENTIFICATION OF UNANTICIPATED OPERATING CONDITIONS (cont.)

Aspect to inspect	Origin/effects/actions
Indication of cable abnormally twisted or elongated	Verify if there are signs of cuts, cracks or fissures on the insulation and jacket due to a faulty installation
Structural damage on trays or lack of edge protection elements	Verify if there are signs of cuts, cracks or fissures on the cable jacket
Concentric cracks (in thermoplastic materials)	Verify the existence of local overheating or faulty connections
Surface with opaque, rough or dusty appearance	Verify if there has been contact with chemical agents or solutions
Expanding, deformed or softened cables	Verify the presence of high temperatures or radiation doses

TABLE 4.3. IDENTIFICATION OF ELECTRICAL PROBLEMS

Aspect to inspect	Origin/effects/actions
Abnormal noise in the proximity of cables (buzzing, whistling)	Possible electrical discharges
Erratic measurements of instruments	Possible leakage currents
Soot coatings or marks on the surface	Possible electrical discharges
Discolouration of ground cable	Possible current or earth fault in the system

4.2.6.3. Walkdown types

Depending on when and how often walkdowns are carried out, they can be classified as routine, specific or maintenance walkdowns.

Routine walkdowns are performed with the plant in operation and are used to detect abnormal power cable self-heating when the cables will normally be energized. These walkdowns are recommended to be done in areas with a large amount of cables and high temperature piping. Cables to be inspected must be accessible without the need for dismounting of equipment or plant structures.

Specific walkdowns are applied under situations when specific environmental or service situations which may lead to significant cable degradation have been identified and immediate action is needed.

Walkdowns associated with maintenance or outage activities are performed when the areas cannot be visited during normal plant operation or cables are not directly accessible. The walkdowns are performed alongside other plant maintenance activities in order to access cables in areas such as:

— Equipment connection boxes;
— Areas with limited access due to irradiation conditions;
— Closed cable ducts or conduits;
— Cables in areas of difficult access.

4.2.7. Use of thermography in walkdowns

Thermography is potentially a useful method for identifying environmental hot spots and unanticipated operating conditions at an NPP but has significant limitations for use as a diagnostic tool. Hot spots arising from self-heating of power cables tend to occur at poor contacts (e.g. from corrosion or loose connections). These would normally be inside enclosures and thus not be visible to the thermography equipment. However, if enclosures can be opened for inspection when cables are energized, thermography can be very useful for fault location.

Locating hot spots from external heat sources (e.g. missing thermal insulation) is feasible using thermography but does need to be carried out during full power operation of the plant. This may limit access to some areas of the plant. Thermography is best used as a supplement to plant walkdowns to check whether cable degradation is due to a localized hot spot or unanticipated operating condition, and to provide ‘snapshots’ of the plant at various intervals (e.g. every ten years) during its lifetime.

4.2.8. Walkdown observations

Any anomalies observed during walkdowns must be evaluated and documented. For example, cables that have been observed to be located in an environment for which they were not qualified must be evaluated to determine the impact of the environmental conditions on the qualification of the cables.

4.3. CABLE CONDITION MONITORING REQUIREMENTS

The CM objectives can be grouped into the following two categories:

(1) Assessment of the current state of cable degradation in terms of electrical and mechanical properties. Usually, elongation at break is the reference indicator used to assess the degradation state of cable insulation. A widely used limiting value is 50% absolute elongation. For many of the polymeric materials used in cables, this value represents the retention of sufficient mechanical properties to maintain cable integrity. However, the real indication of degradation is the loss of electrical properties such as resistance or dielectric parameters. The correlation between mechanical and electrical parameters is not usually linear or easy to evaluate.
(2) Prediction of the remaining cable lifetime. This is a challenging task because of the non-linear, time-dependent properties of the polymeric materials used in cable construction and their relationships with stressors such as high temperatures and ionizing radiation. However, the CM techniques presented and described in Sections 4.4–4.7 show the potential to generate data on the current state of ageing in polymeric cable materials. In combination with appropriate material ageing models and knowledge of environmental conditions, these data can also be used to estimate residual material lifetimes. This is only possible when sufficient data has been generated to validate predictive ageing models for the specific cable material being considered (see Annex A–5).

Some concern has been expressed about the ability of low voltage cables to survive DBA events after their current qualified life of 40 years [19]. In addition, some cables, after a simulated ageing period of 60 years, have shown unacceptably high leakage currents during post-DBA voltage withstand tests. These important observations suggest that some form of CM should be carried out during plant operation for comparison with QLD. So long as it can be repeatedly demonstrated that the cable is in a condition that will survive a DBA, acceptable safety margins can be applied during any extended period of operation (e.g. from 40–60 years).

The ideal CM technique would need to satisfy a range of requirements. Important considerations associated with these requirements are listed below:

- No disturbance of cables or sample removal during testing;
- Indicator of structural integrity and electrical functionality;
- No disconnection of equipment;
- Usable during normal operation where appropriate;
- Applicable to all materials;
- Well correlated with real cable degradation;
- Usable in areas of limited access;
- Reproducible in different environments (e.g. temperature, humidity, vibration);
- Cost effective;
- Able to detect defects at any location;
- Provide adequate time for corrective action to be taken before cable failure.

In reality, there are no currently available techniques that satisfy all of these requirements, but a number of methods have been evaluated for use at NPPs as part of a monitoring programme. For the most developed of the CM techniques, standards for the test method have now been written to enable their use in CBQ [23, 24, 28].

The generic characteristics of a broad range of CM techniques are shown in Table 4.4. Most of these methods are appropriate for use in evaluating ageing degradation in laboratory studies and potentially for use in plants. Not all of these have been fully evaluated yet, but these methods have been selected because encouraging results have been achieved by several organizations around the world. Other methods can be found in Ref. [20]. In addition, the NRC has commissioned a review of currently available CM techniques [21].

TABLE 4.4. CM METHODS DESCRIBED IN THIS REPORT

Testing method	Monitored property	Field/lab	Destructive/intrusive	Local/full-length	Materials applicable
Visual/tactile Inspection	Visual	Field	No /no	L	All
Illuminated borescope	Visual	Field	No/yes	L	All
Elongation at break	Mechanical	Lab	Yes/yes	L	All
Thermography	Physical	Field	No/No	L	All
OIT/OITP	Chemical	Lab	Microsampling required	L	EPR, PE, XLPE, PVC
TGA	Chemical	Lab	Microsampling required	L	PVC, CSPE, EPR
Gel fraction	Chemical	Lab	Microsampling required	L	All (so long as suitable solvent) SiR not applicable
Density	Chemical	Lab	Microsampling required	L	XLPE, other thermoplastics and some elastomers (EPR)
Oxygen consumption	Chemical	Lab	Microsampling required	L	All
Nuclear Magnetic Resonance (NMR)	Physico-chemical	Lab	Microsampling required	L	All
Microhardness	Physical	Lab	Microsampling required	L	Elastomers
Infrared analysis	Chemical	Lab	Yes/yes	L	PVC, XLPE, EPR, PE
EMPA	Chemical	Lab	Yes/yes	L	All
Indenter modulus	Physical	Both	No/no	L	PVC, CSPE, EPR, EPDM
Indenter recovery time	Physical	Both	No/no	L	All
Near infrared reflectance	Chemical	Both	No/no (but some microsampling possible)	L	EPR, PE
Sonic velocity	Physical	Both	No/disconnection required	L	PVC, PE, EPR
Partial discharge	Electrical	Both	No/disconnection required	F	All (medium voltage cables only)
FDR/LIRA	Electrical	Both	No/disconnection	F	All

TABLE 4.4. CM METHODS DESCRIBED IN THIS REPORT (cont.)

Testing method	Monitored property	Field/lab	Destructive/intrusive	Local/full-length	Materials applicable
Dielectric loss	Electrical	Both	No/disconnection required	F	EPR, XLPE
LCR	Electrical	Both	No/disconnection required	F	All
Insulation resistance	Electrical	Both	No/disconnection required	F	All
TDR	Electrical	Both	No/disconnection required	F	All
RTDR	Electrical	Both	No/disconnection required	F	All
AgeAlert™	Electrical	Both	No/no	L	All

The CM techniques listed in Table 4.4 are described in more detail in the following sections. Qualitative methods are described in Section 4.4, techniques requiring sample removal in Section 4.5, techniques not requiring sample removal in Section 4.6 and electrical techniques in Section 4.7. Many of these methods only measure the jacket material unless access to the insulation is possible (e.g. at terminations). The correlation between the ageing of the jacket and the insulation material will need to be established.

4.4. CM QUALITATIVE METHODS

4.4.1. Visual and tactile inspection

Visual and tactile inspection is a very valuable tool for the evaluation of cable condition when carried out by a skilled technician [18]. It can be used to detect structural inhomogeneity from manufacture or operational conditions, as well as to detect possible loss of additives or absorption of humidity. When ageing is detected in a visual inspection, it is possible to take the decision to use more sophisticated CM techniques such as those described in Sections 4.5–4.7 to quantify the degree of ageing.

It is not appropriate to apply the more sophisticated CM techniques to all of the cables at an NPP. Visual and tactile inspections are useful methods of identifying which cables should be considered for more detailed testing.

Tactile inspection consists of manipulating the cable (by applying a limited twist or flex, but not beyond the radius of permissible curvature), looking for any change of colour (normally discoloration) or cracks in the external jacket and to listen for any cracking sounds when the cable is flexed. Visual inspection should also include looking for any surface deposits that might indicate a loss of additives or external contamination.

Advantages

— Visual and tactile inspection can be carried out at relatively low cost and does not require special equipment.
— Applicable to all materials.
— Samples do not need to be taken from the cables.
— It is possible to carry out in situ and obtain immediate information on the cable condition.

Disadvantages

- — The cable to be inspected has to be visible and accessible.
- — It is usually only possible to inspect the jacket except at terminations.
- — Quantitative information is not obtained.
- — It is essential to have experienced, trained personnel.

4.4.2. Illuminated borescope

The use of an illuminated borescope to inspect inaccessible cables has been shown to be a useful technique for identifying stressors that can lead to cable degradation. It can also detect visible cable damage. The borescope can be inserted into conduits or other locations containing cables that would ordinarily be inaccessible for inspection for mechanical damage that may have been caused during installation or service, or for indications that water has been present indicating submergence of the cables during service. The borescope can also detect the presence of other contaminants such as dirt, sharp metal debris or chemicals that can cause accelerated degradation of the cables. Based upon the results of a borescope inspection, a decision can be made as to whether additional, more intrusive testing is needed.

Advantages of this technique are that it is non-destructive, simple to perform and requires little training to be successful. A disadvantage is that it does not provide quantitative data that can be trended; therefore, its main benefit is as a screening technique to determine if additional testing is needed. Care must be taken not to damage the cables when inspecting them in conduits.

4.5. CM TECHNIQUES THAT REQUIRE SOME FORM OF SAMPLE REMOVAL OR INTRUSION

No diagnostic CM technique that is currently available can be described as truly non-intrusive as the cables will generally require some form of disturbance to carry out a test. The level of intrusion or disturbance, however, must be kept to a minimum. This especially applies to cables that might be heavily aged. The requirement for sample removal must, in the first instance, be thought of as a primary limitation and in some cases sample removal might not be an option. However, with the current status of development of CM techniques, sample removal might be the only viable option for some materials.

All of the CM techniques described in this section require some form of sample removal or intrusion. A viable technique must keep sample size and intrusion levels to a minimum. All of the techniques described in this section, excluding elongation at break (Section 4.5.1), have been selected or developed to follow these rules. However even the minimum level of intrusion must be considered as a disadvantage. The methods described in this section are best applied to samples in a cable deposit or from cables taken out of service. Microsampling of operational cables may be possible provided that approved sampling techniques are available. Some country -specific regulatory requirements do not permit such sampling on operational cables.

These methods will only provide information on the cable conditions at the specific locations from which samples are removed. The most developed of the methods, elongation at break and oxidation induction, would be appropriate to use in a CM programme for CBQ.

4.5.1. Elongation at break — tensile testing

The elongation at break of a polymeric cable material during a tensile test is the benchmark property by which the structural integrity of the cable, and therefore its functionality, is usually assessed. Historically a value of 50% absolute elongation at break has defined the end-of-life condition. This value was determined by considering a conservative estimate of cable ageing that defines the ability of an aged cable to survive DBA conditions. Current standards suggest that values of either 50% absolute or 50% relative can be used to define end of life. There are varied opinions as to the applicability of these values as suitable end-of-life indicators. Nevertheless, the above mentioned values are used because they demonstrate a reasonable value to ensure flexibility and ability to withstand some movements and vibrations during normal operation as well as during postulated accidents. Certain cable compositions may have different characteristics. Verification through actual tests is the preferred approach to establish the qualified condition.

For tensile test measurements on polymeric materials that have been formed into cables, sufficient lengths of the cables must first be removed from the plant (normally a few metres). The cable must then be stripped down into its individual components so that the jacket, bedding layer and insulation can be cut into suitable dimensions for testing. In some cases, the cable samples might need some form of treatment before testing (e.g. removal of the ridges on insulations associated with multiple conductors). The samples are then placed in an appropriate tensile test machine and pulled until they break. The elongation at break and tensile strength are the two mechanical properties that are normally recorded for each sample, although for some polymeric materials (e.g. thermoplastics), the tensile strength only starts to decrease after significant ageing has occurred. A representation of a set of tensile results for a thermoplastic polymer after progressive stages of ageing is shown in Fig. 4.1.

It is important to define the test methodology and keep parameters such as sample size and tensile test speed consistent, as variations in test parameters can lead to misleading test results. In many cases, appropriate 'dumb-bell' samples can be cut out of cable jackets and bedding layers, but the smaller cable insulation samples usually comprise hollow tubes, and in this case, it is again important to ensure that sample preparation methods are consistent. Standards for the use of elongation at break as a CM technique are now available [22].

Although this test method generates the optimum data for cable condition assessment, it is impractical to use it as a routine CM method because it is destructive, intrusive and because of the large downtime associated with cable removal and replacement. However, the method is particularly useful where cable samples have been placed in a sample deposit, specifically for CM.

4.5.2. Oxidation induction tests

In most polymers, many of the dominant processes associated with radiation and thermal degradation are controlled by oxidation. That is why most polymers contain antioxidants (sometimes called antirads) in their formulation. During exposure to radiation and thermal ageing conditions, the antioxidants act as radical scavengers

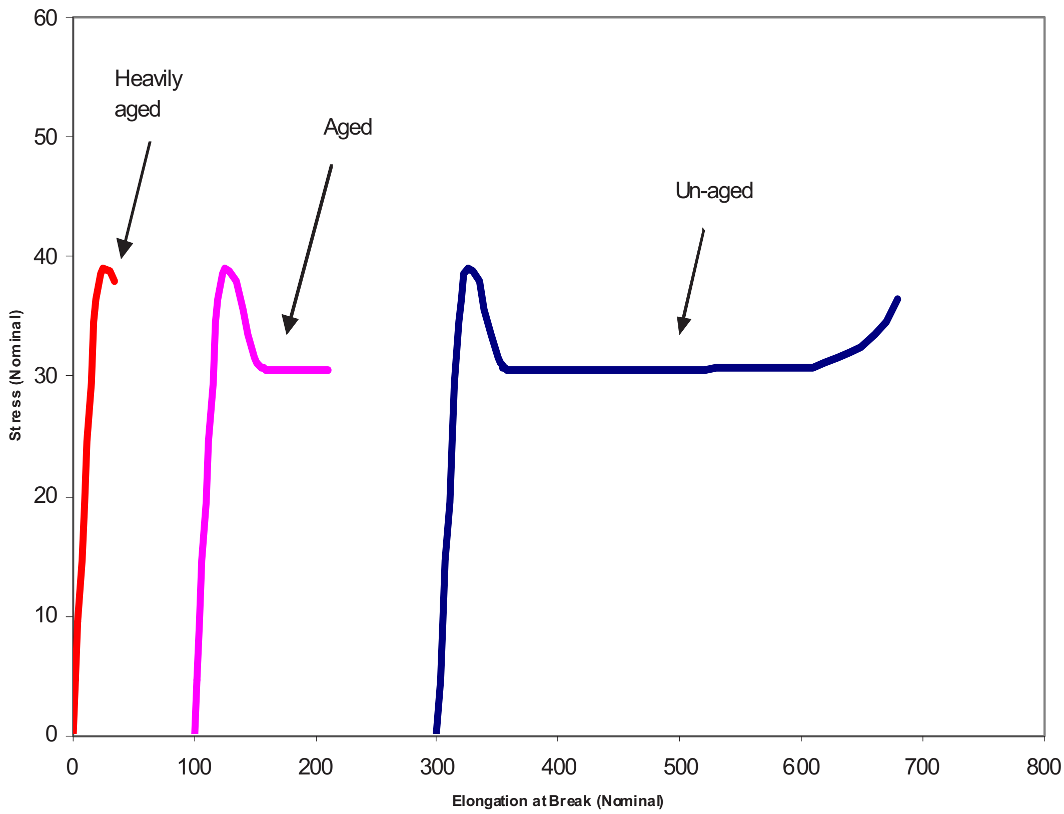

FIG. 4.1. A typical set of degradation curves for a thermoplastic material.

and are consumed at a rate defined by the severity of the ageing conditions. When they have been consumed, the polymer usually begins to degrade rapidly. Polymer properties known as oxidation induction time (OIT) and Oxidation induction temperature (OITP) can be determined on standard differential scanning calorimetry (DSC) instruments, and these properties are dependent on the remaining levels of antioxidants and the extent of oxidation (or degradation). Therefore, if values of OIT or OITP can be measured for a cable material, there is a strong possibility that they will correlate with degradation as measured by elongation at break.

4.5.2.1. Oxidation induction time

OIT is carried out on small polymer samples weighing 1–10 mg. The sample is usually cut up into small pieces and placed in the sample pan of a DSC. These instruments measure the difference in heat flow between a polymer sample in one sample pan and an identical empty sample pan while both are heated in a closed cell. The sample is heated quickly to a predetermined temperature (e.g. 200ºC) in an inert atmosphere (usually nitrogen) and once the heat flow has stabilized, the inert gas is replaced by oxygen. After an induction period, the sample begins to oxidize, and the time at which this occurs can be measured because there is an exothermal heat flow associated with the oxidation process that can be read from the instrument. A typical OIT trace is shown in Fig. 4.2.

The length of time that is required for oxidation of the polymer to initiate is defined as the oxygen induction time, and this time period is dependent on the levels of antioxidant in the sample. The induction time is defined as the time at which a particular heat flow threshold relative to the baseline (usually 0.1 W/g) is exceeded, and reading off the point at which the tangent intersects the baseline. For instance, a long induction time may denote a sample with significant levels of antioxidant and a low degree of degradation. A short induction time measured at the same temperature is likely to denote low levels of antioxidants and a potentially heavily aged sample. This method has been standardized for use in CM [23, 24]. OIT has been shown to correlate well with the degradation of polyethylene and ethylene-propylene rubbers, and also CSPE and PCP [25]. However, for halogenated materials, great care has to be exercised as the degradation products from these materials can damage expensive calorimeter cells. It is considered impractical to carry out continued multiple OIT testing on halogenated materials unless specific non-corrossible cells are used.

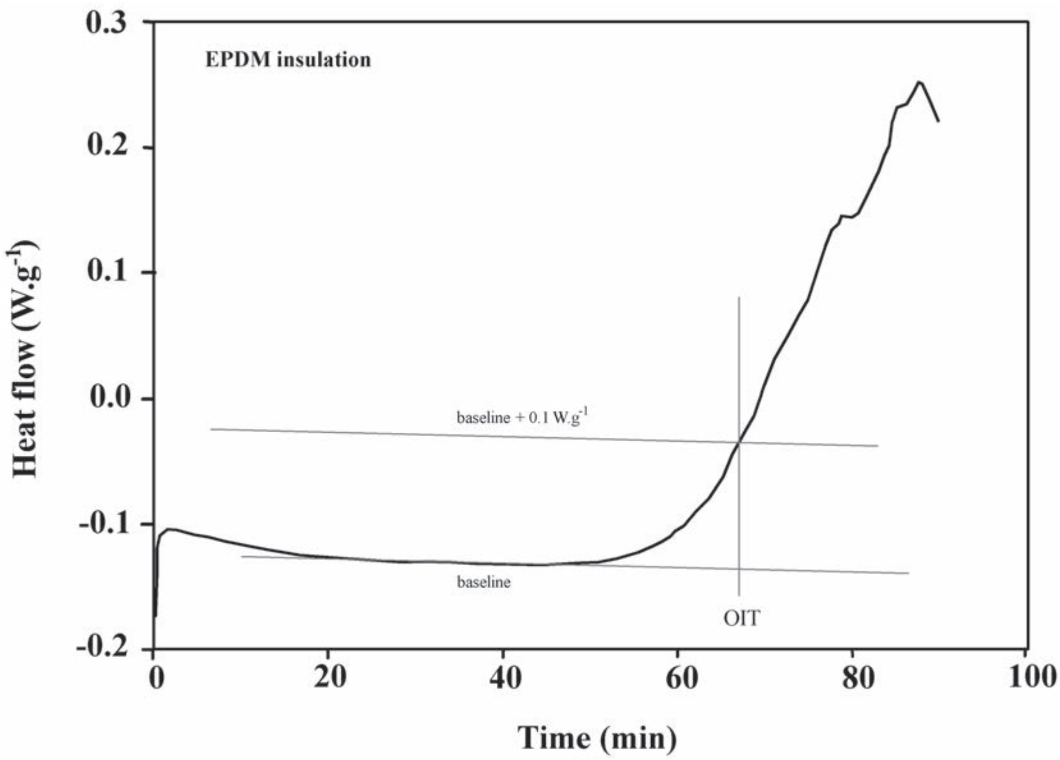

FIG. 4.2. A typical OIT plot showing a threshold measurement at 0.1 W/g.

4.5.2.2. Oxidation induction temperature

The sample preparation and instrumentation for OITP is identical to that for OIT, but in this case, the sample is heated at a slow ramp rate (usually 10ºC/min) in flowing oxygen. Oxidation in the sample is characterized by an increase in exothermic heat flow, which accelerates as the temperature increases. Unlike the OIT test, physical transitions such as glass transition and melting points may appear on the instrument chart (see Fig. 4.3).

In a similar manner to OIT, the value of OITP is read from the temperature at which a threshold relative to the baseline (usually 0.5 W/g) is exceeded. As the level of ageing increases, the OITP usually decreases, and this decrease can be correlated to elongation at break for certain polymers.

4.5.3. Thermogravimetric analysis (TGA)

Thermogravimetric analysis is carried out using commercially available thermal analysis instruments and requires sample sizes similar to those used for OIT/OITP. In this case, the sample weight is monitored as the sample is heated in a chamber at a constant rate. The temperature at which the sample weight has decreased to 95% of its original value is usually taken as the reference point. The value of this temperature depends on the level of ageing in the polymer and will tend to decrease with increased ageing levels. The tests can be carried out in an air or oxygen purge through the sample chamber, but the nature of the purge will affect the TGA temperature. TGA testing is usually carried out on samples that evolve corrosive degradation products (CSPE, PCP, PTFE) as the sample chambers in TGA equipment are chemically far more robust than those used in DSC.

A typical TGA trace consists of a plot of sample mass against temperature. The TGA reference temperature (i.e. at 95% of original value) is determined using the instrument software by one of two methods: either the temperature at which a 5% mass loss occurs or the temperature corresponding to the point at which the maximum rate of weight loss occurs (see Fig. 4.4).

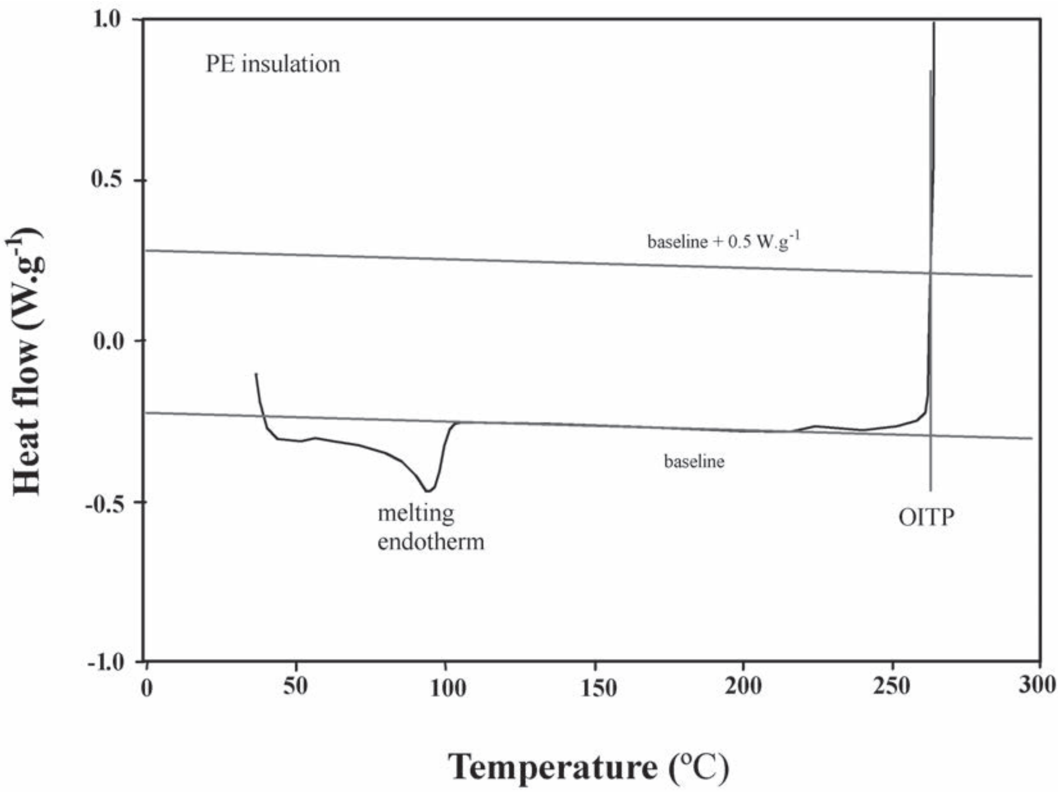

FIG. 4.3. A typical DSC trace for a thermoplastic polymer indicating measuring point for OITP.

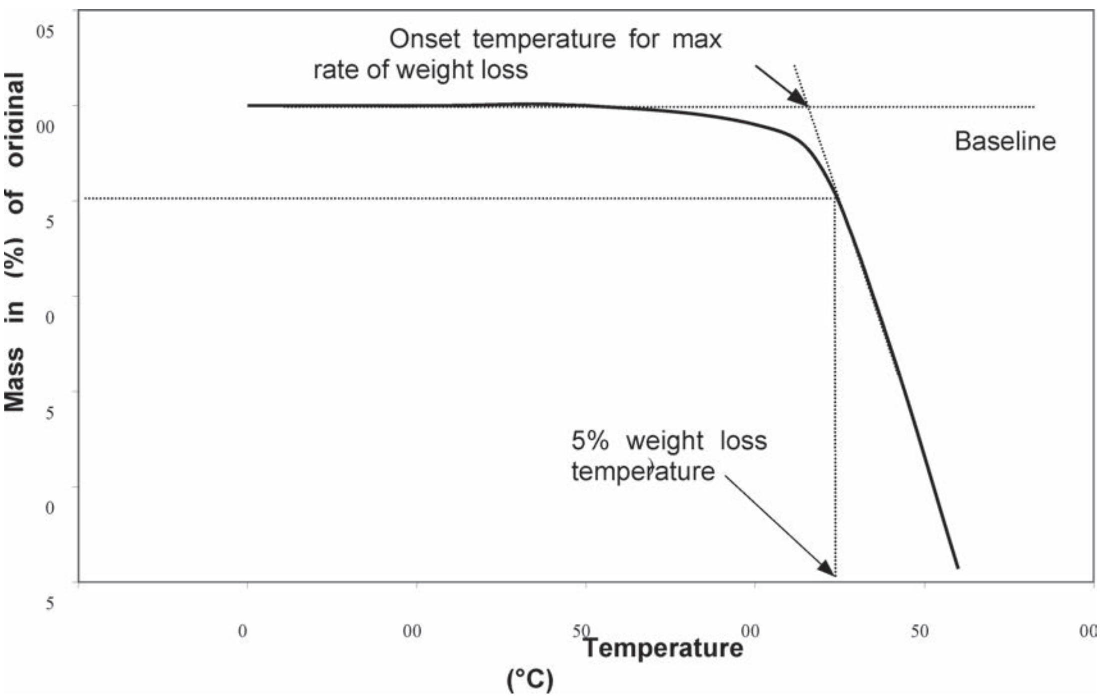

FIG. 4.4. A typical TGA trace showing 5% weight loss temperature and maximum weight loss temperature.

The TGA test is cost effective, quick and simple to use. It has shown to be effective for cross-correlating radiation degradation in PVC materials. The technique provides an alternative thermal test method for CSPE and PCP although the data are limited for these materials and suggest a lack of sensitivity for thermally degraded CSPE.

4.5.4. Gel fraction and solvent uptake factor

The amount of cross-linking or chain scission defines the level of ageing in a polymer, and a common method for evaluating the level of cross-linking is the determination of the gel fraction and solvent uptake factor. This involves placing a sample in a solvent and refluxing, weighing the sample when swollen by the solvent and then driving off the solvent using a vacuum chamber. The final weight of the sample after drying divided by the as-received weight before swelling gives the gel fraction for the sample. The weight when swollen divided by the final weight gives the solvent uptake factor. Both of these properties are dependant on the amount of cross-linking that has occurred in the sample. If the dominant process in the ageing reaction is cross-linking, the percentage gel fraction goes up, and the solvent uptake factor goes down. If the dominant process is chain scission, the opposite occurs. A measure of crosslink density or level of chain scission should correlate with structural integrity and therefore with elongation at break. Data in the literature suggest some success in correlations of these parameters for polyethylene, CSPE and PCP on samples weighing as little as 1 mg.

This technique is a relatively simple, cost effective test method, and samples of small size are usually required. An example plot of solvent uptake factor and elongation at break against ageing time for a CSPE material is shown in Fig. 4.5 [26].

4.5.5. Density measurement

Density measurement is a well established means of evaluating ageing in polymers. As oxidation dominates the degradation process when polymers age in air, the oxidation products that are generated usually lead to an increase in density, but the density may decrease in some materials. Clearly, the higher the level of ageing, the greater the concentration of oxidation products and the higher the density. The measurement of density in small samples of polymer can be achieved in two ways: the Archimedes approach or by using a density gradient column.

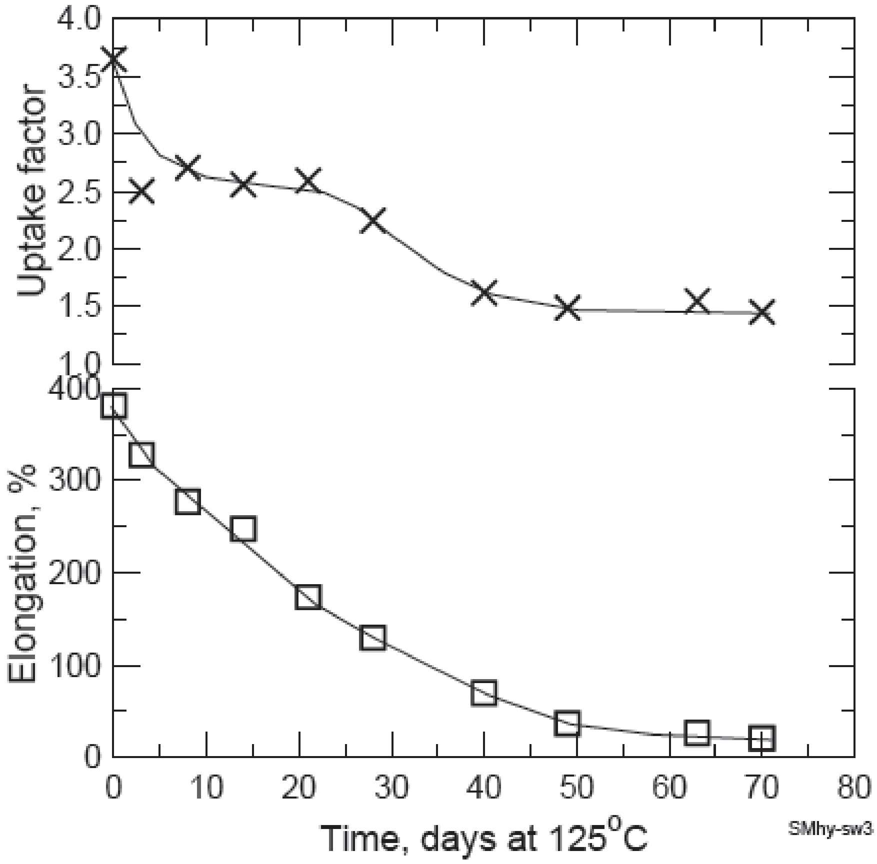

FIG. 4.5. Example plots of the solvent uptake factor and elongation at break against ageing time for a CSPE material.

4.5.5.1. Archimedes approach

The Archimedes method is normally carried out on samples weighing tens of milligrams where the sample is weighed in air and then in a liquid of known density, from which the density can be calculated from the simple equation:

$$\rho = \left[\frac{W_{air}}{W_{air} - W_{liq}} \right] \rho_{liq} \qquad (4.1)$$

where W_{air} is the weight in air, W_{liq} is the weight in liquid and ρ_{liq} is the density of the liquid.

4.5.5.2. Density gradient column

For very small samples (e.g. thin scrapings of insulation and jacket materials), a more convenient method of density measurement consists of using a density gradient column. The column consists of a graduated glass tube of about 1 m in length suspended vertically in a water bath held at constant temperature, usually 20–25ºC. The column is then filled using two miscible liquids of different densities in such a way that a linear density gradient is obtained decreasing from bottom to top.

The column is calibrated by carefully introducing specially prepared glass beads into the column, their equilibrium position defining the density at that point. Samples are then introduced into the column and allowed to reach their equilibrium positions from which their density can be measured. An accuracy of 0.0005 g cm^{-3} can be achieved with this method.

Density is a relatively quick and cost effective method of characterizing polymer degradation, and the column method can be particularly effective in monitoring degradation through a sample thickness if the sample is sliced using a microtome and each slice is suspended in the density column. The Archimedes approach, however, can be misleading where density is measured in larger samples if heterogeneous ageing has occurred. Dense materials (e.g. PTFE) are difficult to measure in the density gradient column because the liquids required to set up the column are harmful and require safety precautions. The density column can also suffer from instability due to vibration.

Density measurement in general has been correlated to degradation for many polymeric materials, including CSPE, Neoprene, polyethylene and SIR [26].

4.5.6. Oxygen consumption rates

The rationale of some CM techniques is based on the measurement of a secondary property of the cable material, which changes as a result of oxidation (e.g. density). For oxidation to occur in a polymer, oxygen must be available in the ageing environment and also be able to permeate into the sample. When oxidation occurs, oxygen must be consumed from the local environment.

Researchers [26] have developed a CM method whereby an extremely accurate measure of the amount of oxygen consumed by a cable material may be determined for any specific ageing condition. A sample of the cable material is placed in a sealed vessel with a known partial pressure of oxygen. The vessel is then exposed to radiation or high temperatures or combinations of the two for a fixed period of time. On completion of the exposure, the partial pressure of oxygen is recalculated using gas-chromatography methods. The difference between the new and old partial pressure over the time period gives the oxygen consumption rate. These measurements can be measured to sensitivities of 1×10^{-13} $mol \cdot g^{-1} \cdot s^{-1}$(moles per gram of material per second). If the amount of oxygen required to degrade a sample to end of life is known (this can be measured experimentally), an accurate measure of the level of ageing can be achieved.

Figure 4.6 shows oxygen consumption data generated from a PCP sample aged in air at different temperatures. Note the unique sensitivity of this technique at low temperatures.

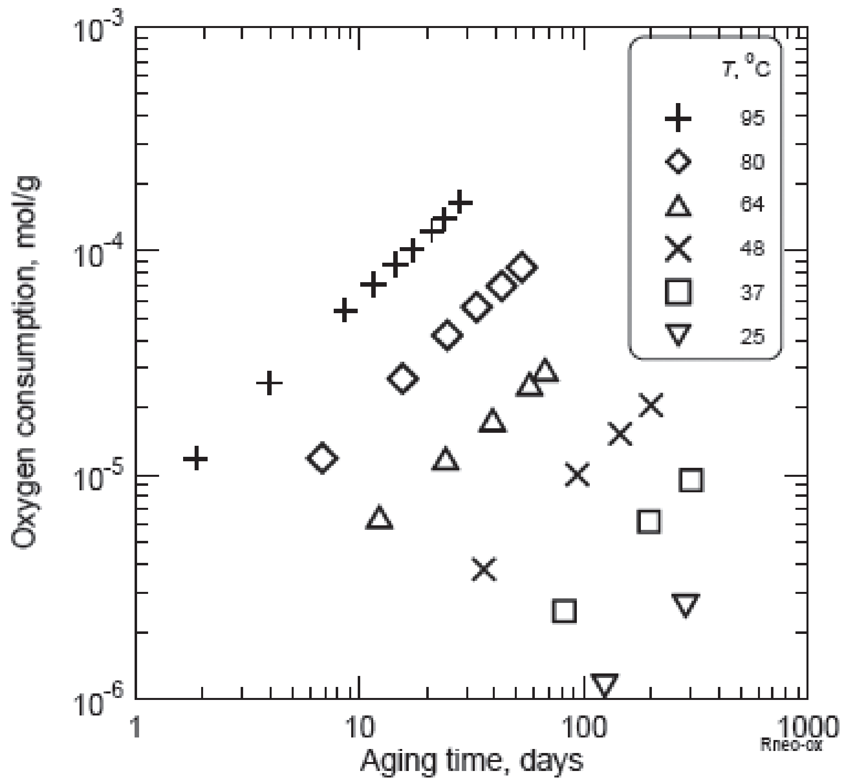

FIG. 4.6. Plots of oxidation consumption against ageing time for a thermally aged PCP sample.

4.5.7. Nuclear magnetic resonance (NMR) relaxation time, T_2

Another technique based on swelling a sample in an appropriate solvent is nuclear magnetic resonance (NMR) relaxation time (often abbreviated to T_2), which is related to the mobility of the polymer chains. As the polymer degrades, the chain mobility will alter producing a measurable change in T_2. This method is based on the fact that the sensitivity of NMR relaxation increases when the sample is swollen with a solvent. As the material ages and degrades, the NMR relaxation time decreases. The measurements are easily carried out using commercial NMR machines, are reproducible and typically require less than 15 to 20 minutes for sample preparation, data accumulation and data analysis. Screening studies of thermally aged materials indicate that the NMR approach is applicable to most cable materials.

NMR relaxation times are sensitive to the cross-link density in the amorphous phase of a polymer and are therefore applicable to most polymer types. The sample size typically required for this technique is of the order of 10 mg. However, successful data have been obtained on samples as small as 100 µg, which implies that the technique can be used with a minimum of intrusion.

Figure 4.7 shows a good correlation of NMR results (proton spin–spin relaxation time, T_2) to elongation at break data for a thermally aged, polyethylene based insulation [26].

4.5.8. Microhardness (modulus) profiling techniques

This technique is primarily used to confirm that homogeneous oxidation is occurring, rather than as a CM technique. This method should not be confused with the indenter modulus data generated from the indenter (Section 4.6.1). Microhardness profiles (sometimes referred to as modulus profiles) can be used to accurately measure the properties of a polymer through its thickness by sequentially measuring hardness/modulus through its

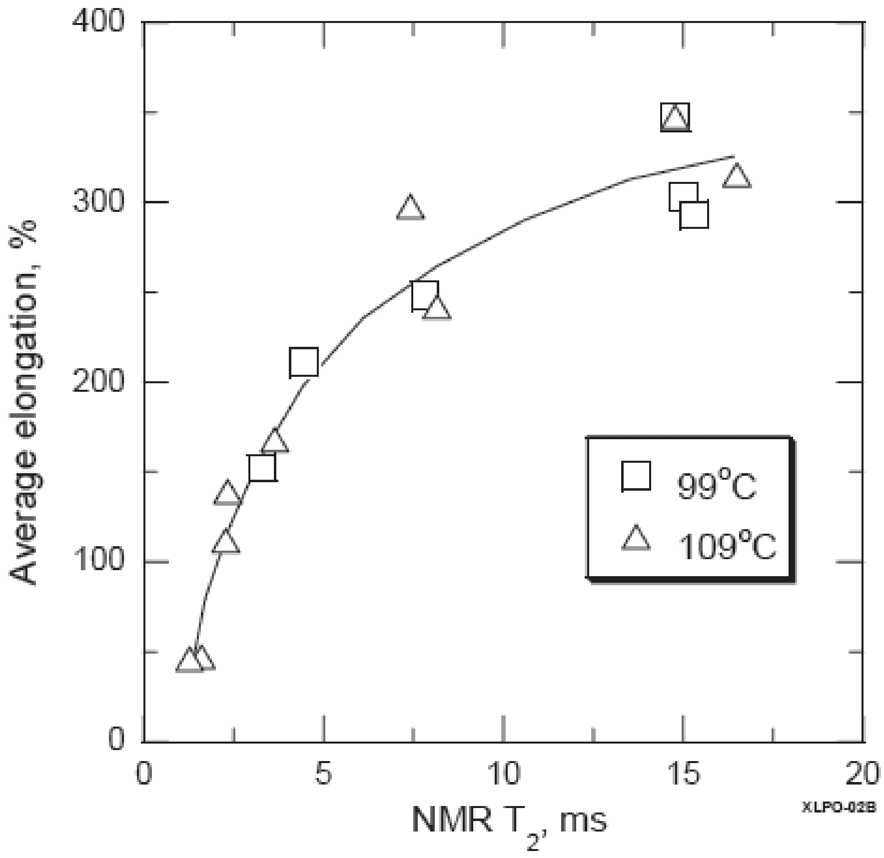

FIG. 4.7. Correlation of NMR relaxation time, T_2 to elongation at break data for a thermally aged, polyethylene based insulation.

cross-section. Some techniques can measure in steps as small as 25 µm so a detailed profile can be made for small samples, if required.

This is an excellent way of determining whether diffusion limited oxidation effects have occurred during ageing (particularly during accelerated tests) but can be time consuming in terms of sample preparation unless automated instruments are used. Microhardness profiling is usually an excellent tool for the study of ageing in elastomers but not usually applicable to thermoplastics.

4.5.9. Infrared analysis

This technique utilizes the fact that, as polymers degrade, the changes in structure that occur result in the formation of new chemical bonds that have different light absorption characteristics than the bonds in the original unaged material. The dominant oxidation mechanisms for polymers aged in air produce carbonyl species that absorb infrared light at characteristic wavenumbers around 1720 cm^{-1}. Therefore a measure of the amount of degradation in a polymer can be inferred from the ratio of absorbance at ~1720 cm^{-1} and another characteristic absorbance in the spectrum for that particular polymer, which will give a measurement of the oxidation levels (see Fig. 4.8). The absorbance at 1720 cm^{-1} tends to increase with increasing degradation.

Historically, infrared analyses have been carried out on thin films of around 100 µm thickness sliced from samples removed from cables. Infrared light in the range of 600 to 4000 cm^{-1} is usually transmitted through the film, and an appropriate detector analyses the frequencies absorbed by the film. This particular technique is limited to thin samples as thicker samples absorb all of the incident light. Samples analysed this way are usually prepared by microtome.

With the development of more advanced technologies, handheld Fourier transform infrared reflectance laser instruments have become available. These instruments function by analysing infrared light reflected from the surface of a sample and can generate spectral data in an identical form to that produced by analysis of films. This means that what was once an invasive technique requiring sample removal has been transformed into the closest thing to a truly non-invasive CM technique that is currently available. This technique is not applicable to polymers that contain heavily absorbant materials such as carbon black (e.g CSPE and PCP).

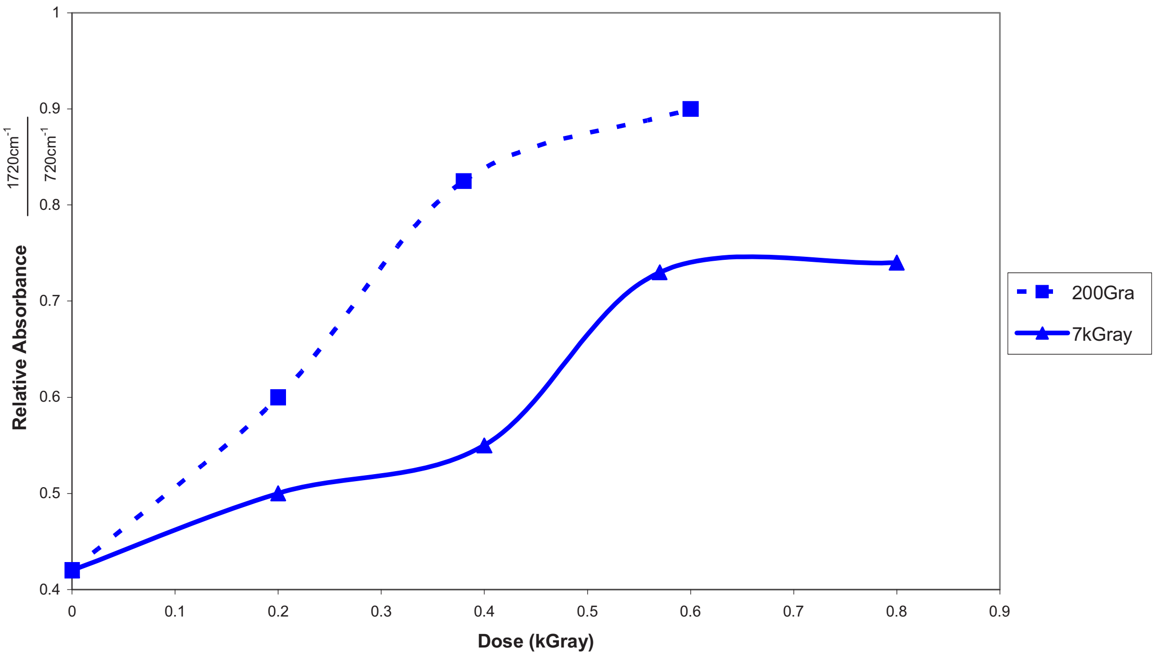

FIG. 4.8. Infrared analysis of a polyethylene material comparing the ratio of absorbance at 1720 and 720 cm^{-1} for unaged and irradiated samples.

4.5.10. Electron microprobe analysis (EMPA)

In a similar manner to the microhardness profiling techniques described in Section 4.5.8, oxidation profiles can be generated by use of electron microprobe analysis (EMPA). Polymeric cable material samples that have been exposed to radiation and/or elevated temperatures can be soaked in a potassium hydroxide solution, KOH. The high reactivity of the KOH results in the bonding of potassium to oxidized species in the cable sample. The concentration of potassium on the treated polymer surface (and therefore the level of oxidation in the cable sample) as a function of sample geometry can then be mapped with high spatial resolution by analysis in an electron microprobe.

While this is a powerful full field technique and can be used on most polymeric cable materials, the samples are often large and normally inconsistent with the requirements for the removal of cable samples at a NPP.

4.6. CM TECHNIQUES NOT REQUIRING SAMPLE REMOVAL

All of these methods only provide information on the cable condition at the location tested and could all be used on operational cables. The most developed of the methods, indenter modulus, would be appropriate to use in a CM programme for CBQ.

4.6.1. Indenter modulus

Indentation is one of the few non-destructive and mainly non-intrusive cable CM methods currently available that is also widely used (some cable movement is usually required, so care should be taken for heavily aged cables). To carry out a measurement, the instrument must clamp around the cable jacket or insulation to be measured, and the probe only penetrates the surface of the test material a few hundred microns.

The indenter modulus (IM) is a parameter associated with the specific compressive stiffness of a polymeric cable material. If a probe of known dimensions is driven into the surface of a sample at a carefully controlled speed, the depth of penetration of the probe can be recorded against the force exerted on the probe. The IM can be evaluated from a plot of the penetration depth against force. A schematic indenter curve is shown in Fig. 4.9; the IM may be calculated from the gradient of the straight line between two predetermined points, in this case set at typical load limits of 1 and 5 N. However, the calculation might be performed preferably on the part of the indentation curve showing best linearity. Standards for use of the indenter as a cable CM tool are now available [27].

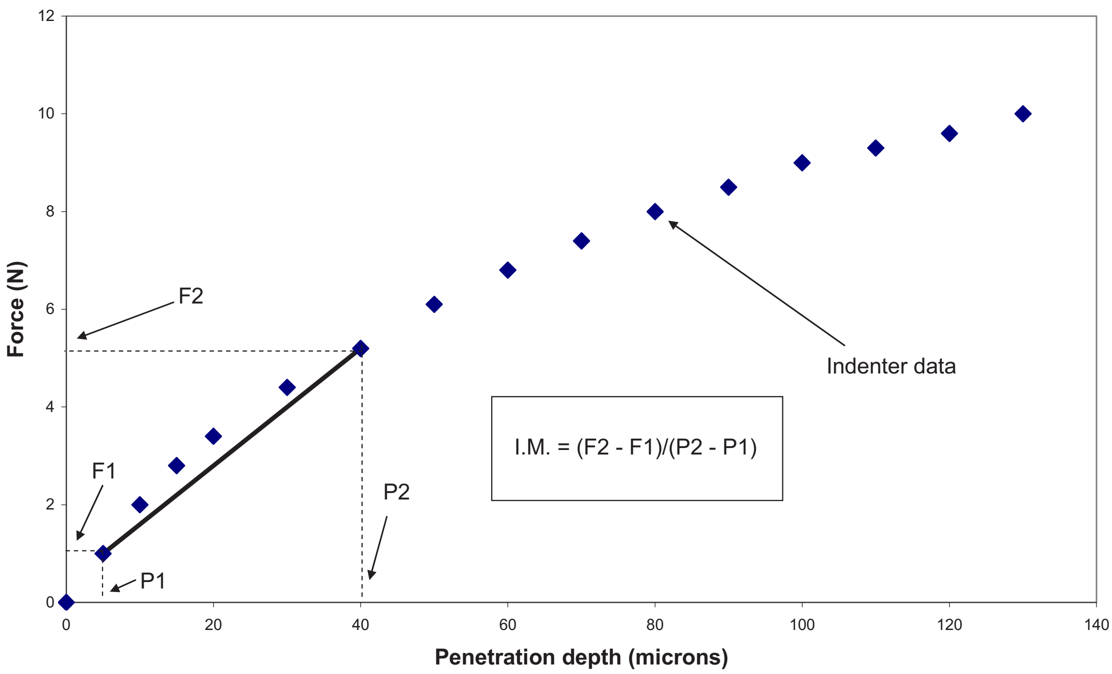

FIG. 4.9. A schematic plot of force against penetration depth, typical of an indenter instrument.

The measured value of the IM of any particular cable material depends on several factors, including probe size, probe speed, test temperature and calculation limits. The probe consists of a truncated cone whose dimensions should be of a standard size and stated for any set of test data. The probe speed should be defined for the particular material being tested, but a speed of 5 mm/min is an acceptable value for most materials. It is important to record the temperature during testing as the IM will tend to decrease with increasing test temperature. The value of IM is also dependent on the limit values set for calculation from the indenter curve, and these values should also be stated in the test data.

It is usual practice to make six measurements of IM around the circumference of the cable at one location. As the test time for one IM measurement is short (i.e. 20–30 seconds is typical), many measurements can be made in a short period of time. The first production model of the indenter was demonstrated in the USA in the early 1990s. This was quite bulky and difficult to handle, but improvements in the technology have resulted in modules that are smaller and significantly more portable with large data storage capabilities, enabling many measurements to be made in sections of the plant with difficult or limited access.

Clearly a small, portable, non-destructive test device would be a significant benefit for cable CM in limited access areas. There are however some limitations associated with this technique. Good correlation data between IM and degradation have been demonstrated for elastomeric materials and thermally aged polyvinyl chloride (PVC), but little or no correlation has been observed for irradiated PVC and for semi-crystalline polymeric cable materials (e.g. polyethylene). The generic structure of semi-crystalline polymers includes highly crystalline regions linked to each other by tie molecules in an amorphous matrix. The hardness related properties are associated with the crystalline regions, and the ability to deform and elongate are associated with the amorphous phase. As the material ages, the amorphous phase degrades but the crystalline regions remain reasonably intact, therefore the elongation at break decreases but the hardness or IM remains constant (see Fig. 4.1). This is why little or no correlation exists between IM and elongation at break for semi-crystalline cable materials. Recent work has shown that a good correlation can be obtained for certain types of polyethylene [9].

The size of cables that can be measured is limited, with currently available indenter instruments having the ability to measure cable diameters up to 30 mm. Small diameter cables and insulation as low as 3 mm in diameter can be measured, but higher levels of variability can occur with the smaller diameters.

In many cases, when carrying out measurements, only the cable jacket is available for testing unless access is available at cable ends or in switch boxes where some form of thin extension adapter to the instrument is required. Where access is limited to the cable jacket, it is usually not possible to infer the condition of the interior cable components (i.e. bedding layer or insulation from measurements on the jacket). Indenter measurements on insulation are only possible at terminations or on samples in a cable deposit specifically for CM measurements.

4.6.2. Recovery time

Indenters can also be used to generate relevant post-indentation parameters. A parameter that has recently proven very useful to assess the degradation of cables is the time to recover a set deformation resulting from prior indentation. The recovery time is measured during the post-indentation phase, following a force relaxation phase, and upon retraction of the indenter probe.

The recovery time is an indicator of the viscoelastic properties of the material. This parameter has been shown to be very sensitive to degradation resulting from thermal ageing and/or irradiation for a variety of materials tested to date (PVC, XLPE, EPR, CSPE) as shown in Figs 4.10 and 4.11 [28]. For all cases tested to date, the sensitivity to degradation was higher than when using the IM value, and in many cases, the correlation of recovery time with elongation was very strong.

The measurement of recovery time has been incorporated into a recently developed portable indenter [28]. Therefore, this technique can be used for on-site measurements.

4.6.3. Near infrared reflectance

As described in Section 4.5.9, polymer ageing causes the development of infrared absorption due to the formation of oxidized species during ageing. The ability to carry out infrared analyses in reflectance mode has allowed the development of a portable, near infrared spectrometer. This type of instrument has only been used so far in a cable identification capacity [29].

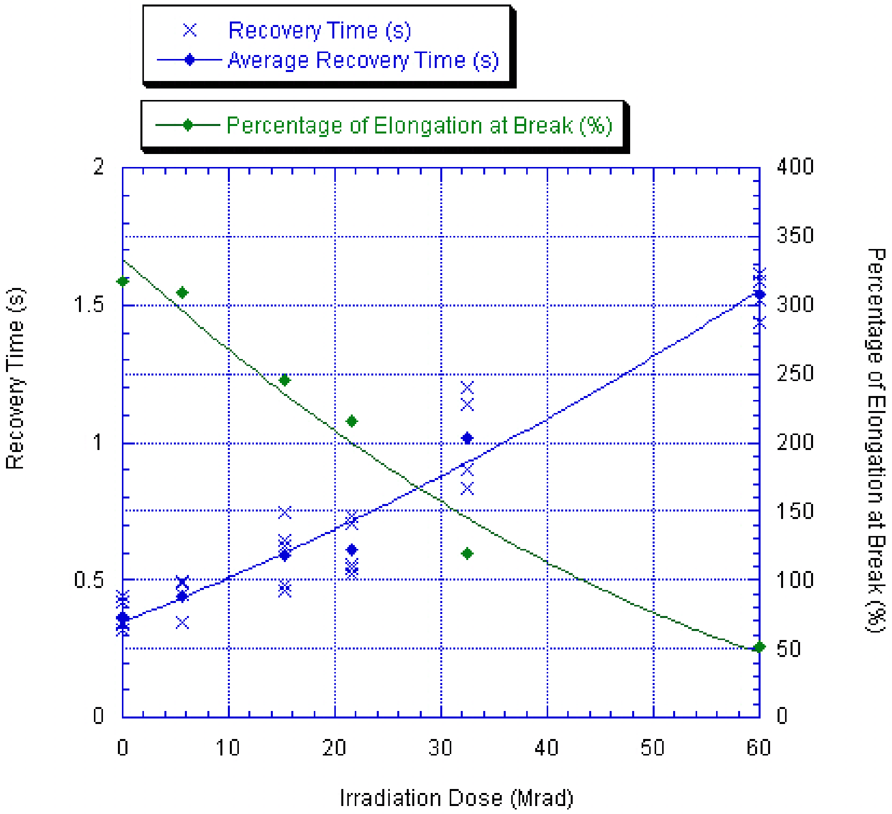

FIG. 4.10. Elongation and recovery time for an irradiated PVC jacket.

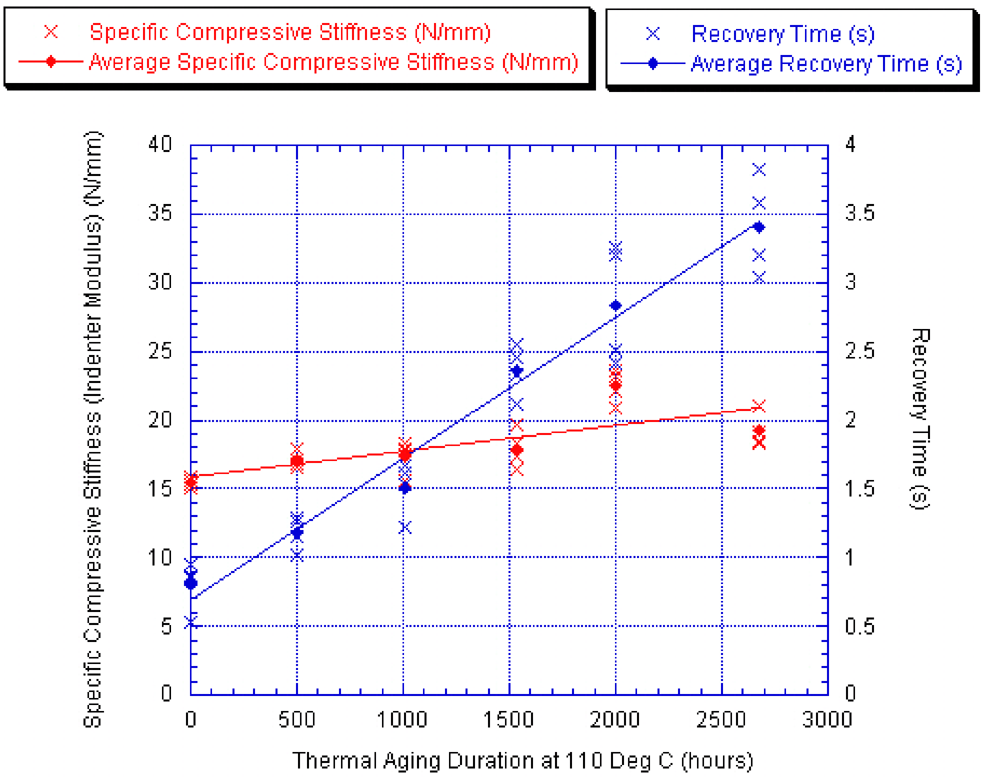

FIG. 4.11. Recovery time and indenter modulus for EPR insulation.

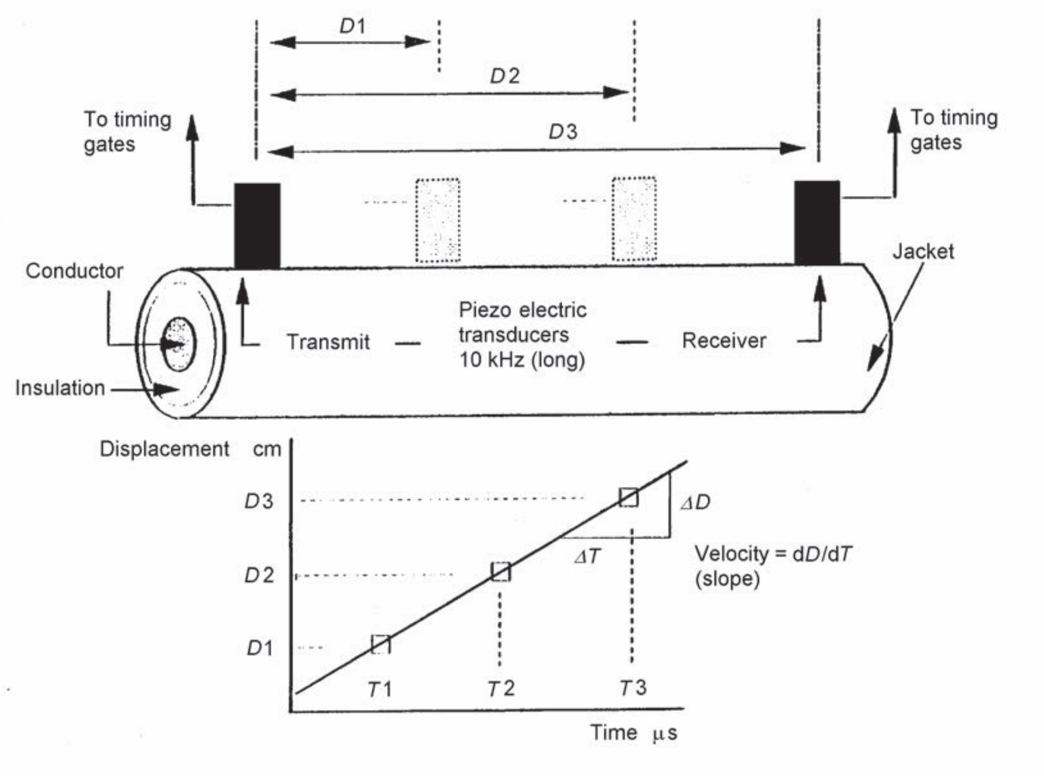

FIG. 4.12. Schematic diagram of sonic velocity test apparatus.

4.6.4. Sonic velocity

Sonic velocity testing is based on the fact that the velocity of sound in a solid medium is dependent on both the density and the modulus, and is given by:

$$C^2 = \frac{E}{\rho} \tag{4.2}$$

where C is the sonic velocity; E is the elastic modulus; ρ is the polymer density.

Since both the elastic modulus and density can change during the ageing of cable materials, and as the sonic velocity is directly related to both of these parameters, changes in sonic velocity would also be expected to occur as the cable material ages. A sonic velocity test instrument uses piezoelectric transducers to transmit and receive a series of pulses as shown schematically in Fig. 4.12. The signal transit times can be plotted as a function of transducer separation distance (up to a few centimetres) to obtain the slope, which represents velocity. Sonic velocity measurements have been made at 20 kHz on a series of PVC jacketed cables and on strips of jacket material cut from the cables.

Comparisons between data generated for test strips and complete cables has shown that the technique is dependent on the cable geometry, particularly adjacent shielding and insulating components. The magnitude of the sonic velocity at 10 kHz can vary considerably with different formulations of PVC, therefore baseline data would be required for each type of cable used in a plant if the technique was to be of practical use. Other work using 1 MHz pulses [30, 31] found the sonic velocity to be heavily dependent on the degradation of the PVC jacket materials but independent of cable geometry and PVC formulation (see Figs 4.13 and 4.14).

The sonic velocity tester measures properties of the cable jacket over a small volume between the transducer probes. The measurements obtained can be strongly dependent on the cable construction and the specific formulation of the jacket material. Therefore, extensive baseline data may be required. The technique is still under

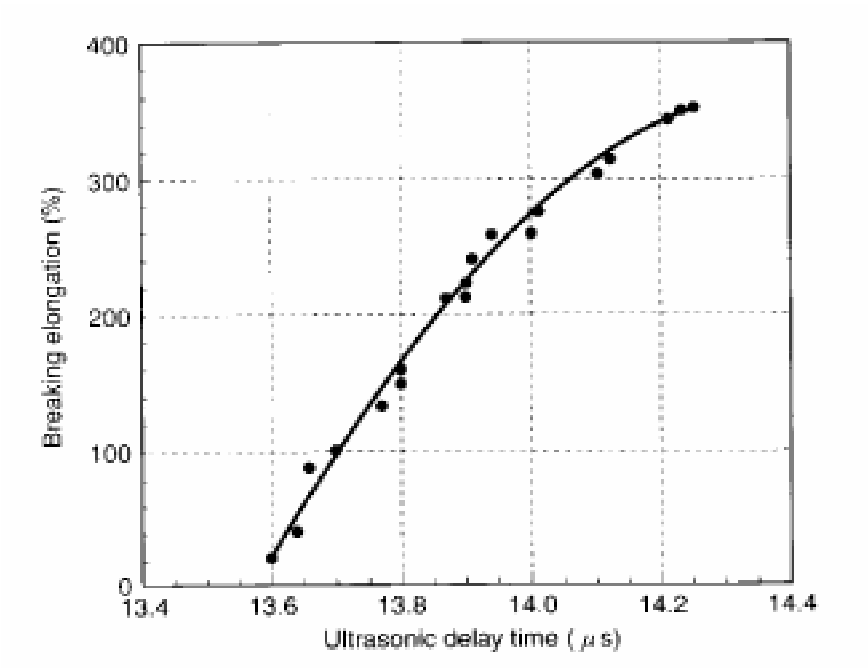

FIG. 4.13. An example of the correlation between the propagation time of ultrasonic waves and elongation at break for a PVC sheath material.

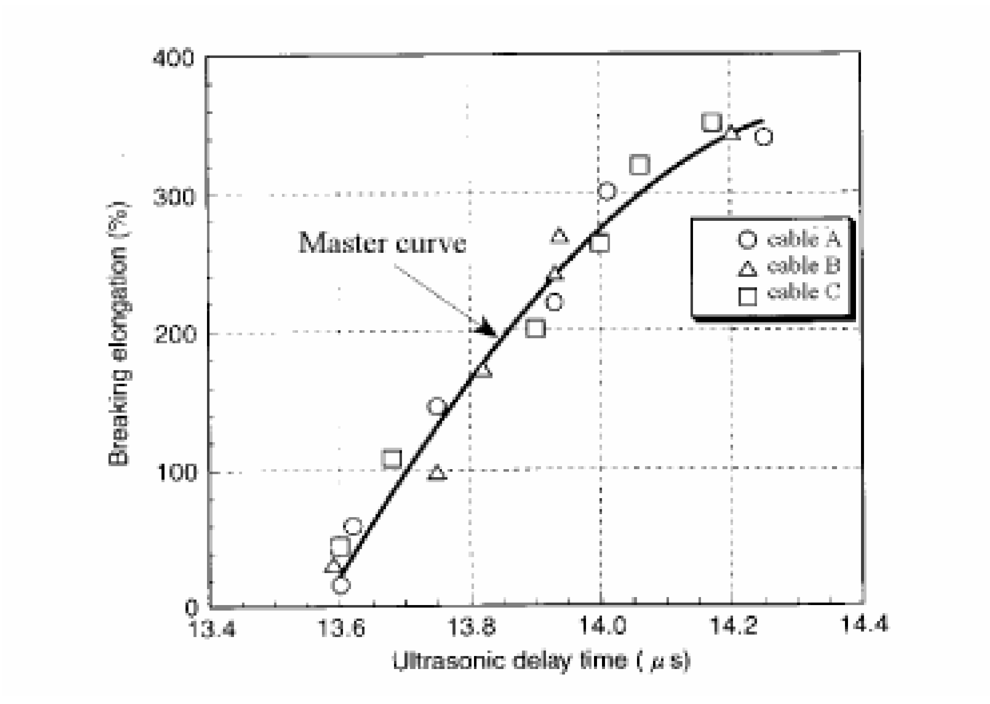

FIG. 4.14. Comparison of the correlation data for various cables from different manufacturers to the master curve for PVC.

development and has so far only been tested on PVC jacketed cables. At present, a prototype portable tester has been developed but has not been used for field use. Its high sensitivity to ageing degradation indicates that it may well be worth further development.

4.7. TECHNIQUES BASED ON ELECTRICAL MEASUREMENTS

The ideal CM methodology for the assessment of cables at NPPs would be based on structural integrity and electrical functionality. Some examples of electrical functionality tests are insulation resistance (IR), polarization index (PI), voltage withstand and dielectric breakdown. Most of these tests are certainly effective as pass/fail indicators of functionality, but studies over many years in the nuclear industry suggest that there are no reliable data yet available that allow an appropriate correlation between these measurements and cable ageing. Some of these tests require high voltages (dielectric breakdown is a destructive test), and thus may be considered inappropriate for use on I&C cables in situ for fear of insulation damage.

Electrical measurements are mostly applicable to cabling systems, including conductors, connectors, splices and penetrations although they can also reveal problems in cable insulation material. Most of the techniques are not very sensitive to insulation degradation but can be sensitive to conductor integrity (e.g. loose connections, corrosion of connectors). The advantage of electrical techniques is in their in situ and remote testing capability. Many of the electrical measurements can be performed on installed cables in an operating plant and can often reveal problems along the whole length of a cable. This is in contrast with methods that are limited to providing data at the localized point where the test is performed.

At present, there are no CM methods based on electrical measurements that are applicable to CBQ programmes. They are most useful in identifying and locating problems in NPP cable systems and confirming functional performance. Some have shown potential for measuring ageing degradation, but more research is needed to validate their use.

The success of nearly all electrical techniques relies on the existence of baseline measurements on the specific circuit being tested so that changes in a specific circuit can be readily identified. One of the practical limitations is often in determining a suitable ground plane for electrical measurements. For unshielded cables, this is a major disadvantage. Where cable is shielded, the shield can often be used as a more reliable ground plane for measurements.

4.7.1. Partial discharge

Partial discharges (PDs) are electrical discharges that can take place in gaseous inclusions, which may accidentally occur in solid insulation. PDs do not bridge the whole insulation (i.e. they do not extend from conductor to ground) but can lead to ultimate failure. A PD takes place in a nanosecond and causes high frequency currents, which are measurable by PD detection equipment to flow in the external circuit. After a discharge, both positive and negative charges are deposited on the surfaces of the voids or tree channels. These charges change the localized electrical field, thereby controlling the time when the next PD will take place along with the change in field due to the sinusoidal voltage applied.

The net result is that a pattern of PDs of various magnitudes, repetition rates and phase angles relative to the applied voltage can be seen. During testing in which the voltage is slowly raised, the voltage at which discharges are observed in each cycle is known as the PD inception voltage. On decreasing the voltage slowly from above the PD inception voltage value, the voltage at which PD ceases is referred to as the PD extinction voltage. PD will often become intermittent before complete extinction occurs. Due to the deposition of charges on the surfaces of the voids caused by PD, the PD extinction voltage can theoretically be as low as 50% of the inception voltage. In practice, the difference is between 10 and 25%. To ensure that a cable is discharge-free at the operating voltage, it is necessary to test for PD at levels up to twice the operating voltage.

Decreases in the PD inception voltage are an indication of significant degradation of the insulation material. A cable that has PD at operating voltage or within 1.5 times the operating voltage is generally significantly deteriorated and may fail in the near future. Cables that have no significant PD at levels up to twice the operating voltage have no immediate expectation of failure from PD and will operate satisfactorily for a significant period of time.

Modern PD detection equipment can provide three-dimensional plots showing the phase, magnitude and number of PDs. From the characteristics of these plots, it may be possible to identify the source of the PD (e.g. from spherical or flat cavities or voids, electrical trees, or interfaces).

The PD test is potentially damaging since the discharges induced can cause degradation of the insulation over a period of time due to localized overheating. This test has limitations for use in the field since it requires relatively high voltages to be applied to the cable, which would be a concern due to the potential for damaging the cable or surrounding equipment. As a result, PD is typically performed on medium voltage cables. Additionally, nearby operating electrical equipment in a plant environment could interfere with the test due to noise interference, so this test is most successful on shielded cables.

4.7.2. Frequency domain reflectometry

Frequency domain reflectometry (FDR) is a non-destructive cable testing technique based on transmission line theory. A transmission line is the part of an electrical circuit that provides a link between a generator and a load. The behaviour of a transmission line depends on its length in comparison with the wavelength of the electrical signal travelling into it.

4.7.2.1. Principles of the FDR technique

When the transmission line length (l) is much lower than the wavelength (λ), as occurs when the cable is short and the signal frequency is low, the line has no influence on the circuit behaviour, and the circuit impedance, as seen from the generator side, is equal to the load impedance at any time.

However, if the line length and/or the signal frequency are high enough, so that $l \geq \lambda$, the line characteristics take an important role, and the circuit impedance seen from the generator does not match the load except in some very particular cases.

The velocity of propagation (V_p) is defined as the speed at which electrical energy travels in a media relative to its speed in a vacuum. The V_p for different cable types is a fraction of the speed of light in a vacuum and is expressed as:

$$Vp = \frac{Vs}{C} \tag{4.3}$$

where

Vs = Speed of an electrical signal in a particular conductor
C = Speed of light in vacuum or 3×10^{8} m/s.

The FDR technique uses a swept frequency signal to transmit through an electrical cable circuit and analyses the circuit impedance changes that are reflected. These reflected signals are measured in the frequency domain and then converted into the time domain using an inverse Fourier transform. The reflected signal can travel through miles of cable without attenuation as long as the cable under test is shorter than the FDR signal wavelength. Fig. 4.15 is an example of a typical FDR trace showing the variation of impedance along a cable, which could be compared with a baseline measurement to identify anomalies along the conductor or insulation material.

4.7.2.2. Line resonance analysis

The line resonance analysis (LIRA) method [32] is an example of a cable testing system based on the FDR principle (see Section 4.7.2). There are other commercial versions of the FDR system.

Line impedance estimation is the basis for local and global degradation assessment. Tests performed with LIRA show that thermal degradation of the cable insulation and mechanical damage of the jacket and/or the insulation do have an impact on the capacitance (C) and to a lesser degree on the inductance (L). Direct measurement of C (and L) would not be effective because the required sensitivity has the same magnitude as the achievable accuracy due to the environmental noise normally present in installed cables (especially for unshielded, twisted pair cables). Some results were achieved with coaxial cables [33]. LIRA monitors C variations through its impact on the complex line impedance, taking advantage of the strong amplification factor on some properties of the phase and amplitude of the impedance figure.

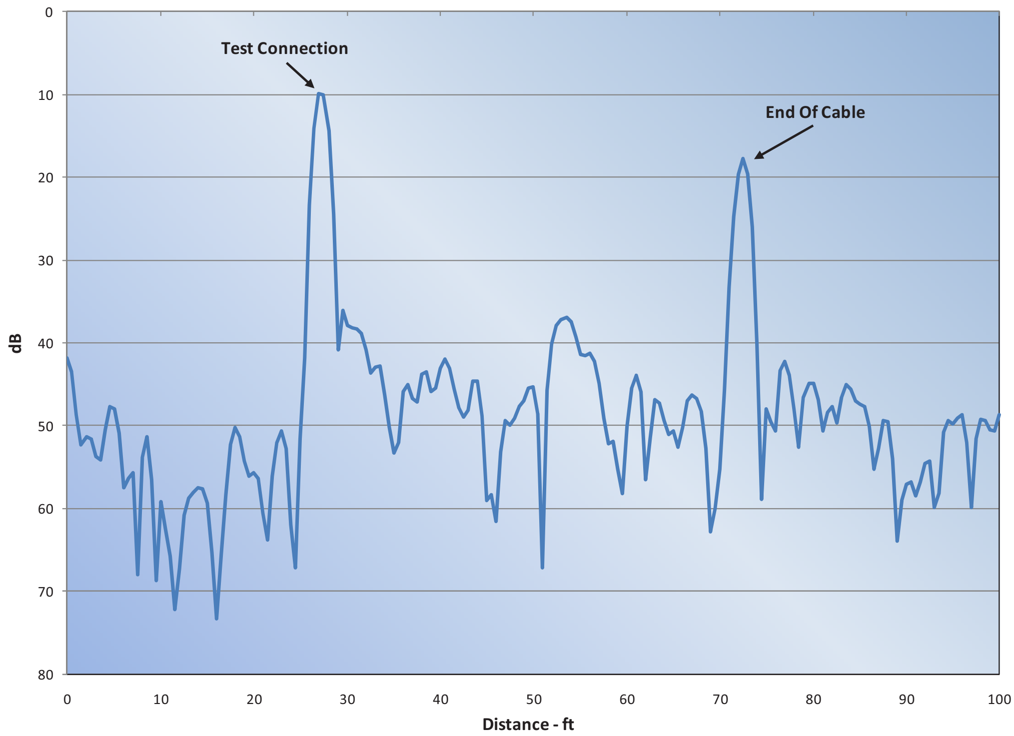

FIG. 4.15. Sample FDR trace.

LIRA implements proprietary algorithms for an accurate estimation of the local degradation severity and position (DNORM), and the global cable condition (CBAC2).

Global condition assessment

Several tests [34] have shown that global degradation in cable insulation results in changes in the dielectric capacitance and cable inductance to some degree. These changes affect the cable attenuation (α), which can be expressed as:

$$\alpha(dB/km) = Kf^{a}\sqrt{\frac{C}{L}} \tag{4.4}$$

where K is a constant for a particular cable type and geometry, and depends on the DC resistance, f is the signal frequency, and the exponent a takes into account the skin effect and ranges between 0.5 and 1. Figure 4.16 shows an example of LIRA calculated cable attenuation as a function of frequency.

The above equation shows that frequency acts as a gain factor in the relation between α and C/L, and for this reason, LIRA uses high-frequency attenuation values as the basis for a global condition indicator.

However, the use of an attenuation figure as it is would not be enough for condition assessment because of its dependence on the ratio C/L. Degradation affects C and L in a complex way, and the change in its ratio might be not be monotonic through the entire cable life. For this reason, LIRA implements a method where the contributions from C and L are isolated (as shown in Fig. 4.17), resulting in an indicator sensitive only to C (CBAC2) and another indicator sensitive only to L (CBAL). Since it has been demonstrated that degradation affects C to a higher degree than L [34], CBAC2 is used as a global condition indicator. Note that no attempt is made to estimate C or L directly. CBAC2 is calculated through the estimation (using frequency analysis) of:

(1) The high frequency attenuation (3rd harmonic analysis);
(2) The cable characteristic impedance Z_0;
(3) The signal phase velocity V_R.

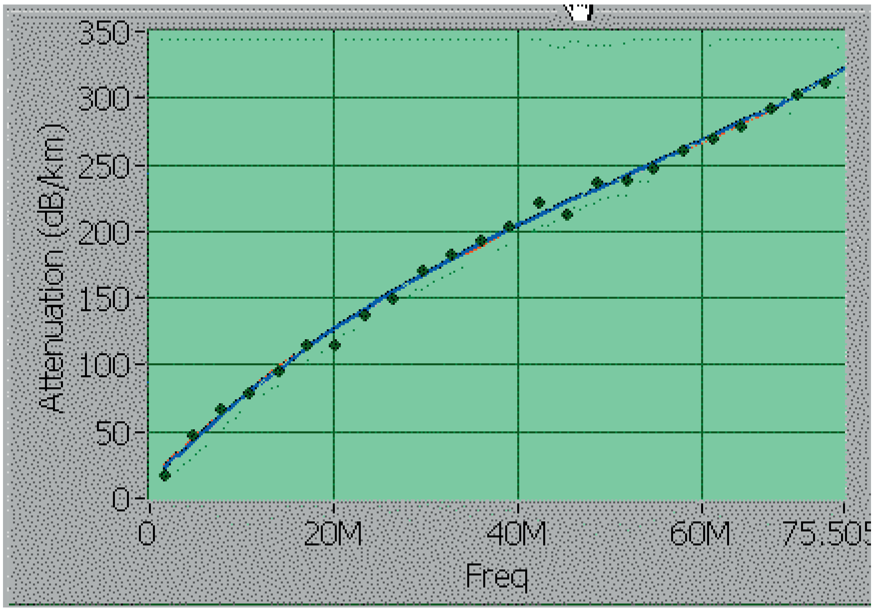

FIG. 4.16. Cable attenuation (estimated by LIRA).

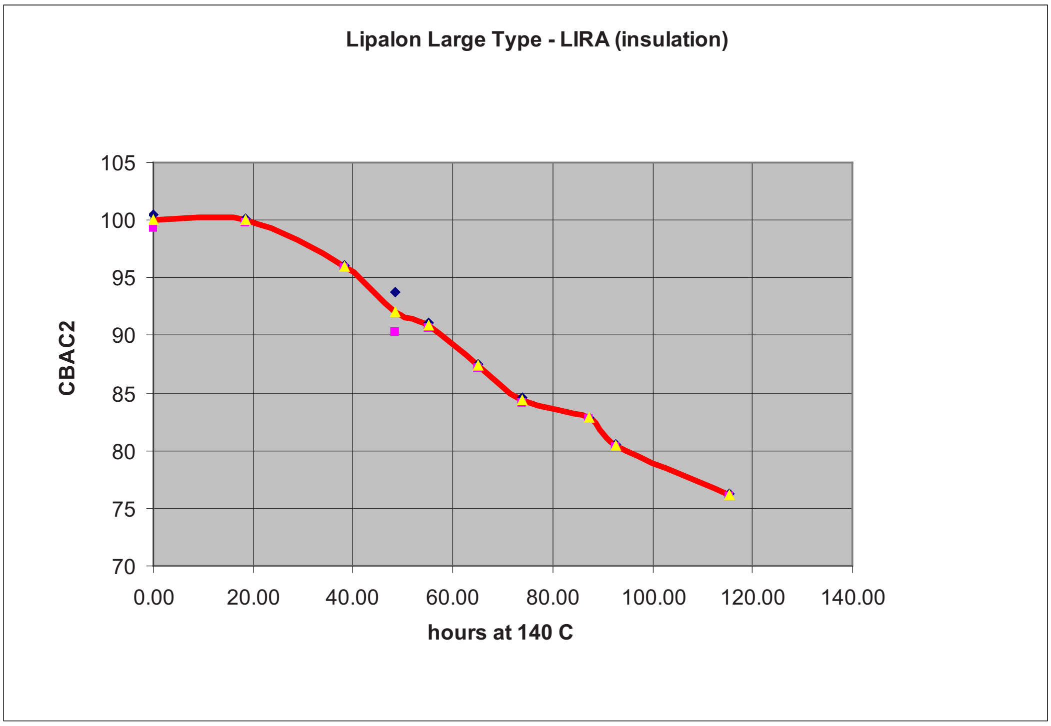

FIG. 4.17. LIRA ageing indicator (CBAC2) versus ageing time, EPDM insulation, low voltage cable.

Local degradation detection

A limited number of cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR) insulated cables were thermally aged along their entire length to evaluate the FDR technique as a potential method for ageing assessment [32]. Preliminary results indicate the potential for determining degradation using a condition indicator (DNORM) that can be used to assess local degradation severity regardless of the cable length and attenuation for both thermal and mechanical degradation/damage. This is an area of ongoing research and evaluation.

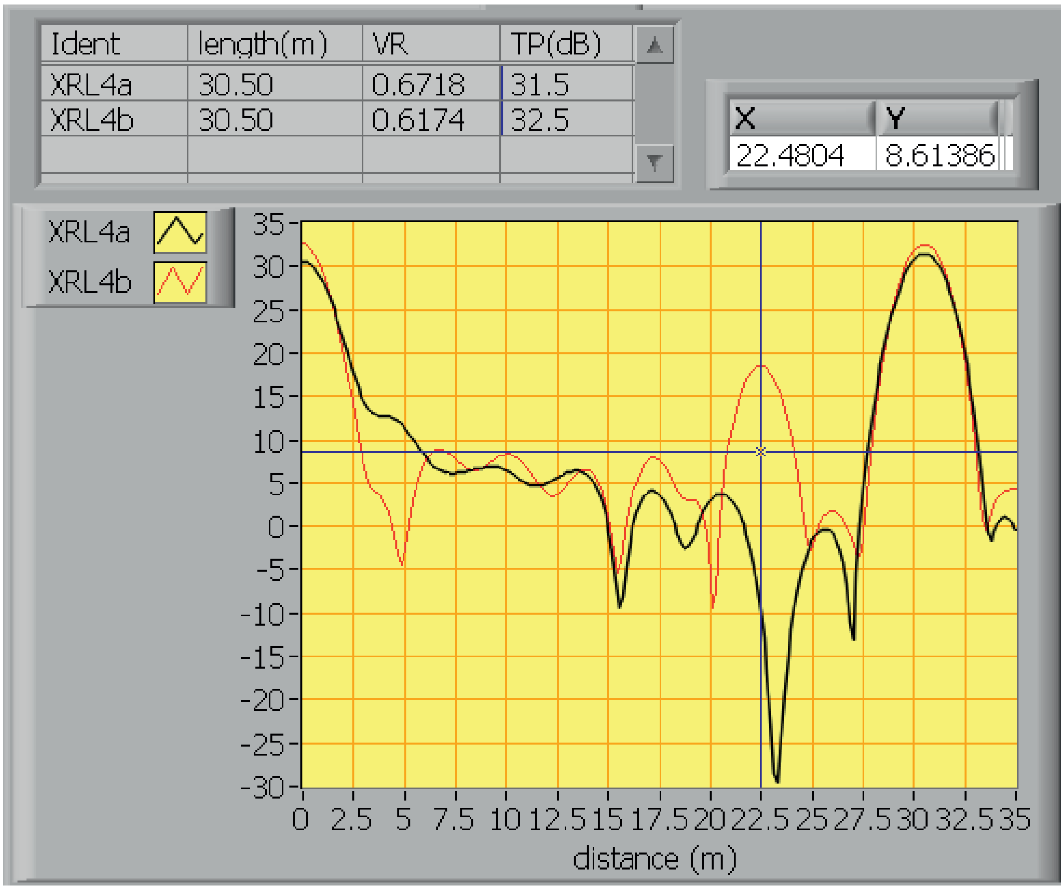

FIG. 4.18. FDR measurement using LIRA on XLPE before (black line) and after (red line) local thermal ageing at 22.5 m.

Figure 4.18 shows an example of a thermal hot spot detection in a XLPE low voltage cable, where trace (1) represents the cable signature before the degradation and trace (2) the signature after the damage.

4.7.3. Time domain reflectometry (TDR) measurements

The TDR technique is based on the transmission line theory just as FDR (see Section 4.7.2). However, the TDR test involves sending a DC pulsed signal through a cable circuit and measuring its reflection to identify the location of any impedance change in the cable and the end device (load). Reflected voltage waves occur when the transmitted signal encounters an impedance mismatch or discontinuity (fault) in the cable, connector or end device. This method provides diagnostic information about the cable conductor and any connector or connection in the circuit, and to a lesser extent, the cable insulation material. It can also provide diagnostics about a device at the end of the cable such as an RTD or thermocouple. The test depends largely on comparisons with a baseline TDR. As such, the success of TDR typically improves significantly if there is a baseline TDR for comparison.

The time that it takes for the TDR signal under test to travel down the cable and back can be converted to distance, which is determined by using the velocity of propagation (Vp).

Variations of TDR exist. For example, spread-spectrum time-domain reflectometry (SSTDR) is used to detect intermittent faults in complex and high-noise systems such as aircraft wiring. It is not currently used at NPPs, but it could become very useful for on-line diagnosis and monitoring, especially to avoid electromagnetic compatability (EMC) constraints.

An example of an actual TDR data set from tests of a NPP sensor is shown in Fig. 4.19. From the example, the amplitude of the reflected TDR signal corresponds to the relative impedance of the cable that the TDR pulse encounters as it travels through the conductor. A rise in the reflected wave is indicative of an increase in impedance, and a decrease in the reflected wave is indicative of a decrease in impedance. Thus, the peaks and dips in a TDR

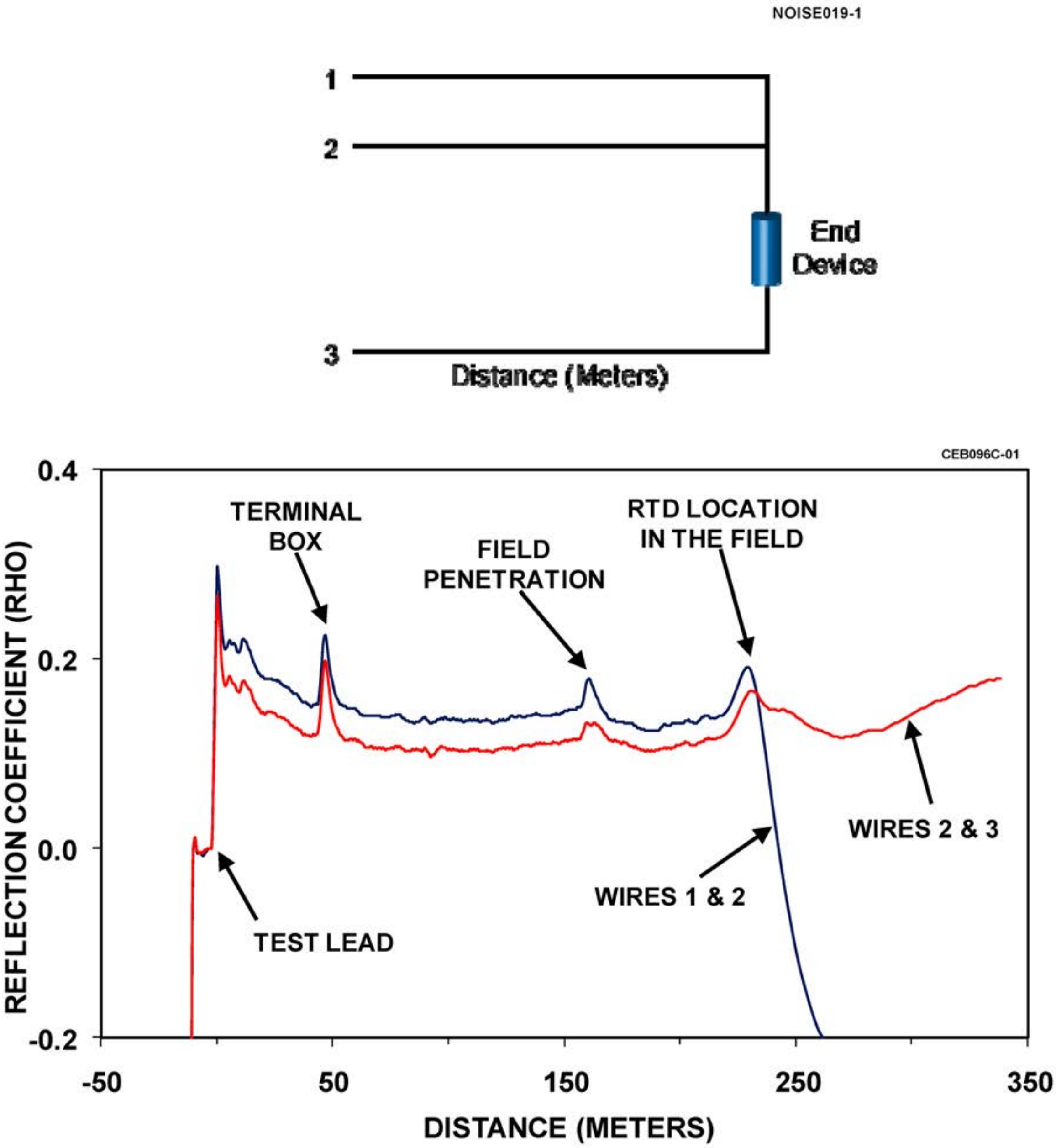

FIG. 4.19. A typical TDR trace involving three wires connected.

plot are used to identify the location of normal and abnormal effects throughout the cable. The first peak observed for both curves in Fig. 4.19 is due to the mismatch between the TDR system and the wired network.

Another example would be for a very good splice in a cable, where the TDR test would not show any impedance mismatch across the splice. However, if the connection degrades, corrodes or loosens, TDR would identify the problem as an impedance change.

4.7.4. Reverse TDR

Reverse time domain reflectometry (RTDR) is a method that simulates the coupling of electrical noise signals into a signal transmitted on an instrument cable. The electrical noise interference typically couples at poor connections or terminations in the cable circuit that tend to degrade through the ageing process, but may also result from damage to the cables or inherent properties of any inline devices. The location of degraded connectors or cable shields is detected by using time delays to determine where the electromagnetic interference (EMI) couples into the

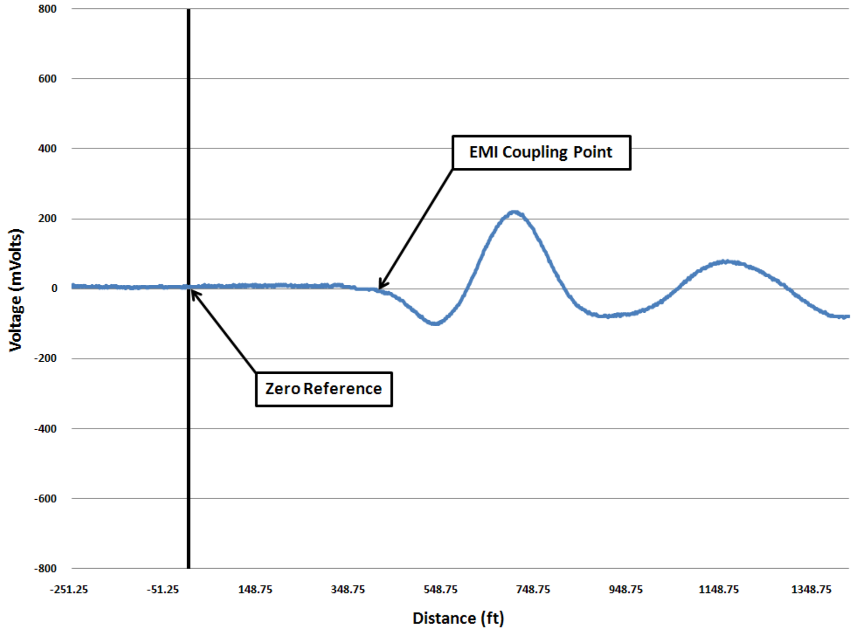

FIG. 4.20. Sample RTDR trace.

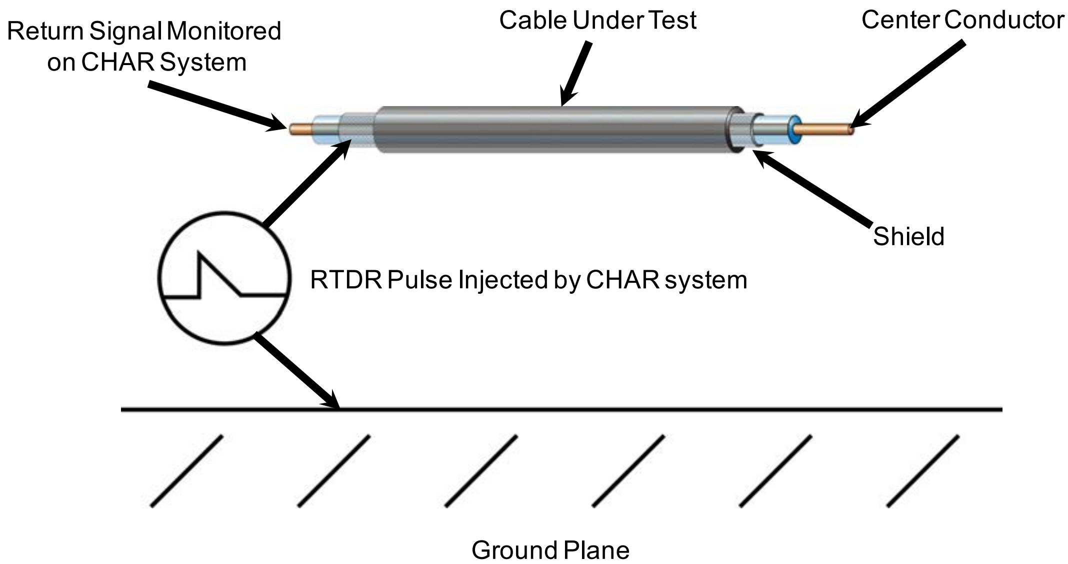

FIG. 4.21. RTDR set-up.

cable system. This test is particularly important in I&C systems that have low signal levels (<100 mV) easily affected by electrical noise intrusion such as source range nuclear instrumentation systems. Figure 4.20 shows a RTDR trace detecting an EMI coupling point.

RTDR is performed similarly to TDR by sending an electrical pulse through the cable system. However, RTDR reveals the distance to any point where noise is coupled into the central conductor of the cable. High-frequency electrical noise is applied to the cable system through the shield of a cable, typically triaxial or coaxial, while the central conductor of the cable is monitored for any return signal (Fig. 4.21). If a return signal is received, the time delay will determine the distance to the point of coupling. Standard TDR signatures are typically used in conjunction with RTDR to determine the location of cable connections.

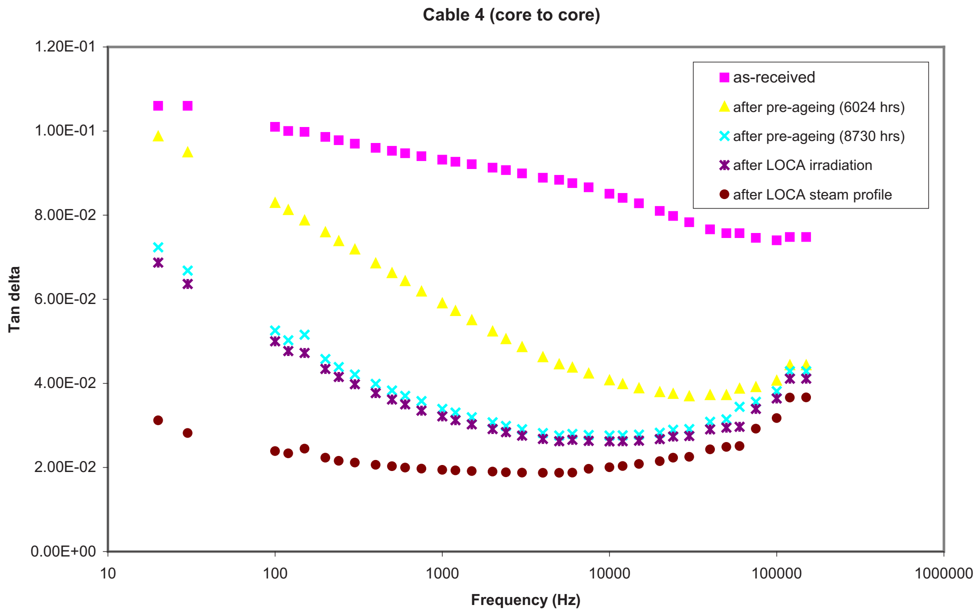

FIG. 4.22. Example plot of tan δ against frequency for an aged EVA insulation.

4.7.5. Dielectric loss measurement

One technique for cable CM that has been studied with some success has been the measurement of the dielectric loss tangent (or dissipation factor tan δ) of the insulating components of cables. The rationale behind this technique is that tan δ is a dimensionless property of a dielectric that is determined by the insulator's structure. Therefore, changes in structure brought about by ageing should affect tan δ. The measurement can be carried out over a range of frequencies at low voltages (500 mV) on lengths of cable using standard impedance bridge instruments. Normally the tan δ of cable insulation or a bedding layer is measured between conductors in adjacent cores or between single conductors and shielding. In some cases, measurements can be carried out on jackets between shielding and an external ground plane (e.g. metal conduit). Figure 4.22 shows the dependence of tan δ on the ageing condition for an EVA elastomeric formulation. Note the steady decrease in tan δ over the range of frequencies with increasing ageing levels.

While this technique does not. require sample removal, it does require disconnection of equipment and is susceptible to interference from electrical noise.

This technique has also been shown to be very sensitive to the detection of water ingress in cables.

4.7.6. Inductance, capacitance and resistance (LCR) measurements

Impedance measurements, including inductance (L), capacitance (C) and resistance (R) are made using an LCR instrument at specific frequencies to verify the characteristics of the cable conductor, insulating material and the end device. Results are evaluated to determine if they are as expected for the type of circuit being tested. Imbalances, mismatches or unexpectedly high or low impedances between the cable leads would indicate problems due to cable degradation and ageing, faulty connections and splices, or physical damage. For example, abnormal capacitance measurements are indicative of a change in the dielectric or insulation of the cable when compared to a calculated value or baseline measurement.

4.7.7. Insulation resistance measurements

Insulation resistance (IR) measurements are made using an IR instrument at specific voltages to validate the cable insulating material characteristics. These measurements have been used for many years to evaluate the isolative quality of the cable insulation. Typically, a voltage lower than the maximum rated voltage of the cable is applied to an inner conductor or the cable shield (if the cable has one) and a ground plane in contact with the cable. Furthermore, the current in the cable is limited to avoid cable damage. IR is expected to change as a cable ages either through oxidation, moisture intrusion or other environmental effects. Oxidation takes place continually and progressively in a cable as it ages. The insulation material changes as oxygen molecules move into and alter the chemical and physical make-up of the insulation material. In the presence of moisture, water molecules also move through and into the insulation material producing changes to the characteristics of the insulation. Both processes result in changes that affect the IR of the cable insulation.

In addition to IR, time-based IR ratios, the dielectric absorption ratio (DAR) and the polarization index (PI) are effective to show changes in cable insulation [35].

4.7.8. Embedded microsensors

AgeAlert™ is a type of microsensor developed to measure ageing or degradation of electrical insulation. The sensor is made using the insulation of a cable and nano-size conductive particles. In this way, the sensor becomes a "variable resistor" responding to temperature, humidity and other environmental stressors in a similar way to the insulation. Comparing sensor resistance to sensors subjected to accelerated ageing and the manufacturer's design testing (such as elongation at break) allows correlation of sensor data to monitored cable condition.

The sensor is embedded in or bonded to the cable so that it is subject to the same environment as the insulation. The sensors are installed on the cable to continuously track ageing of cable due to thermal, chemical and radiation environments and are capable of giving warning before design ageing conditions are exceeded. The cable condition can be read by contact with simple resistance measuring readers or by wireless readers such as a passive radio frequency identification device (RFID).

The sensors can be installed by OEM wire/cable manufacturers during manufacture. Alternatively, they can be bonded to wire cable after installation but before significant ageing has occurred. AgeAlert™ sensors are currently in beta testing.

4.8. ESTABLISHING A QUALIFICATION MONITORING PROGRAMME

Because of the very large number of cables installed at a typical NPP, it is not practical (or necessary) to test all cables in a CM programme. The first requirement of the programme should therefore be to prioritize the selection of cables to be included. The group of cables to be tested should then be chosen such that the results provided in their surveillance can be reasonably and conservatively extrapolated to all of the safety cables of the plant.

The following activities are recommended to prioritize cable selection:

- Identification of cables with safety functions in the NPP;
- Area classification according to the environmental conditions;
- Identification and selection of circuits.

4.8.1. Identification of cables

A list or catalogue of cables with safety functions at the NPP should be prepared. This may already exist in the form of an EQ master list. The list should hold representative information on the cables, which should include the following information:

- Circuit ID.
- Cable type.
- Application (low voltage power, control, instrumentation).
- Safety class.
- Manufacturer.

— Technical characteristics:
  - Electrical (voltage, current rating),
  - Materials (insulation, jacket, conductor),
  - Thickness (insulation and jacket),
  - Conductor configuration.
— Service conditions (environmental conditions, voltage, maximum loading, cycle service, installation date).
— Circuit layout (areas, length, identification of trays, conduits).
— Documentation file (purchase specification, data sheet, test and EQ reports, maintenance procedures, maintenance history).

4.8.2. Area classification according to environmental conditions

The different areas of the plant with cables that have safety functions should be classified according to their maximum environmental conditions based on the temperature and radiation dose corresponding to normal and to accident conditions since these parameters are the most relevant with regard to cable degradation. Where there are specific concerns over other stressors, such as vibration or moisture, these parameters should also be considered when classifying areas.

The environmental parameters to be used for the assessment of normal operational conditions should preferably be based on values determined during environmental monitoring (see Section 4.2).

The different areas can be grouped into several categories according to the specific conditions of the plant. Table 4.5 includes an example of area classification.

4.8.3. Identification and selection of circuits

For the selection of a representative group of circuits for monitoring, the following basic criteria should be taken into consideration:

— Cable types. The selection shall cover all of the cable types at the NPP as per their service, manufacturer and materials;
— Environmental and installation conditions;
— Safety class and qualification status;
— Self-heating for power cables;
— Maintenance and inspection histories;
— Accessibility for inspection and testing;
— Thickness of insulation.

TABLE 4.5. EXAMPLE OF AREA CLASSIFICATION AT AN NPP

Group	Applicable environmental conditions		
	Maximum values in normal service		Accident
	Temperature (ºC)	Radiation (Gy)[a]	
A	≤40	$\leq 10^2$	Not applicable
B	≤50	$\leq 5 \times 10^4$	Not applicable
C	≤50	$\leq 5 \times 10^4$	Applicable
D[b]			Applicable

[a] Total integrated dose at 40 years.
[b] Area with localized environmental conditions higher than those corresponding to group C (e.g. hot spot areas).

Initially, the cables at the NPP will be classified in groups according to their use (e.g. low voltage power, control, instrumentation, special cables, coaxial/triaxial), manufacturer and materials of jacket and insulation.

In a second stage, each cable will be assigned to one of the established environmental classes. For each group, the circuits associated with the most severe environmental class would be selected. In addition to these, circuits in hot spot areas will be included.

For the circuits identified above, the following final selection criteria will be established to arrive at the number of circuits manageable within the NPP. Typically, a total of 60 to 80 circuits may be considered reasonable and manageable for detailed CM. A larger number of circuits may also be considered for less intensive monitoring.

The suggested selection criteria are as follows:

— Cables in hot spots are to be included while the hot spots last.
— Cables with insufficient qualification margin have priority.
— In power cables, those with higher duty cycle and service conditions.
— Cables with more severe installed conditions.
— Cables that have inspection and maintenance records.
— Cables more readily accessible for inspection and testing.
— Within the same family, those cables with the lowest insulation thickness.

4.8.4. Monitoring programme

It is recommended that two types of surveillance activities be performed on the selected circuits:

— Inspection and tests in situ;
— Tests on the cable sample (e.g. either microsampling or cable deposits).

Inspection and tests in situ would apply to all of the selected cables. Historically, the following techniques have been used as a primary indicator of cable condition:

— Visual and tactile inspection (for those cables that are accessible);
— IR and PI (these are pass/fail indicators but do not give any indication of gradual degradation).

For those instrumentation cables that correspond to low level signal systems, the measurement of IR and PI were excluded if calibration tests of the system were performed on the whole circuit, including the cables.

More recent approaches have included additional techniques such as:

— "Indenter" modulus — this method is not recommended for materials such as XLPE and Tefzel;
— TDR and FDR, LCR measurements;
— PD and dielectric loss (Tan delta).

The electrical tests are primarily used for the troubleshooting of circuits and the detection of gross degradation of cable insulation at present rather than for the assessment of gradual degradation. It is expected that in the future, more comprehensive programmes will use a selection of newer or additional techniques such as those listed in Table 4.4.

If destructive techniques such as elongation at break are to be used, it is recommended that they should only be applied in the following cases:

— Sacrificial cables located in some NPPs specifically for the application of a CM programme (e.g. in a cable deposit);
— Cables that are out of service;
— Inspected or tested in situ cables that show signs of significant damage and are being replaced. The CM tests can be performed after removing the cables from the plant.

It is recommended that the CM programme be performed at intervals not greater than 5 years or three refuelling outages. The frequency of inspection may be adjusted based on the CM results. Qualitative tests such as visual inspection may be carried out more frequently.

5. ADDITIONAL CONSIDERATIONS FOR CABLE MANAGEMENT

5.1. QUALITY ASSURANCE

All activities relating to EQ should be carried out within the requirements of an approved QA programme. Qualification of installed plant equipment is achieved with a high level of confidence only when the broad spectrum of activities affecting the equipment's capability and qualification are correctly performed. These activities include but are not limited to design, procurement, qualification, production quality control, shipping, storage, installation, maintenance and periodic testing. Proper control of these activities provides confidence in the qualification of installed equipment. The proper performance (i.e. quality) of these activities is the direct responsibility of those performing them. It is the role of the QA organization to check that all EQ activities are performed according to the approved procedures and controls necessary to establish and maintain qualification. In order to properly implement these responsibilities, QA organization activities may include, for example:

- Developing/accepting overall programmes and procedures, including calibration of test equipment;
- Determining the acceptability of vendor QA programmes;
- Performing audits, inspections and verifications of selected utility and vendor activities;
- Determining that corrective actions have been implemented when problems are identified.

A variety of organizations and personnel are directly or indirectly involved in achieving the objectives of EQ, including:

- Equipment manufacturers;
- Material, parts and service suppliers;
- Qualification laboratories;
- Qualification consultants;
- Plant design engineers;
- Procurement and spare parts personnel;
- Installation personnel;
- Maintenance personnel.

It is particularly important that the formulation of the cable material is traceable and documented. Manufacturers may vary their formulations (driven by the suppliers of additives, fillers etc.) and procedures over time, which can significantly affect the degradation behaviour.

Mistakes associated with any activities related to qualification can result in installed equipment incapable of performing as required. It takes only one omission, error, invalid assumption or questionable conclusion to negate the considerable cost and resource commitment necessary to implement and monitor qualification for a particular piece of equipment.

5.2. CABLE EQUIPMENT OUTSIDE HARSH ENVIRONMENTS

Cables that are not subjected to harsh environments but support systems important to safety still need to be qualified for their normal operating environment. The operating environment could include high operational radiation and temperatures, exposure to moisture, submergence and various combinations of these environments. In areas where equipment is subjected to extremes of temperature and/or radiation, an acceptable level of degradation can be assigned for managing its maintenance and/or replacement cycle.

Known failure modes have to be addressed through a suitable maintenance programme or through a maintenance rule (e.g. see Ref. [36]). It needs to be demonstrated through equipment availability and reliability that the cables can perform in these areas to prevent plant trip or transients.

The EQ programme can be used selectively to suit specific applications. The same basic approach to EQ described in Section 3 can be used, omitting the final DBA test.

Qualification for applications outside harsh environments is established by the design/purchase specifications containing functional requirements and service conditions under normal and anticipated operational events combined with well supported maintenance/surveillance programmes [6]. For example, a certificate of conformance indicates that the equipment can function in the environment in which it is specified. This approach is considered generally adequate because such components can be serviced even during accident conditions.

5.3. CABLE MANAGEMENT FOR LIFE EXTENSION IN PLANTS WITH EXISTING EQ

Many of the activities described in this section are applicable to NPPs during their initial qualified life but are of particular importance when considering the needs of plant life extension. This section relates primarily to cables that are expected to be exposed to harsh environments where the cable is required to survive a DBA. The information is applicable to instrumentation, control and low voltage power cables (<1.5 kV). Cable supporting systems important to safety that are not exposed to harsh environments will also need to be considered for life extension.

It is recommended that PVC cables not be considered for life extension because of the fire hazard associated with this material but should be subjected to a planned replacement programme. It is recognized that extensive use is made of PVC based cables in some NPPs, and this may not be a practical option in the short term. However, the risk to surrounding equipment from the corrosive by-products of a possible PVC cable fire needs to be balanced against the cost benefit of replacement or mitigation.

A management programme for cables for life extension would consist of 3 main phases:

- — Evaluation of the existing EQ documentation and other data relevant to cable ageing;
- — Assessment of the current condition of the cables;
- — Life cycle management.

These phases are discussed in more detail in the following sections.

5.3.1. Evaluation

5.3.1.1. Existing EQ documentation

The first phase in any cable ageing management programme for life extension should be to re-evaluate the existing EQ documentation. It is important to understand the assumptions that were used in the original qualification process, particularly for the pre-ageing, which was carried out prior to the DBA testing of the cables.

The main information within the existing EQ documentation that should be examined is:

- — The activation energy E_A assumed for thermal ageing;
- — Whether E_A was measured or taken from the literature;
- — The acceleration factor used for thermal ageing and the test temperature;
- — Pre-ageing sequence;

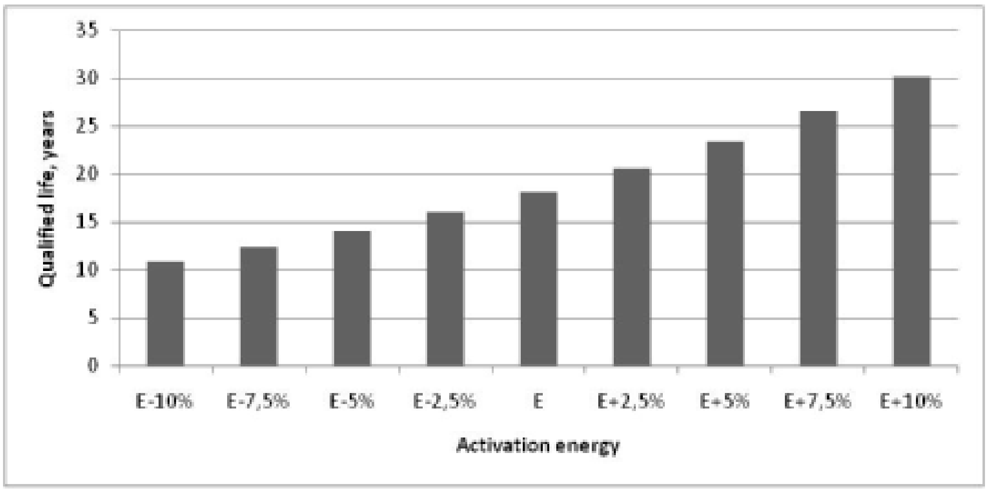

FIG. 5.1. Example of the influence of changes in the assumed value of activation energy E on qualified life determined from artificial thermal ageing at 110ºC extrapolated to a normal service temperature of 50ºC.

- — The radiation dose rate used for operational ageing;
- — Whether cable ageing parameters (e.g. elongation at break) were measured at the end of the pre-ageing, before the DBA test and electrical properties after DBA;
- — Whether the service temperature and dose rate assumed in the simulation of operational conditions was consistent with the actual operational conditions;
- — What profile was used for the DBA tests, the margins assumed and was it appropriate for the specific plant's functionality tests during DBA;
- — Dose rate for the DBA radiation test.

Activation energy: In many cases, literature values of E_A were used for thermal pre-ageing, but these were rarely for the identical cable materials. Values of E_A can vary significantly for cable materials of the same generic polymeric material; for example, a recent study of EPR-based cables from 3 different manufacturers measured E_A values ranging from 84 to 110 kJ/mol [3] (20.0 to 26.2 kcal/mol) for the temperature range 110–120ºC [9]. E_A also varies with the temperature of testing. The value is usually lower at lower temperatures (i.e. nearer to the actual operating temperatures in an NPP). For example, for an EPR-based insulation, the value decreased from 130 kJ/mol above 120ºC to 62.8 kJ/mol below 100ºC [37]. The value of E_A used is critical in terms of calculating a qualified life, since an error of 10% in the value can change the qualified life by a significant factor. Figure 5.1 illustrates how sensitive the qualified life is to the value of E_A assumed. The example used assumes a value of 0.9 eV for E_A, which is typical for cable insulation materials. For a variation in the value of ± 5%, the qualified life would vary between 14 and 23 years. It is recommended that E_A is measured for the specific cable material being assessed. Suitable methods are described in Annex A–3.

Acceleration factor: The temperature used for the thermal component of pre-ageing has in the past been selected to give a test time as short as 100 hours to simulate a 40-year exposure to operational conditions. This was the minimum ageing time permitted under the 1974 version of IEEE 323 [4]. At such high acceleration rates, there is a strong possibility that the degradation mechanisms occurring during the test are not the same as those that occur during operational use. For example, in semi-crystalline polymers (such as XLPE), the ageing would have been carried out well above the crystalline melting point, which is typically 90–120ºC, whereas operational use is primarily below this temperature. In this case, the Arrhenius relationship would not be applicable, since the temperature range spans a physical transition in the polymer. In radiation ageing, some EQ tests used dose rates up to 10 kGy/h. At such high acceleration rates, diffusion-limited oxidation would be expected to be significant for most of the materials commonly used in cables. In addition, dose rate effects would also become important.

[3] 1 eV = 96.48 kJ/mol.

Sequential thermal and radiation ageing: The sequence of thermal and radiation ageing carried out in the pre-ageing of cables can have a significant effect on the degradation that occurs (see Section 3.6.1). Simultaneous thermal and radiation ageing provide the most severe conditions for pre-ageing for many polymeric materials but have rarely been used in EQ programmes. In most cases, the radiation component of the pre-ageing was carried out after thermal ageing and sometimes included with the DBA radiation dose. Extensive work on the effects of sequential versus simultaneous ageing has shown that for most cable materials, thermal followed by radiation gives significantly less degradation than radiation followed by thermal or simultaneous thermal/radiation ageing [9]. Where the operational dose is very low and thermal ageing dominates, it may be acceptable to use thermal followed by radiation, but in other cases, the pre-ageing used in EQ is likely to have been underestimated.

Parameters measured: If degradation parameters such as elongation at break were measured after the pre-ageing, before the DBA test was carried out, then some of the uncertainties in the pre-ageing can be resolved by using the value of that QLD parameter as a qualified condition for comparison with the current condition of the cables. The QLD used needs to reflect the state of degradation of the cable insulation material (e.g. elongation at break, indenter modulus), not just a functional parameter (e.g. electrical characteristics).

Evaluation of pre-ageing margins: The pre-ageing carried out during EQ usually contains significant margins in terms of the maximum temperatures and radiation doses assumed to be applicable to the cable. However, these margins may not be sufficient to account for all of the uncertainties present in the pre-ageing process. Typically, the following uncertainties have incorrectly been addressed by utilizing margins, although the margins were originally intended only to account for using single cable samples in type tests:

— Type tests on a single cable type without allowance for the variation in properties of the cable between different cable sizes, configurations and times of manufacture;
— The use of sequential rather than simultaneous ageing;
— The use of excessive acceleration factors;
— The use of inappropriate activation energies;
— An additional factor present during the DBA test phase of EQ is the use of small test chambers where the oxygen present in the chamber is consumed rapidly in the early stages of the test. The absence of oxygen during a large part of the DBA test will significantly reduce the severity of the test.

Each of these factors will take up part or all of the margins present. The margins are unlikely to be sufficient to account for all of these uncertainties.

DBA profile: The maximum temperature and pressure profile assumed for the DBA profile should be appropriate for the specific NPP. Differences between the required and test profiles that are used for representing the DBA conditions should be evaluated (see Annex A–5.5). A check should be made that the appropriate margins were applied to the enveloping conditions. Cable functionality must be tested both during and after DBA.

5.3.1.2. Operational experience

The second part of the evaluation phase is to examine operational experience at the plant. A check should be made of the actual plant conditions during normal operation and shutdowns using environmental monitoring (see Section 4.2). Clarify whether the temperatures (both ambient and local temperatures from self-heating) and radiation doses are within the envelope of values assumed for the simulation of pre-ageing. Equally important, identify whether they are much less than originally assumed. If so, then it may be possible to justify an extended qualified life based on the actual operational temperatures, provided that the value of E_A used is appropriate.

Operational experience of cable failure or damage should also be examined. Identify whether there any indications of localized cable damage at hot spots, mechanical damage during shutdowns or chemical contamination (e.g. from oil leaks). It is unlikely that cables in such areas would have their lives extended and would need to be scheduled for replacement.

5.3.2. Assessment of current condition

Assuming that the preliminary evaluation of EQ documentation and operational experience within the plant is positive, then the current situation of the cables needs to be assessed in more detail. The extent of this phase will depend on the level of monitoring and inspection that is already in existence at the plant.

Systematic visual and tactile inspection of cables via dedicated walkdowns using experienced personnel can give a good indication of the general level of degradation within the plant and can help to identify hot spot areas where localized areas of high temperature or radiation dose exist [17]. Section 4.2.6 gives details of what aspects should be examined in such inspections.

Environmental monitoring of both temperature (ambient and self-heating) and radiation dose should be carried out if not already in place. This is particularly important where power uprating or increases in cable loading have occured. Section 4.2 gives more details on environmental monitoring.

The actual state of degradation of the cables needs to be assessed using CM methods (see Sections 4.4–4.7 for information on these techniques). Such monitoring can be carried out on cable samples taken from the plant or on recently replaced cables that have been exposed to real time ageing or on samples from a dedicated cable deposit. If such a deposit is in place, it is recommended that testing be carried out at regular intervals of five to eight years (or up to three refuelling outages) during the plant life to assess the rate of degradation on materials that have been subjected to natural ageing. However, the frequency should be adjusted based on the results of the testing.

An estimate of the residual life to the qualified condition can be made for those cables where environmental conditions are known.

5.3.3. Life cycle management

The assessment of the current condition of cables should indicate where they are on the life curve if data is available on the condition of the cable prior to DBA testing from the original EQ. If such data is not available, an estimate can be made of the pre-DBA condition by repeating the pre-ageing part of the original EQ test. This pre-ageing would need to be carried out on samples of unaged cable (either from storage or from a mild environment in the plant where ageing is insignificant). The pre-ageing method used in the original EQ should be repeated with the measurement of CM parameters (e.g. elongation at break) at intervals. This might be at ¼, ½, ¾ and the full pre-ageing time carried out in the original test (see Fig. 5.2).

The actual values of the monitoring parameters determined from the assessment of current conditions can then be compared with the life curve. This will give an indication of the service life available before the end of the existing qualification. If the current condition is nearing the limit (QLD), a DBA test may need to be repeated on cables that have been naturally aged in the plant (either replaced cable or samples from a deposit). Alternatively, planned replacement of the cable with qualified cable should be considered.

Having evaluated existing documentation and assessed the current condition of cables and operating experience, a decision needs to be made as to whether there is a cost benefit in replacing cable rather than carrying out the additional testing required to extend life. The benefit of replacing existing cable with state of the art cable (e.g. halogen-free materials, shielded instrumentation cable) may well outweigh the cost of the additional testing. The payback time of the extended life of the plant should be considered.

It may be appropriate to assume that all cables between 40 and 60 years old should be considered as near end-of-life, unless there is demonstrable evidence to the contrary. This might include detailed CM and environmental monitoring, combined with life curves generated during EQ pre-ageing which was carried out under conditions that minimized uncertainties. Where practical, PVC cables should not be considered for life extension because of their fire hazard, even if their degradation levels are low. Cable penetrations containing PVC should also be considered for replacement.

5.3.4. Plant modifications

EQ could be influenced by most modification or maintenance activities conducted at the NPP. Any activity that changes environmental temperature, radiation or humidity directly influences qualified life, equipment performance and possibly immediate operability. For example, the removal of heat insulation from piping during

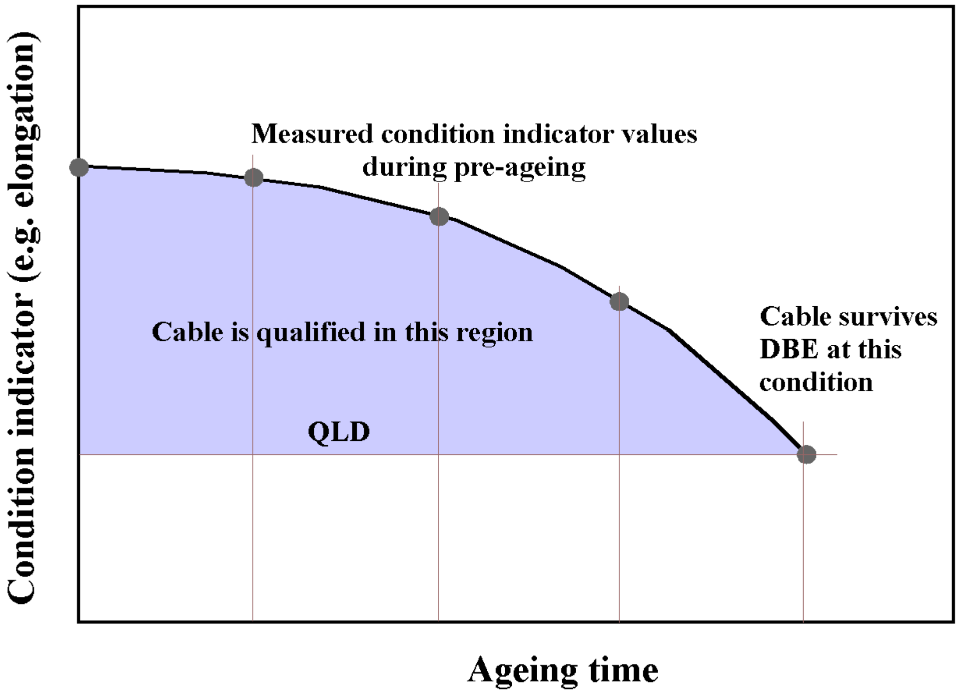

FIG. 5.2. A life curve generated during the pre-ageing stage of EQ for comparison with actual condition of cable.

maintenance operations can significantly increase the degradation of adjacent cables. Handling of cables and other human activities during maintenance (e.g. erection of scaffolding can have a detrimental effect on cables).

Plant modifications should always be assessed to determine whether they will affect the environmental conditions to which qualified cables will be exposed, particularly modifications related to power plant uprating. Any impacts on the qualification should be documented. Therefore, the persons responsible for EQ should be kept informed of any activity that involves any change to these parameters in the proximity of qualified equipment.

5.4. DEVELOPMENT OF EQ ON OPERATING PLANT WITHOUT EXISTING EQ

Where there is no existing qualification for I&C and low voltage power cables that are required to survive a DBA, initially a search for information relevant to the cable types used should be made, using all available literature and database sources. Such sources could include the SCAP and EQDB databases and those from owner groups. SCAP is a database containing ageing degradation data collected under the auspices of the OECD/NEA [38], and the EQDB database is maintained by the EPRI (Electric Power Research Institute, USA) [39].

A preliminary assessment should be made for any indication of significant degradation of cables in the plant. This would utilize visual and tactile inspection, environmental monitoring for temperature and radiation doses and possibly CM of selected cables that have been exposed to the highest temperature and dose areas. If degradation is already significant, priority should be given to replacement of those cables with appropriately qualified cables. Where PVC cables are installed, it is recommended that these should be replaced because of the fire concerns (see Section 6.2).

If the cables are not yet significantly aged, then it is necessary to generate formal EQ for existing cable types if they are not being replaced. This will require samples of the original cable materials, either as unaged samples from storage or samples that have been naturally aged in the plant, which have been replaced with qualified cable. The availability of suitable samples is likely to be the limiting factor for carrying out EQ tests. A systematic grouping of cable types (e.g. by polymer formulation, manufacturer) may be necessary to get the best information from such tests where material is limited.

A full EQ test then needs to be carried out using the procedures described in Section 3. It is important that the methods used for the pre-ageing and DBA simulation phases of the EQ test are carried out as recommended in Section 3 to reduce the uncertainties. The pre-ageing used in the EQ test must simulate the full lifetime of the plant for samples taken from storage. For naturally aged samples, the pre-ageing must simulate the remainder of the plant life.

Knowledge of the activation energy is essential for the pre-ageing phase of the EQ test. This should be obtained by testing rather than from the literature so as to reduce the uncertainties inherent in accelerated thermal ageing. Where there is little information available on the types of cable material installed, it may be preferable to replace existing cable with qualified cable.

It is recommended that life curves be generated during the pre-ageing phase (as shown in Section 5.3.3) to enable CM to be carried out after EQ is established.

6. RECOMMENDED PRACTICES

A number of recommended practices have been developed for EQ of cables and for cable ageing management. It is desirable that all recommended practices in this section be applied to those cables that are subject to EQ. For cables that are not subject to EQ, the items related to EQ are excluded; however certain elements of the programme may be adopted based on specific needs. Practices of particular importance to new plants are summarized in Section 6.2.

6.1. FOR EXISTING PLANTS

6.1.1. Specification aspects

Preservation of cable technical data. It is very important for cable specifications, normally acquired during cable procurement, to be preserved. During plant life (typically 40+ years), design modifications and maintenance activities are likely to change the original plant cable population or its routing. Assessments of cable ageing are vital for life extension operations and require information on cable types, materials and locations. Without traceability of such information, life extension evaluation becomes very difficult for cables. Often the original cable manufacturers no longer exist, and such information is unavailable from sources other than the original procurement documents.

6.1.2. Inspection and maintenance

Hot spot identification. The main concern with hot spots is that the cable would eventually fail at the hot spot location much earlier than expected from the general condition of the cable. Hot spots need to be properly identified and the cause corrected or the cable replaced/repaired. Section 4.2.4 gives a summary of suitable methods for hot spot identification. Electrical CM methods show some potential for the identification of the presence of hot spots along the cable by detecting localized degradation of the cable. Periodical testing of cables in situ may identify their location before the degradation becomes too severe.

Environmental monitoring. Obtaining detailed knowledge of temperature and dose rate is an essential part of a cable ageing management programme. A broad range of locations within the NPP should be monitored. Methods for environmental monitoring are described in Section 4.2.

Mitigation of operational cable environments. Another approach to ageing management used in several countries is to manage the environment to which cables are subjected in their service. The normal operating environment for the cable could be amended with additional shielding from heat or radiation, or improved ventilation to reduce the impact of operational ageing and extend cable life. Rerouting of cables to avoid high-radiation areas has also been used.

Cable repair. This is not a common maintenance practice in some countries. Usually when damaged cables are found, the normal practice is to replace them as soon as possible. Before replacement, the damaged cables may be temporarily repaired by splicing in new cable to replace the damaged section using qualified heat-shrink sleeves. Certain models of these heat-shrink materials are qualified for safety application and in certain cases for harsh environments [40].

Removal of heat insulation. In various locations of the plant, a variety of heat insulation materials (e.g. reflective metallic insulation, asbestos fibre, wool wrap) are used either to shield the plant environment from high temperatures or to preserve the heat within the pipes and components for thermal efficiency. These insulation materials are often removed for maintenance activities. Since most of the heat insulation activities are performed by non-electrical staff, the vulnerability of cable materials to high temperatures is often not considered. As a result, the removal of heat insulation or its faulty replacement can lead to over-heating of cables in the immediate proximity and is one of the common sources of hot spots at NPPs. Post-maintenance walkdowns are a useful means of avoiding such problems.

6.1.3. Maintaining qualification

Condition monitoring. A wide range of CM methods are now available for the cable materials used at NPPs. These methods are summarized in Sections 4.4–4.7. CM is an essential part of condition-based qualification and is a useful technique to support life extension programmes. The CM test results, when compared against the QLD, can provide information on the remaining life of the cable and whether limited degradation has occurred to support life extension. Acceptance criteria for CM are being developed both for normal operation outside of harsh environments and for survivability of a DBA.

Cable deposit. The placement of cable samples, both whole cable and pre-prepared samples for measurements of mechanical and electrical properties, in a temperature and/or dose rate region typical of the most severe operational conditions at an NPP forms a very useful element of a cable ageing management programme. For example, in a PWR, a position near the steam generator would be appropriate. For power cables where ohmic heating is significant, the environmental conditions used should encompass this self-heating.

A typical deposit inside containment would consist of samples on a separate tray or stand as shown in Fig. 6.1. Such cable deposits are best prepared at the early stages of plant lifetime but can be successfully applied at a later stage if the deposit samples are pre-aged. By placing samples in an area where operational conditions are harsher than those seen by most cables, early warning can be obtained of potential problems with cable degradation. It is important that the samples have unrestricted air access to avoid diffusion-limited oxidation and that they are identified using metal ID tags that will not degrade during the time period of the deposit, which may be 40+ years. Enough samples are required for CM tests to be carried out at regular intervals during the plant's lifetime. Suitable intervals may be around five years after an initial period of ten years, the interval shortening if significant degradation is observed.

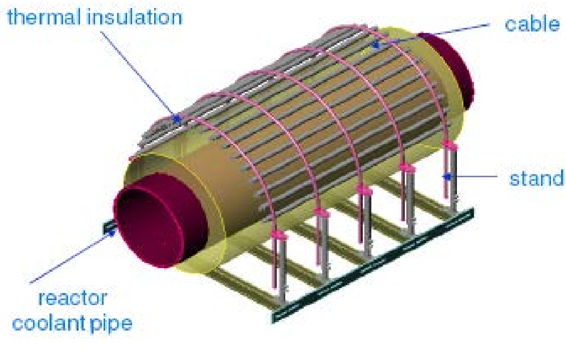

FIG. 6.1. The stand for deposit of reference specimen in the plant containment [38].

The long timescales for a cable deposit programme require test procedures that are very well defined. International standards are being prepared for the most developed CM methods currently available [22, 23, 27].

Cable replacement. This can be a cost effective way of dealing with plant life extension for cables that are subject to harsh environments and have already been in operation for 25–35 years. Such cables are likely to have been originally qualified using EQ procedures with considerable uncertainties in the pre-ageing phase. Planned replacement with modern cable materials may give additional benefits to the NPP in terms of better fire retardency, halogen-free materials, shielding and degradation characteristics. New cable with measured condition indicators can also be used in condition-based qualification.

6.2. NEW PLANTS

New NPPs have the opportunity to make best use of the advances in understanding of cable degradation that have been developed over the last decade. The following practices are of particular relevance to new plants.

Shielded cable. CM of power cables has become a necessity to monitor the degradation up to the QLD and to ensure the operational readiness of the cable. Cables that have a continuous shield as part of the cable jacket provide much wider and better options for CM. Therefore, power cables for new plants or replacement cables for operating plants should consider using only cables with a metallic shield [38].

Revised EQ procedure to reduce uncertainties. For new plants, the improved EQ procedures now available should be used to enable more realistic simulation of operational ageing (see Section 3). The addition of CM measurements during the pre-ageing phase means that condition-based qualification is available to the NPP, reducing uncertainties.

Cable deposit. The use of a cable deposit is strongly recommended for new plants to enable routine CM of cables through the plant's lifetime. Such deposits are best set up at the start of a plant's operation as part of the cable ageing management programme.

Environmental monitoring. As indicated in 8.1, environmental monitoring of temperature and radiation within the NPP is an essential part of cable ageing management and should be in place from the start of operation.

Condition monitoring. Making use of CM methods appropriate to the cable materials in plant should form an integral part of the cable ageing management programme. CM on samples within a cable deposit can be used as part of a condition-based qualification programme.

Undesirability of PVC cable insulation. New NPP installations in Europe have significant restrictions on the use of certain chemical elements under European Utility Requirements [41]. Such requirements restrict, for example, the amount of halogens to < 200 ppm. There are also requirements concerning other elements such as sulphur, zinc, lead, mercury and asbestos. These requirements disqualify PVC cables for future nuclear installations. In view of the fire hazards (smoke emission, corrosive degradation products) associated with PVC, even the more modern formulations of PVC, which have improved fire retardency, should not be considered for use in new installations.

6.3. CABLE AGEING DATABASE

Ageing effects, especially material degradation, have been experienced worldwide and progressively since the start of NPP operation. Material degradation is expected to continue as plants age and operating licences are extended. Stress corrosion cracking (SCC) and the degradation of cable insulation were the subjects of the SCC and Cable Ageing Project (SCAP). In the area of cable ageing, several countries joined the project to share knowledge, establish a complete database of major ageing phenomena, establish a knowledge base in these areas by compiling and evaluating the collected data and information systematically, and identify commendable practices.

The scope of this project involved the development of a knowledge base and commendable practices that address common elements in the management of ageing and mitigation of failures for components and cables, including: the study of ageing effects, investigation of failure mechanisms, mitigation of influencing factors, prediction of conditions for replacement, safety assessment of components, qualification testing (EQ for cables) and CM.

The SCAP database covers cables important to safety (e.g. those that support emergency core cooling and cables required to prevent and mitigate design basis accidents) and cables important to plant operation (cables whose failure could cause a plant trip or reduction in plant power). The scope of the database includes cables with voltage levels up to 15kV AC and 500 V DC, including I&C cables. This project developed an up-to-date encyclopaedic source of data on unique cables, and condition monitoring techniques have been gathered to help monitor and predict cable performance.

The final report discusses CM techniques used in the countries that participated in the project and the strengths and weaknesses of the various techniques. Furthermore, the report lists recommendations for continued research in the cable area, including the development of an electrical diagnostics and CM method that can scan the entire length of an installed cable system and determine its current condition, establishing the correlation between cable system condition indicators and the functional performance of the cable system during design basis accidents, and providing the technical basis for developing and/or updating qualification methods and standards to reflect past operating experience and realistic plant operating conditions.

7. SUMMARY AND CONCLUSIONS

This report provides a comprehensive assessment of qualification methods, ageing stressors and CM techniques for low voltage cables that have important applications at NPPs, with an emphasis on cables that play a role in plant safety. For example, I&C cables play a major role in the operation and safety of NPPs and are therefore emphasized in this report. Equipment ageing, life extension and long-life operation were among the reasons that stimulated the writing of this report.

Some specific issues that have been raised in this report are:

- Areas of concern in the qualification process have been identified, and specific recommendations have been made to address these concerns, including:
  - Misuse of margins;
  - Sequential testing;
  - Lack of oxygen in DBA testing;
  - Radiation dose rate;
  - Misapplication of Arrhenius equation;
  - Non-Arrhenius behaviour of XLPE.
- A step-by-step guide to the processes required for condition-based qualification is provided.
- Qualification monitoring using a combination of environmental monitoring and cable condition monitoring to maintain EQ is discussed:
  - A summary and characteristics of a wide range of cable CM techniques that could be used is presented. There is no single technique that covers all requirements, but a number of techniques have shown potential for CM.
  - New CM techniques under development are discussed.
  - The main aspects of a QM programme are outlined.
- Considerations for cable ageing management are discussed, including:
  - Cable management for life extension;
  - Development of EQ for plants without existing EQ;
  - Cables outside of harsh environments;
  - Recommended practices for both existing and new NPPs.

Cable ageing has been identified as one of the most important issues in relation to plant life management and life extension. As such, this report is very timely and will serve to enlighten cable manufacturers, utilities and new reactor designers as to how cables may be qualified for long-life operation and what must be considered to ensure that they are reliable throughout their service life.

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Annex

DEGRADATION OF POLYMERIC CABLE MATERIALS IN NUCLEAR POWER PLANTS

A–1. AGEING STRESSORS

The environmental service conditions at an NPP will induce chemical and/or physical changes to polymeric materials, which may cause changes/degradation in the functional characteristics of cable. For electrical cable, the most relevant components that will suffer significant degradation are the polymeric insulation and jacket materials.

There are a number of important ageing stressors in the degradation that occurs at an NPP. These are briefly discussed below.

Thermal

Polymers at NPPs are mostly degraded by thermal oxidation in the presence of oxygen as a result of chain scission or cross-linking among chains and the accumulation of oxidative products. For some polymer materials, the migration of additives and plasticizers can also be significant. The rate of degradation is usually accelerated by an increase in temperature (XLPE may be an exception — see Annex A–2.7). The relation between the rate constant for degradation (k) and ageing temperature (T) is determined by the Arrhenius equation Eq. (A–1):

$$k = A \exp(-E_A/RT) \qquad \text{(A–1)}$$

where E_A is the activation energy, A is the frequency factor and R is the gas constant. As a rough approximation, the degradation rate will increase by approximately 2 times for a 10°C rise in temperature for the values of activation energy that have typically been used in the past for cable materials.

Radiation

Gamma and neutron radiation are the most significant stressors for cables exposed to radiation during normal operation of an NPP, especially in the presence of oxygen. During accidents, beta radiation may also play an important role if the cable is not protected by a conduit. The effect of radiation degradation consists mainly of oxidative degradation. In general, the cable properties degrade with increasing absorbed doses, but many polymers are also sensitive to the radiation dose rate. The rate of degradation can be a very complicated function of absorbed dose and is usually non-linear (see A–2.5). There are predictive models available that have proven to be of practical use in predicting the behaviour of polymers in radiation environments (see A–5) [43].

Self-heating

Self-heating due to ohmic heating (Joule heating) is a common stressor for power cables that needs to be taken into account during qualification. The level of this stressor depends on the time that the cable is energized and the current it is carrying as well as its installed configuration (e.g. existence of fire barrier coatings, depth of fill in cable trays).

Other stressors

Ozone (O_3) produced in a radiation atmosphere, humidity (H_2O), mechanical stress (including vibration), mineral oil and chemicals are also stressors. These stressors are usually minor and not simulated during qualification. However, in some cases, the qualification may also cover the consequence of some of these factors. Vibration may need to be taken into account for cables that are attached to vibrating components since vibration may increase the severity of ageing by introducing small cracks that affect the dielectric behaviour when exposed to high-pressure steam in a DBA. In medium voltage cables, the presence of water and electrical stresses can give rise to treeing damage. UV damage may need to be considered for cables exposed to fluorescent lights inside buildings or to sunshine outside.

A–2. UNCERTAINTIES IN ACCELERATED AGEING

As a better understanding of the ageing behaviour of polymeric materials has been developed, the uncertainties that are present during accelerated ageing are now better appreciated. The following sections deal with the main uncertainties that will be present during EQ testing.

A–2.1. Diffusion limited oxidation

Since both thermal and radiation degradation are mainly due to oxidation reactions, the presence of oxygen in the polymer is of prime importance. Under normal operational conditions at an NPP, degradation (and hence oxidation) will proceed at a rate that is sufficiently slow for oxygen to diffuse into the polymeric material from the surrounding atmosphere. The oxidation processes will not be limited by the rate of diffusion under these conditions, and oxidation will be homogenous through the thickness of the polymer.

However, under accelerated ageing conditions, the rate of oxygen consumption will be much higher and may be faster than the rate at which oxygen can diffuse into the material. Under these conditions, there will be a smooth decrease in oxygen concentration from its equilibrium sorption value at the sample surface to a reduced value inside the material. This can give rise to heterogeneous oxidation through the thickness of the polymer.

The importance of diffusion limited oxidation will depend on the geometry of the material combined with the oxygen consumption rate, the permeability of the polymer to oxygen and the partial pressure of oxygen in the surrounding atmosphere. The consumption rate and the permeability will also be functions of temperature and/or the radiation dose rate. It is of most concern when carrying out accelerated testing on thick samples (e.g. whole cables) for both thermal and radiation ageing.

An estimate of the sample thickness (L) at which diffusion limited oxidation is insignificant can be made using the following equation.

$$L \sim 2\,[p\,P_{ox}/\varphi\,]^{0.5} \qquad \text{(A–2)}$$

where p is the partial pressure of oxygen surrounding the sample, P is the oxygen permeation rate and φ is the oxygen consumption rate in the material [26]. If this condition is satisfied, then the integrated oxidation through the thickness will be at least 95% of the homogeneous value.

An example of heterogeneous oxidation is shown in Fig. A–1 using modulus profiling (see Section 4.5.8) to show the changes that occur through the thickness of a sample at progressive ageing intervals during thermal ageing in an air-circulated oven. Note that the hardness at the edge of the sample after 23 days at 138ºC is approximately two to three times higher than the hardness in the centre of the sample, indicating a significant difference between the degradation at the surface and in the middle of the sample.

A–2.2. Dose rate effects

In most polymers, the degradation that is observed is not only dependent on the total absorbed radiation dose but also on the dose rate. Degradation at low dose rates, such as those present at an NPP under normal operational conditions, is significantly higher than degradation that occurs for the same total dose at a higher dose rate, such as in accelerated testing. In many cases, the observed dose rate effect arises from the effects of diffusion limited oxidation, which gives rise to heterogeneous oxidation (as discussed in Section A–2.1), particularly in thick samples.

Even when the effects of diffusion limited oxidation are eliminated, some polymers will still exhibit significant dose rate effects. Figure A–2 shows an example of this effect for a XLPE insulation material irradiated at 20ºC. This type of behaviour is quite common in polyolefins and EPR materials.

The recommended maximum dose rates for accelerated ageing are 100 Gy/h for operational ageing and 10 kGy/h for DBE radiation tests.

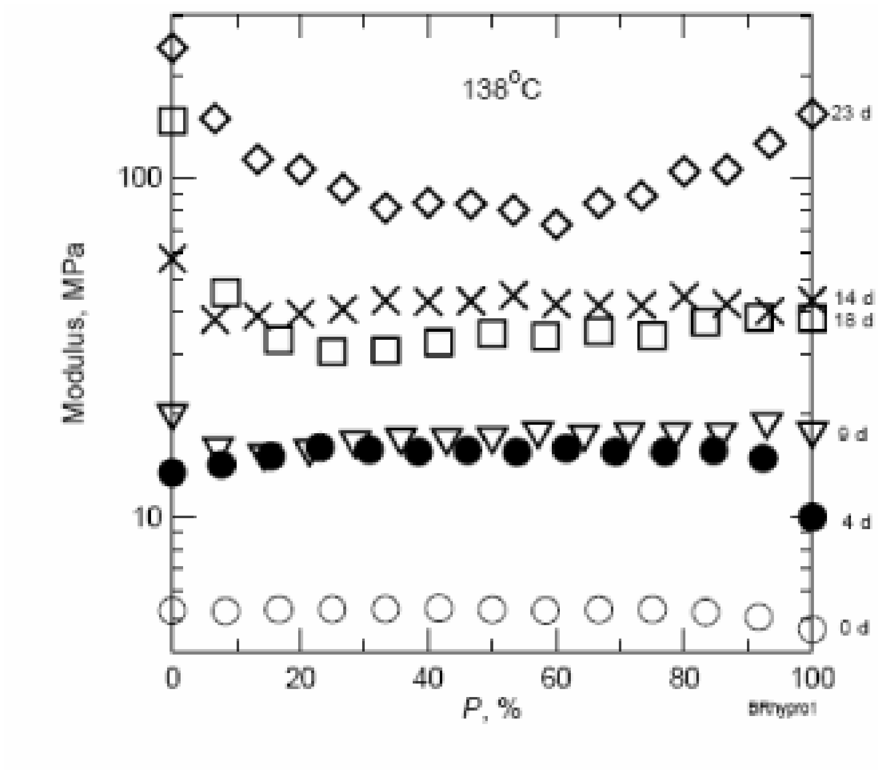


FIG. A–1. Modulus profiling of a CSPE material aged at 138ºC where P is the thickness of the sample (1.6 mm) [26].

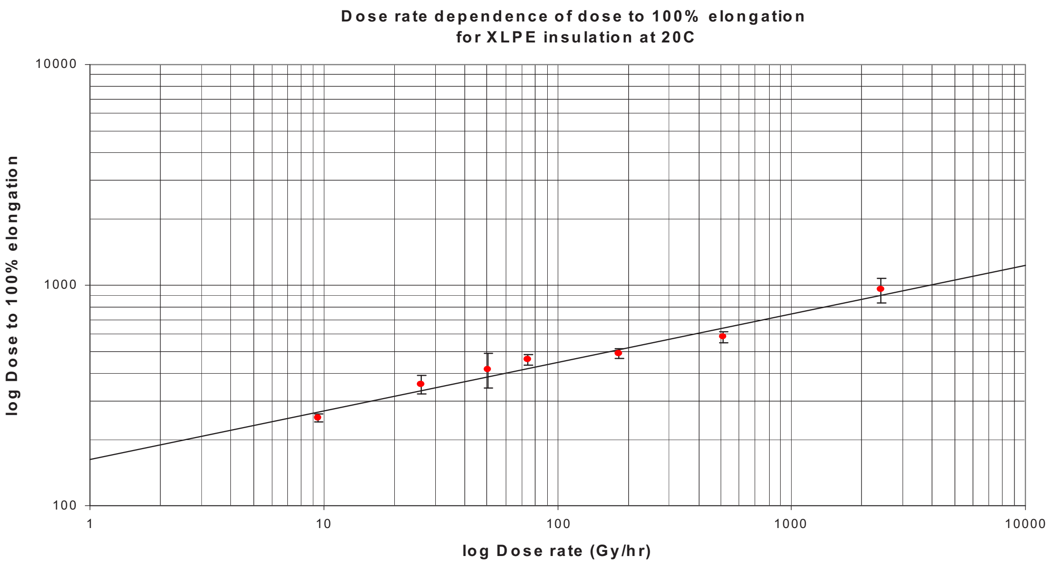


FIG. A–2. Dose required to reach an elongation at break value of 100% absolute as a function of dose rate for an XLPE cable insulation material irradiated at 20ºC.

A–2.3. Application of the Arrhenius model

The Arrhenius equation is widely used as the basis for accelerated thermal ageing, but some of its limitations need to be understood. It is only applicable if the same reaction is occurring at the higher temperature as occurs at the service temperature. If the degradation mechanism changes, the equation is not applicable. An example of this arises in PVC materials, where plasticizer loss is the dominant mechanism at low temperatures but where hydrochloric acid (HCl) evolution dominates at temperatures >70ºC [42].

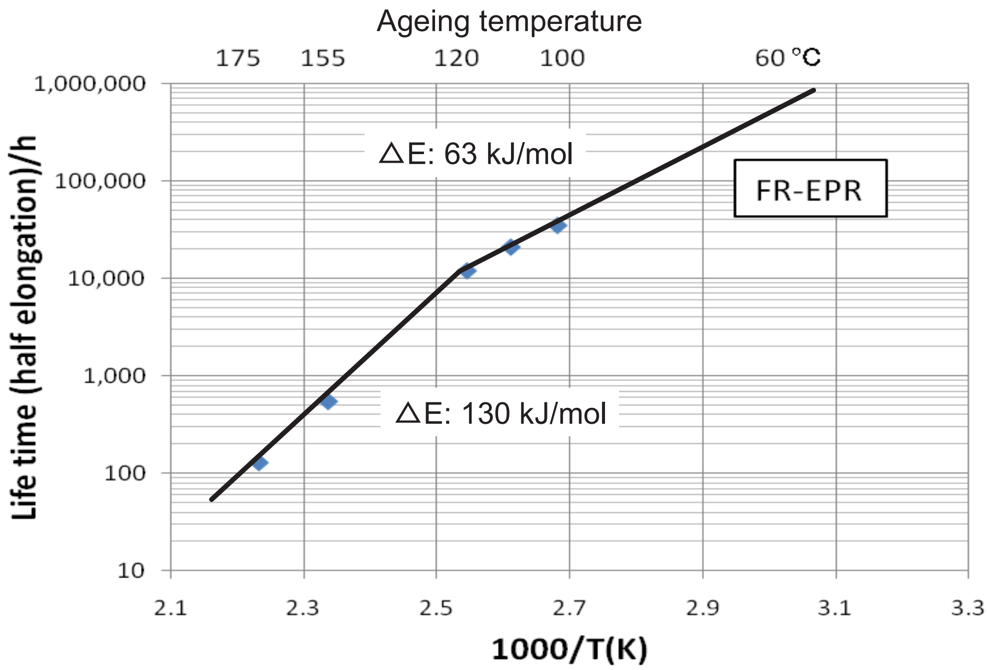


FIG. A–3. Arrhenius plot for an EPR cable material [9].

The Arrhenius equation also cannot be applied across a physical transition of the material. For example, in semi-crystalline materials such as XLPE, there is a crystalline melting point in the temperature range 90–120ºC. In operational use at an NPP, such materials would normally be used at a temperature below this melting point. However, accelerated ageing is often carried out at temperatures >120ºC where the material would be amorphous rather than semi-crystalline. The degradation at these accelerated temperatures, therefore, does not satisfactorily simulate the degradation that occurs at lower service temperatures.

A–2.4. Limitations of activation energy values

The most important parameter for use of the Arrhenius equation is the activation energy (E_A). The qualified life calculated from the equation is very sensitive to the value used (as shown in Section 5.3). It is usually assumed that E_A will be a constant over the full temperature range of interest, but this is rarely a valid assumption. Activation energies are usually determined from accelerated ageing at elevated temperatures, typically >120ºC, but as more sensitive methods have been developed, it has become possible to measure E_A at much lower temperatures, which are more appropriate to the range of service temperatures. In many cases, the value is significantly lower at temperatures <100ºC [9]. Note that in Fig. A–3, the parameters ΔE are the activation energies for the two temperature ranges shown.

Typical E_A values used for cable materials are in the range 0.9 to 1.2 eV (1 eV = 96.48 kJ/mol), but at temperatures <100ºC, a more appropriate value is likely to be 0.65 eV.

It is very important that an appropriate value of E_A is used to estimate the degradation that would occur at the temperatures relevant to operational conditions at an NPP. If measured values of E_A at these temperatures are not available, it is recommended that a value of 62.8 kJ/mol is used for temperatures below 100ºC.

Methods for measuring E_A are given in Section A–3.

A–2.5. Synergistic effects

In qualification testing, the assumption is usually made that thermal degradation and radiation degradation are additive, and that there are no synergistic effects. However, for many polymers, synergistic effects can be significant so that the degradation becomes a complex function of temperature, dose and dose rate. There are

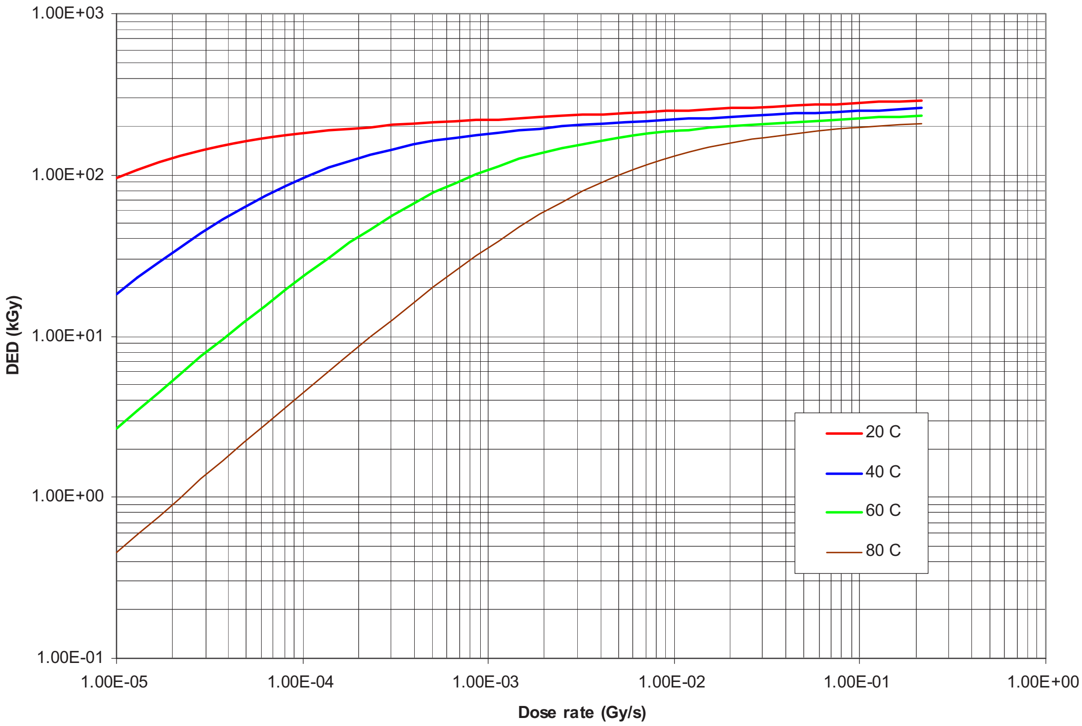


FIG. A–4. Generic plot of the dose required to reach a specific level of degradation (DED) as a function of dose rate at different temperatures for a typical polymeric cable material.

predictive models available that can take into account such effects [26, 43]. Figure A–4 shows an example of the typical generic shape of curves of dose to equivalent damage (DED)[1] as a function of temperature and dose rate.

Note that at high dose rates, an increase in temperature has very little effect on the DED value, whereas at low dose rates, temperature has a very large effect. At high dose rates, radiation degradation mechanisms will dominate the overall degradation process. At low dose rates, thermal degradation processes will dominate, and the slope of the plot of DED versus dose rate will approach a value of 1 (i.e. a constant time). In polymers that show no significant synergy, the curves at high dose rates will approach a single line of constant DED independent of temperature. For the example shown in Fig. A–4, there is some synergy so that temperature still has some effect at the high dose rates, and DED is also a function of the dose rate.

The existence of synergistic effects can only be checked by carrying out simultaneous radiation and thermal ageing on samples of the polymer material. Tests carried out at dose rates < 500 Gy/h and at moderate temperatures (e.g. 25ºC and 60ºC) will usually indicate whether synergistic effects need to be taken into account during accelerated testing.

Another type of synergistic effect that may need to be considered in the ageing of cable materials arises from interactions between the different materials used in the cable construction. Degradation products from one part of the cable may affect other parts of the cable. This can be checked by comparing the ageing observed in samples aged as whole cable with samples aged as separate components.

A–2.6. Oxygenation of the DBA chamber

The test chambers used for simulation of the thermal profile of a DBA during qualification are often quite small with a limited partial pressure of oxygen present due to their small volume. Diffusion limited oxidation effects can then become significant in terms of restricting the total degradation that will occur during the thermal profile. Oxidation will not necessarily be heterogeneous but is likely to be significantly less than would occur

[1] DED is the radiation dose required to reach a specific level of degradation (e.g. an elongation at break of 100% absolute).

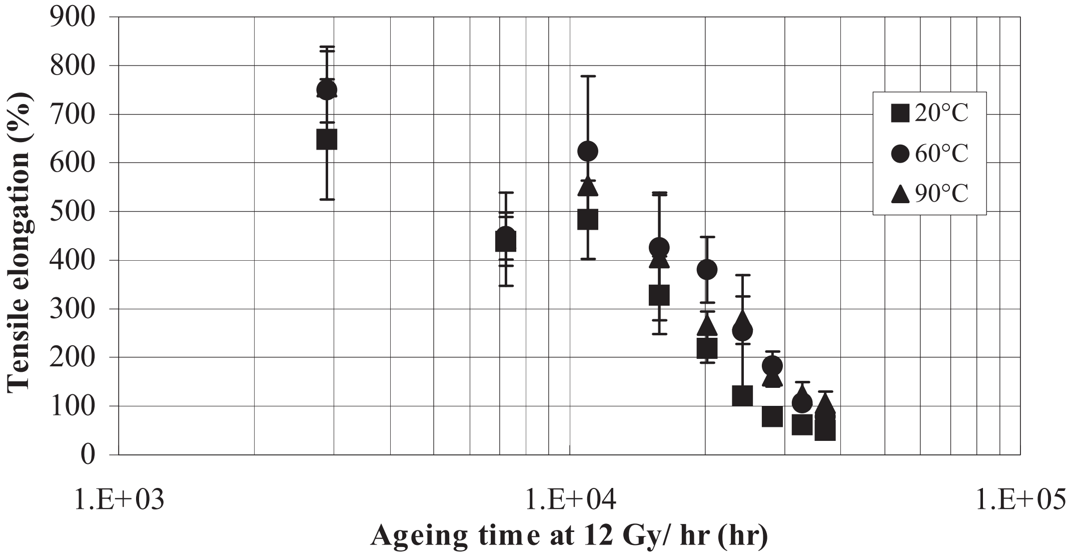


FIG. A–5. Tensile elongation data for XLPE insulation as a function of ageing time at 12 Gy/h.

during an actual DBA where the oxygen content is not restricted. This means that the degradation produced by the DBA may be significantly underestimated.

Consideration should be given to supplementing the oxygen content of the test chamber during the thermal profile to ensure that diffusion limited oxidation does not take place.

A–2.7. Reverse temperature effect

The reverse temperature effect is a phenomenon that has only recently been recognized. It has been seen in polyolefin materials that have been radiation aged in air at temperatures below their crystalline melting points [2, 44, 45]. Under these conditions, degradation is more rapid at lower temperatures than at higher temperatures, which is opposite to what would be expected from the normal kinetics of chemical reactions (see Fig. A–5). However it is now realized that the reverse temperature effect is a function of the semi-crystalline nature of the polyolefins. It is not expected that this effect would be significant in polymers with limited crystallinity (e.g. some EPR-based materials).

Polyethylene-based materials such as XLPE are semi-crystalline, and their mechanical properties are determined by their microstructure at the supermolecular level. The material contains randomly oriented crystalline regions linked by amorphous tie molecules. During radiation ageing, reactive species such as radicals are generated uniformly throughout both crystalline and amorphous regions. In the crystalline regions at temperatures well below their melting point, these species are trapped and are unable to react to form oxidative products because of the low chain mobility and the low oxygen diffusion rate in the crystalline region. Degradation then proceeds primarily through oxidative scission reactions in the amorphous regions where both chain mobility and oxygen diffusion rates are higher. Since the amorphous regions form the tie molecules between the crystalline blocks, chain scission in these regions has a marked effect on the mechanical properties.

If the radiation ageing occurs at slightly higher temperatures nearer the melting region for the crystalline portion, then chain mobility is high enough for the trapped species to react to form chemical cross links. In addition, the enhanced mobility enables some recrystallization to occur, which can reform tie molecules that were broken by oxidative scission in the amorphous regions. The combination of these effects is to effectively ‘heal’ some of the damage that is created by the radiation ageing. The overall macroscopic effect is a reduced rate of degradation at higher temperatures during radiation ageing.

A–2.8. An approach to pre-ageing in an EQ test for XLPE

In Section 2.6.2, concerns were raised on the non-Arrhenius behaviour of semi-crystalline polymers such as XLPE. Extensive studies using ultra-sensitive methods to measure activation energies at low temperatures [27] indicate that it may be practical to use the Arrhenius equation to extrapolate from high-temperature thermal ageing to operational temperatures for some of these materials, provided that a suitable value for E_A (typically 70–75 kJ/mol) is used. However, this is only possible if the radiation ageing component of operational ageing is insignificant (i.e. <0.1 Gy/h). For NPPs where the radiation ageing component is >0.1 Gy/h, a possible approach to pre-ageing for such materials could make use of the known radiation ageing behaviour of these materials.

The power law model (see Annex A–5.1) is known to work for such materials at near ambient temperature, so there is a starting point for modelling when data is available from radiation ageing. Generally, the value of the power function (*n)* is between 0 and 0.3.

The general shape of the transition from constant time to failure (thermal degradation) to a dose rate dependent time to failure (radiation degradation) is also known from the superposition model (see Annex A–5.2). As a first approximation, this curve shape could be used (using a value of $x = 1 – n$ in the superposition model) to make an estimate of how the transition will occur in polyolefins. What will be unknown is the dose rate at which the curves will diverge. The first indication of this will be a non-linearity of the power law line at low dose rates.

This approach would give an estimate of how the material would work in reality. However, the pre-ageing required for EQ testing is usually assumed to be dominated by the thermal ageing component in cables. These materials show non-Arrhenius behaviour and often a negative temperature effect; so using accelerated ageing at higher temperatures to simulate thermal ageing is not valid.

A way forward would be to use the estimated service dose and dose rate to work out the likely degradation at the intended service life, then calculate from the power law what dose rate and time is required to reach the same degree of degradation in a practical timescale. This approach would require preliminary work on radiation ageing at different dose rates to generate the power law parameters and the shape of the degradation curve. Because the lowest service temperature would be the worst-case scenario, the radiation testing would be done at ambient temperature, therefore avoiding the cost of doing combined thermal/radiation ageing.

When using this approach, it would also be necessary to carry out some spot checks at a low dose rate, elevated temperature (at the maximum service temperature) and thermal-only ageing to verify that the negative temperature effect does occur in the material. This would confirm that radiation ageing at an ambient temperature is the worst case.

An example of real data for a XLPE insulation material is shown below. This material has a broad melting endotherm, peaking at about 120ºC, with a broad shoulder to the endotherm starting at about 60ºC (Fig. A–6).

There is extensive data on this material for radiation ageing at 20ºC over a wide range of dose rates, showing that it obeys the power law. This material has also been the subject of combined thermal/radiation ageing measurements at elevated temperatures and is known to obey the time dependent superposition model for temperatures >90ºC (i.e. above the crystalline melting point).

Figure A–7 shows the total dose required to reach 100% elongation (DED) as a function of dose rate for this XLPE material. The red data points are for radiation ageing at 20ºC, and the red line shows the best fit of the power law model to this data. The blue line and the green line show the predicted behaviour at 60ºC and 90ºC, respectively, from the superposition model for this material. Note that although the 90ºC data point (green) lies on the predicted curve, the 60ºC data point (blue) shows much higher degradation than predicted by the superposition model. This demonstrates that this material has a marked negative temperature effect in the range 20ºC to 90ºC.

The data for this XLPE material indicates that the power law approach appears valid, but there is still the uncertainty as to the dose rate at which the material would be expected to be dominated by thermal ageing rather than radiation ageing. This would appear as a divergence from the power law line as the dose rate decreases. In the example shown below, if we assume that the lowest data point is showing some divergence, the predicted curve at lower dose rates might be as shown by the black line. This would be an extreme case in that the predicted time to reach 100% elongation in the absence of radiation would be about 22 years. This is much less than would be expected in reality for a XLPE insulation at 20ºC.

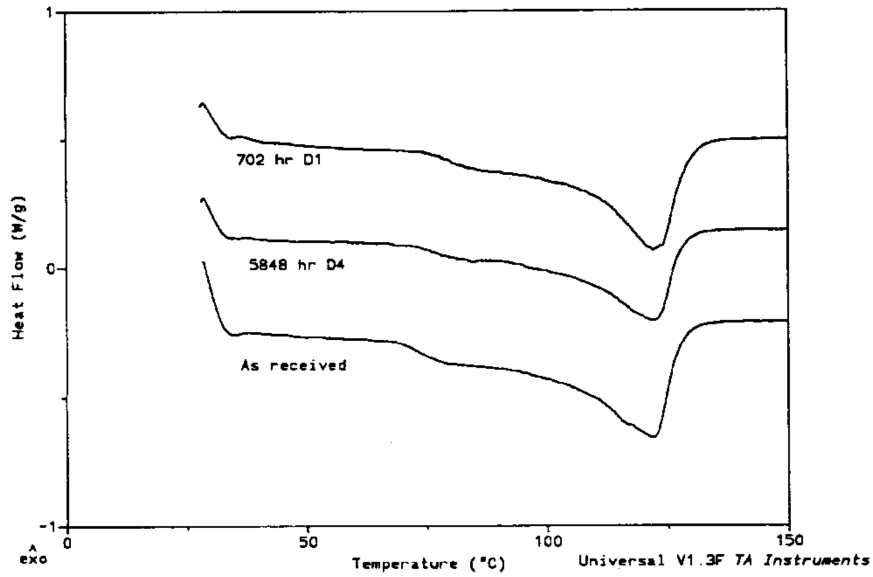


FIG. A–6. DSC traces for a XLPE insulation material showing the crystalline melting endotherm in both unaged and aged material.

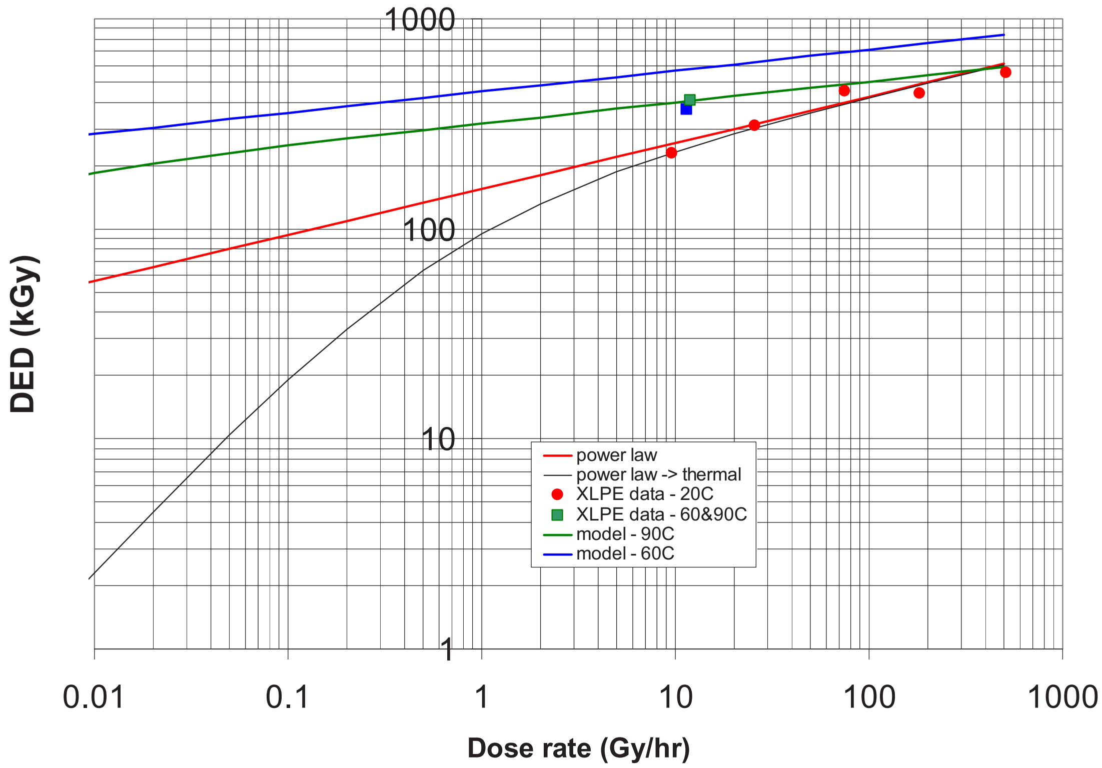


FIG. A–7. Radiation ageing data for an XLPE insulation material as a function of the dose rate.

However if this data point is regarded as being still within the power law (bearing in mind the standard deviation of the data), the divergent curve would be more like the example shown in Fig. A–8. The real situation is most likely to be in between these extremes.

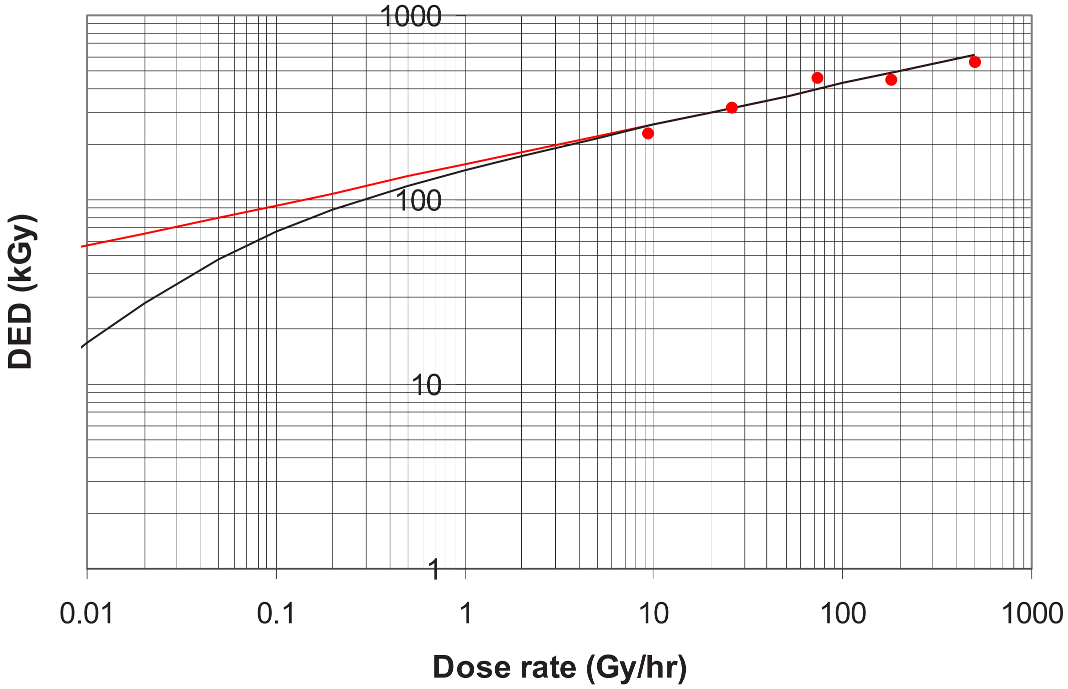


FIG. A–8. An illustration of how the degradation curve for this XLPE might behave at lower dose rates (black line) compared to the power law model (red line).

A–2.9. Avoiding common problems with accelerated ageing

In this section, a simplified flow chart is described (Fig. A–9), which provides a suggested route for avoiding some of the common mistakes that can occur in implementing accelerated ageing studies. This diagram can be applied to all of the polymeric materials that are usually used in commercial electrical cables. By tracing through the flow chart, the main pitfalls commonly experienced in accelerated ageing can be avoided, and the results will be more representative of natural ageing.

The suggested approach involves a small amount of initial checks carried out before the start of an accelerated ageing programme to identify the potential problem areas.

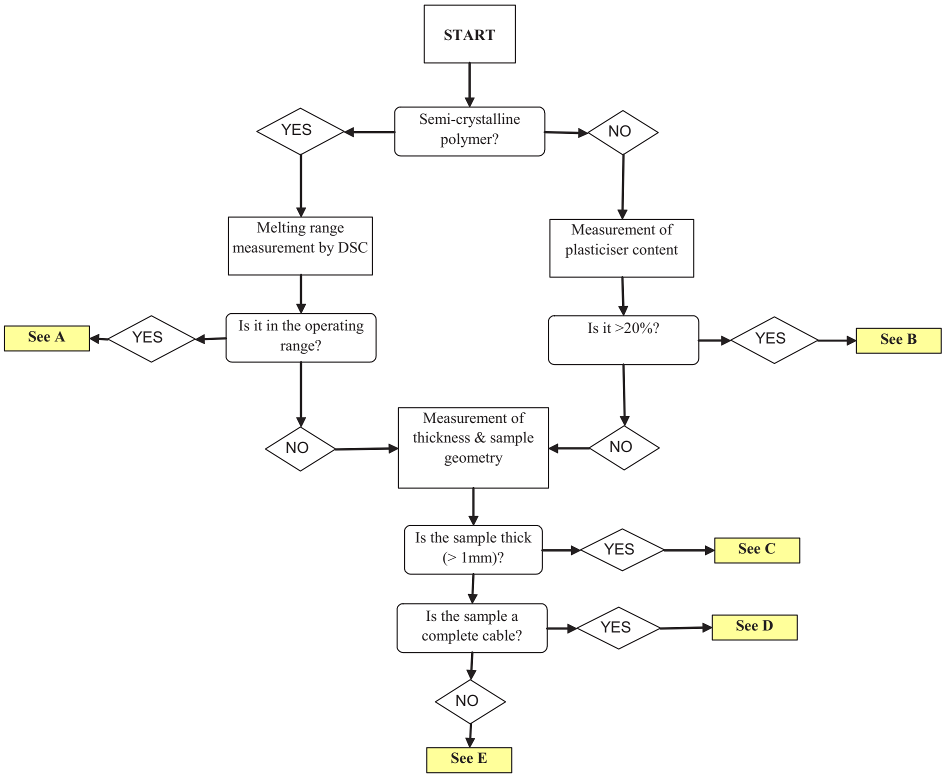
A–3. METHODS FOR MEASURING ACTIVATION ENERGY

Accurate values of activation energies are key to obtaining representative ageing in accelerated ageing tests. The methods recommended for determining the activation energy of thermal ageing (E_A) and for the statistical processing of ageing data are described in a series of guides [14]. The number of samples necessary for a reliable determination of E_A, and the temperature margin for following accelerated thermal ageing are analysed and recommended in Ref. [46].

The value of E_A at ambient temperature should be evaluated carefully even if it is time and labour consuming, and a sophisticated procedure to evaluate E_A is required. Some examples of methods for measuring E_A are given in the following sections.

A–3.1. Using elongation measurements

Measurement of E_A using changes in tensile elongation properties is the most common method in use and is based on the main criterion for qualification. To get a good estimate of E_A using elongation requires a large number of samples and a considerable time period for thermal ageing if it is to be carried out at temperatures close to service conditions.



A: Recrystallization effects; extrapolation through the crystalline melting range should be considered
B: Competition between evaporation/diffusion of plasticizers and degradation should be considered
C: Low acceleration factors should be selected for ageing programmes in order to avoid diffusion-limited oxidation
D: Interaction of materials (plasticizer migration, catalytic effect) can occur
E: No special precautions required

FIG. A–9. Suggested flow chart for identifying potential concerns in accelerated ageing programmes.

E_A measurements should be to the same level of degradation (e.g. by plotting the log of the time it takes to reach 50% absolute elongation against the reciprocal temperature). An alternative is to use the superposition principle to determine the multiplicative shift factors required at each temperature and plot these against the reciprocal temperature.

A–3.2. Using microcalorimetry

The microcalorimetry method uses an instrument capable of measuring the very small heat flows (μW/g) associated with slow ageing processes. This enables measurements to be carried out at temperatures closer to ambient temperature than are generally used in E_A studies. The method is particularly useful for studies on unstabilized materials and for those stabilized materials where the antioxidant has been consumed. Reference [47] gives some examples of E_A measurements made using this method on XLPE, CSPE and EPDM materials.

A–3.3. Using gas analysis

This method is based on measurements of oxygen consumption and CO_2 evolution as a result of the oxidation that occurs when polymer materials are thermally and/or radiation aged [48].

Small amounts of material (approximately 0.5 g) are put into an ampoule (volume 60 mL) with a breakable seal. After degassing, the ampoule is filled with oxygen (at 600 torr). The ampoules are stored at the test temperature with/without irradiation. Then the gas in the ampoule is analysed by gas chromatography to evaluate the oxygen consumed and CO_2 evolved. The time required to reach a fixed amount of oxygen consumption or CO_2 evolution is plotted as a function of test temperature.

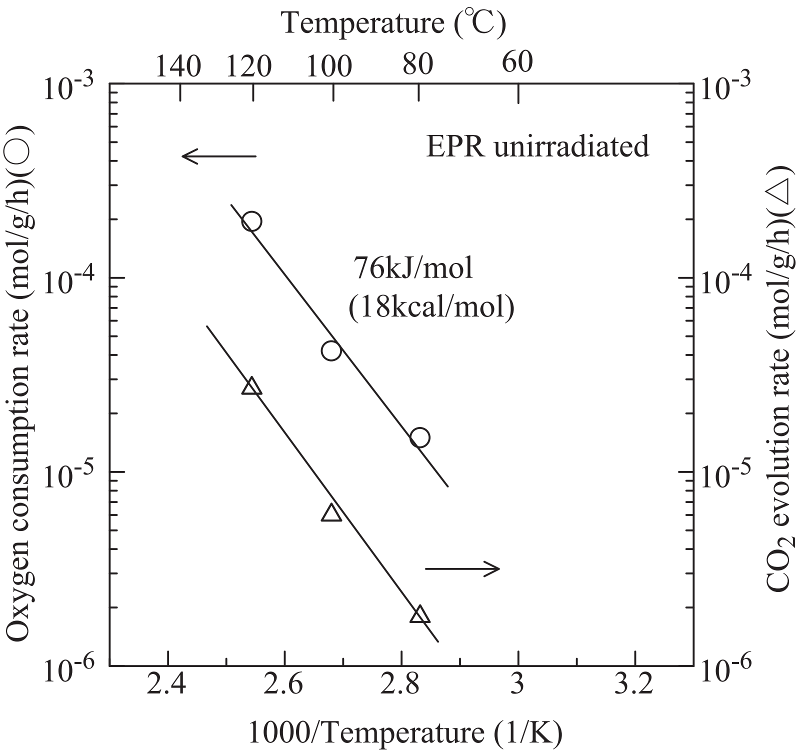


FIG. A–10. Arrhenius plot of oxygen gas consumption and evolved CO_2 for unirradiated EPR.

Figure A–10 shows an example of the Arrhenius plot using gas analysis for an EPDM. The activation energy obtained was 76 kJ/mol at around ambient temperature. This method is sensitive and therefore timesaving compared to tensile testing, and the result successfully agrees with the tensile data.

Irradiation to 100 kGy facilitates the analysis because irradiation consumes antioxidants in the compound and eliminates the induction period of the time profiles of oxygen consumption or CO_2 evolution. Irradiation also accelerates degradation, whereas E_A is kept almost unchanged.

A–3.4. Using chemiluminescence

This method utilizes luminescence from thermally excited ketone groups (>C = O)* [48]. The ketone groups are formed through oxidation of the polymer. A sample of 15 mm x 15 mm was kept in a chamber under flowing oxygen. The luminescence intensity at 350–600 nm was measured at various temperatures. Thermal treatment before measurement was found to be effective in obtaining a stable signal.

Figure A–11 shows the chemiluminescence intensity as a function of the measuring temperature for EPR unirradiated and irradiated to 500 kGy. The E_A value obtained was 58 kJ/mol, which is in good agreement with tensile data at ambient temperature. This method is also sensitive and timesaving compared to tensile testing, and yields successful results.

Figure A–11 also shows that irradiation up to 500 kGy enhances the intensity of the luminescence, with the v value kept unchanged. Irradiation to a certain dose can be convenient for the analysis in this case as well.

A–4. CONDITION SETTING FOR SIMULTANEOUS AGEING IN EQ TESTS

The pre-ageing test conditions used for simultaneous ageing should be based on the expected normal operation conditions and qualified life. The upper limits of temperature and dose rate used for the pre-ageing test should be such that degradation proceeds homogeneously through the full thickness of the material. This should be confirmed using methods suitable for detecting diffusion limited oxidation [9, 49].

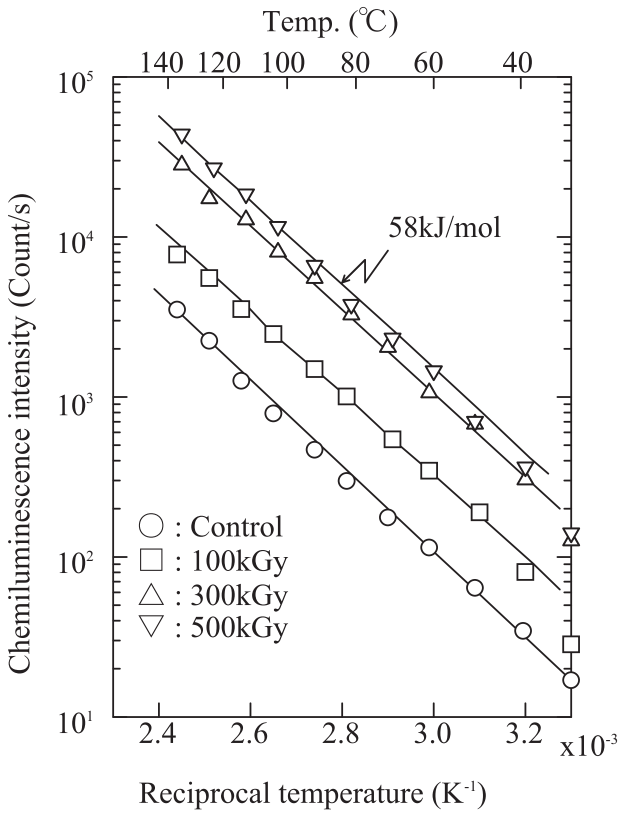


FIG. A–11. Chemiluminescence intensity as a function of measuring temperature for EPR unirradiated and irradiated to 500 kGy.

The simplest condition setting method for simultaneous accelerated ageing is a method that uses “the same acceleration factor”. In the first step of this approach, the temperature of accelerated ageing is decided, not exceeding 120°C, and the acceleration factor is calculated by Eq. (2.2). The next step is to calculate the dose rate for accelerated ageing by multiplying the service dose rate by the acceleration factor. The time for accelerated ageing is calculated by dividing the required service life (qualified life) by the acceleration factor. For example, the acceleration factor would be 64.4 at T_1 = 50°C vs. T_2 = 100°C for E_A = 15 kcal/mol. The disadvantage of this method is that the dose rate of accelerated ageing and the time of accelerated ageing are fixed by the temperature of accelerated ageing. In most cases, the dose rate for accelerated ageing will be lower than the maximum recommended dose rate (100 Gy/h). This approach to simultaneous ageing assumes that there is no synergy between thermal and radiation ageing.

Techniques such as the superposition of time dependent data or the superposition of dose to equivalent damage data can be used to predict cable ageing in the actual plant [43] — see Annex A–5. The condition setting for simultaneous accelerated ageing can be based on these techniques [9]. However, the high cost and long timescale needed to apply the original superposition techniques are not generally practical since so much ageing test data is required. With this being the case, a simplified method using the superposition of dose to equivalent damage data is proposed [9]. When the pre-ageing test conditions are set by this simplified method, the test conditions are more conservative than those set by the original method. But the merit of the simplified method is that ageing test data are not needed to set the pre-ageing test conditions. The acceleration factor can be calculated by Eq. (A–3). In this equation, the value of “*b*” is estimated empirically for each insulation material. For example, the acceleration factor is 107.2 at T_1 = 50°C, D_1 = 0.2 Gy/h vs. T_2 = 100°C, D_2 = 100 Gy/h (E_A = 15 kcal/mol, *b* = 0.5).

$$a = \frac{t_1}{t_2} = \left[e^{\frac{E_A}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)} \times \frac{D_1}{D_2} \right]^b \times \frac{D_2}{D_1} \qquad \text{(A–3)}$$

where

D_1: Service dose rate
D_2: Dose rate of accelerated ageing fixed at 100 Gy/h
b: Constant [Dependent on insulation type, FR-EPDM is 0.65, XLPE/FR-XLPE/EPDM are 0.5, SHPVC is 0.35, SIR is 0.25]

This approach is described in more detail in Ref. [9].

A–5. PREDICTIVE MODELLING OF CABLE AGEING

Predictive modelling of cable ageing has a valuable place in cable ageing management in support of testing cables that have been exposed to either accelerated or natural ageing. Modelling can be used for:

— Initial estimation of cable lifetimes using design basis environments;
— More detailed evaluation of cable degradation where there is sufficient confidence in the model parameters and environmental monitoring history;
— Identification of potential worst-case cable applications where supplementary ageing management actions may be advisable.

There are a wide range of approaches that have been developed by researchers over the past few years.

All of the analytical models outlined here are based on experimental data obtained on cable samples that have been subjected to accelerated ageing. Factors such as dose rate effects and the existence of diffusion-limited oxidation should be taken into account in accelerated ageing programmes.

Some of the analytical methods that have been developed are outlined in the following sections. Analytical methods are generally based on an understanding of the kinetics of the degradation process. In many cases, a semi-empirical approach with simplifying assumptions yields a useful mathematical tool for estimating residual lifetime of cables under environmental conditions (temperature and dose rate) applicable to their use in plant. Current models do not take into account other environmental conditions (e.g. moisture, vibration, chemical contaminants) which may have an effect on the lifetime. For thermal ageing in the absence of radiation, the Arrhenius model has been widely used.

A–5.1. Power law extrapolation model

The simple power law model is based on the extrapolation of radiation ageing data obtained under isothermal conditions at several dose rates. Application of this model and its limitations are described in detail in Ref. [43]. It is particularly useful for materials that show a marked dose rate effect but is generally limited to temperatures near ambient (i.e. <40°C).

The dose required to reach a specific end point criterion (e.g. decrease in elongation to 50% of initial value) is found to follow a simple power law, where

$$\text{Dose to end point} = K.D^{n} \qquad \text{(A–4)}$$

where D is the dose rate, K and n are material-specific parameters; n typically is in the range 0 to 0.3. For materials with no dose rate effect, the parameter n = 0, and the damage is a function of the total absorbed dose only.

A–5.2. Superposition of time dependent data

The superposition model combines data from both thermal and radiation ageing. The model uses the superposition principle applied to time-temperature-dose rate superposition. This generates a series of multiplicative shift factors, which are a function of both temperature and dose rate. A semi-empirical equation can be used to describe the functional relationship between the shift factors a(T,D) and the ageing conditions. The model can take into account both dose rate effects and synergism between radiation and thermal ageing.

$$a(T,D) = \exp -E/R\ (1/T - 1/T_{ref})\ [1 + k.D^x.\exp Ex/R\ (1/T - 1/T_{ref})] \quad \text{(A–5)}$$

where T is the temperature in K, T_{ref} is the reference temperature in K, D is the dose rate and E, k and x are the model parameters. The parameter E is the value of the activation energy for thermal-only ageing. The parameters k and x are determined by fitting the values of a(T,D) obtained experimentally to the empirical equation.

This model is applicable to materials where there is a single dominant ageing mechanism for both thermal and radiation ageing. It has proved to be useful for a number of polymeric materials used in cables. Application of this model and its limitations are described in detail in Ref. [43].

A–5.3. Superposition of end point dose data

This model also uses a superposition approach to radiation and thermal ageing data but can be used in materials where there is not a single dominant degradation mechanism. The model uses superposition to generate a series of curves of end point doses as a function of dose rate for different temperatures. The multiplicative shift factors required to superpose the data are a function of the temperature only and can often be linked to a simple Arrhenius relationship. This model is particularly useful where the material exhibits a strong dose rate effect.

Application of this model and its limitations are described in detail in Ref. [43].

A–5.4. Application of predictive modelling to NPP cables

For new cable installations, in newly constructed NPPs and for new cables in older NPPs, there is a wider choice of approaches than in older plants. Generally, unaged cable material is readily available for accelerated ageing programmes, and there is a selection of predictive methods available. The selection of the most suitable method will depend on the scope of the accelerated ageing programme and the type of data available from it. Some examples are briefly described below.

At Sizewell B (PWR, United Kingdom), all of the cable types used inside containment were included in an accelerated ageing programme during the design and construction phase of the NPP. The programme covered measurements of elongation at break over a matrix of temperatures and dose rates. The experimental data were used with the model based on superposition of time dependent data to predict the behaviour of the cable materials under their expected service conditions. This information was used in support of the NPP's safety case and was carried out in addition to the formal qualification process. A cable deposit has also been installed for future sampling.

For the Temelín NPP (Czech Republic), cable deposits and laboratory testing have been carried out. A location for the deposits has been identified, and the best solution with the most severe environmental conditions appears to be the hot leg between the reactor vessel and the steam generator. Nevertheless, 26 other deposits within the NPP have been created. The environmental conditions vary from 20 to 56°C, and the dose rates vary from 0 to 0.4 Gy/h. About 300 cables 4 to 35 m in length have been placed in these deposits. Temperature monitoring (using a datalogger capable of recording temperatures every 4 hours for up to one year) and radiation monitoring systems (alanine/ESR dosimeter system together with cobalt/nickel activation monitors) have been installed in various deposit locations. Cable samples are periodically measured to provide basic information on the ageing effects of the environment at the deposit. The installation of the cobalt/nickel activation monitors will be performed only for one fuel cycle to verify that neutron fluxes are negligible and have no importance in terms of cable degradation. The accuracy of the environmental data is crucial for cable lifetime prediction.

As a further attempt to understand long term ageing of cable materials, radiation ageing using a ^{60}Co gamma source and thermal ageing at low accelerated ageing temperatures have been implemented in parallel with the cable deposit programme at Temelin. In addition to the room temperature irradiation at several dose rates, irradiation at enhanced temperatures (up to 75°C) have also been performed for comparison with the results of oven ageing at the same temperature. Included in the programme is the preparation of well defined aged cable samples for future LOCA simulation tests. For many of the deposit samples, common CM techniques have been applied.

The main limitation with the application of modelling to older plants is obtaining suitable samples for accelerated ageing programmes. Often, there are no samples available of the original material that could be used as the unaged material for a testing programme. Even where the original cable manufacturer is still in business and the formulation information is available, it is generally not practical for the original cable formulation to be recreated. Any accelerated ageing programme is therefore limited to cable samples removed from the plant, taken from a relatively benign area where ageing is expected to be least advanced. The use of cables from abandoned circuits can also be considered. The amount of material available will often be severely restricted, limiting further the scope of the accelerated ageing programme. Because of these restrictions, modelling tends to utilize the simpler approaches, which require less data for their application. Programmes have been carried out on a number of cable types utilized at Japanese nuclear power stations. These programmes have included extensive accelerated ageing tests, predictive modelling and the correlation of condition indicators with elongation at break for different cable types.

A–5.5. Analysis of DBA profile

The temperature–time profile used in DBA testing is often a generic shape, which may not match the profile required for a specific NPP. There are several ways of addressing this issue. Initially, the user should check that the required profile is up to date. If the test profile does not envelope the required profile, a search in the literature should be made for alternative DBA tests that use the same cable material (Note that this must be the specific formulation, not just the same generic material).

Some NPPs use an analysis of the original test profile (using the margins) to justify use of the existing profile. This method could result in a misinterpretation of margins. This approach is only appropriate where there are slight variations between the test profile and the plant DBA profile. The approach used is outlined in Fig. A–12. The test profile is shown as a thick line in the figure and has an initial region (A) where the temperature is higher than the required profile. At a later stage of the test, the test temperature is lower than the required profile (region B). It may be possible to use the Arrhenius relationship to demonstrate that the excess temperature in region A offsets the lower temperature in region B. Similarly the post-DBA region is usually simulated in a DBA test by a higher temperature for a shorter time (region C) to account for the required profile, which may extend to time periods of about 1 year (region D).

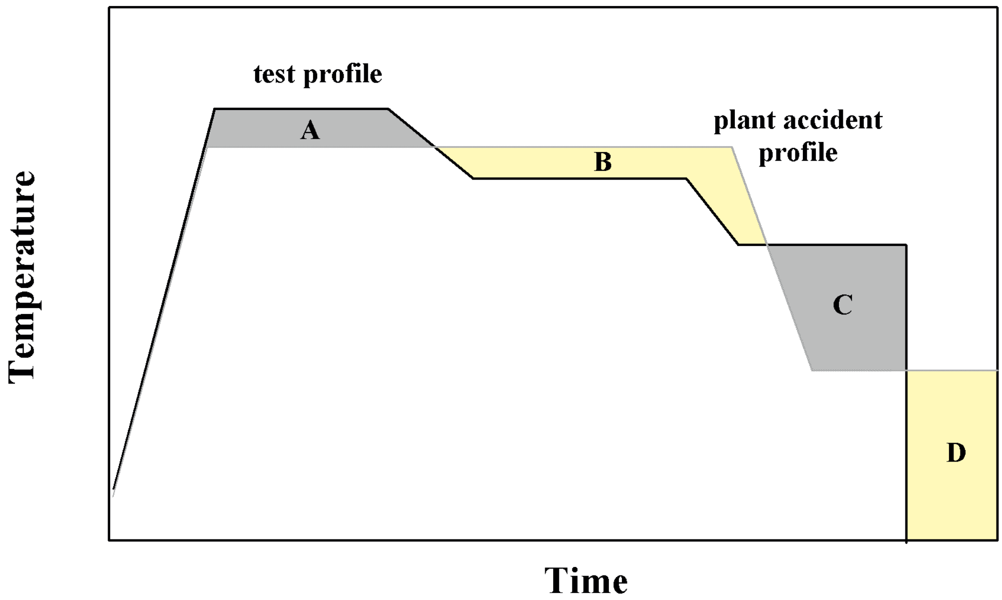


FIG. A–12. Schematic diagram indicating how analysis of DBA test profiles is used.

GLOSSARY

accelerated ageing. Artificial ageing where the simulation of natural ageing approximates the ageing effects of longer term service conditions in a shorter time. (Ageing carried out at higher temperatures and/or dose rates than would be seen in service).

ageing assessment. Evaluation of appropriate information for determining the effects of ageing on the current and future ability of systems, structures and components to function within the acceptance criteria.

ageing management. Engineering, operations and maintenance actions to control, within acceptable limits, the ageing degradation of systems, structures and components.

cable deposit. Selection of cable samples placed inside an NPP at elevated temperatures and/or radiation locations specifically for CM or removal for testing.

design basis accident. Accident conditions against which an NPP has been designed according to established design criteria where damage to the fuel and release of radioactive material are kept within authorized limits.

environmental monitoring. Measurements of ambient environmental conditions, temperature and radiation levels (in particular) within an NPP.

hot spots. Areas (often localized) within an NPP where temperatures and/or radiation dose rates are higher than expected.

service life. Period from initial operation to final withdrawal from service of a system, structure or component.

lead time (for a cable deposit). The increase in equivalent ageing time relative to worst-case cable positions.

ongoing qualification. Activities performed subsequent to initial qualification, including monitoring, maintenance and analysis of operating experience, to extend qualification for an additional period of time.

polyolefins. Generic polymer group covering polyethylene-based materials and copolymers of polyethylene with polypropylene.

qualification. Generation and maintenance of evidence to ensure that the equipment (a cable) will operate on demand, under specified service conditions, to meet system performance requirements.

qualified condition. Condition of a cable expressed in terms of measurable condition indicator for which it has been demonstrated that the cable will meet its performance requirements.

qualified level of degradation (QLD). Used generally for cables subjected to a harsh environment. Condition of a cable expressed in terms of measurable condition indicator for which it has been demonstrated that the cable will meet its performance requirements.

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.

round-robin tests. Tests carried out by different laboratories on identical samples using the same test method to assess the variability of measurements.

walkdown (for cables). Formal visual/tactile inspection of cables by maintenance staff to identify abnormal conditions (e.g. discoloration and hardening).

ABBREVIATIONS

ASTM	American Society for Testing and Materials
CBQ	condition-based qualification
CI	condition indicator
CM	condition monitoring
CSPE	chlorosulphonated polyethylene
DBA	design basis accident (e.g. LOCA or MSLB)
DED	dose to equivalent damage
DSC	differential scanning calorimeter
EMI/RFI	electromagnetic interference/radio frequency interference
EPR/EPDM	ethylene/propylene-based materials
EQ	environmental qualification
ESR	electron spin resonance
EVA	ethylene vinyl acetate
FDR	frequency domain reflectometry
FTIR	Fourier transform infrared spectroscopy
I&C	instrumentation and control
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IM	indenter modulus
IR	insulation resistance
ISO	International Standards Organization
LOCA	loss of coolant accident
LR	licence renewal
MSLB	main steam line break
NPP	nuclear power plant
OIT/OITP	oxidation induction time/temperature
PE	polyethylene
PCP	polychloroprene
PLIM	plant life management
PLEX	plant life extension
PVC	poly vinyl chloride
QLD	qualified level of degradation
QM	qualification monitoring
TDR	time domain reflectometry
TGA	thermogravimetric analysis
XLPE	cross-linked polyethylene

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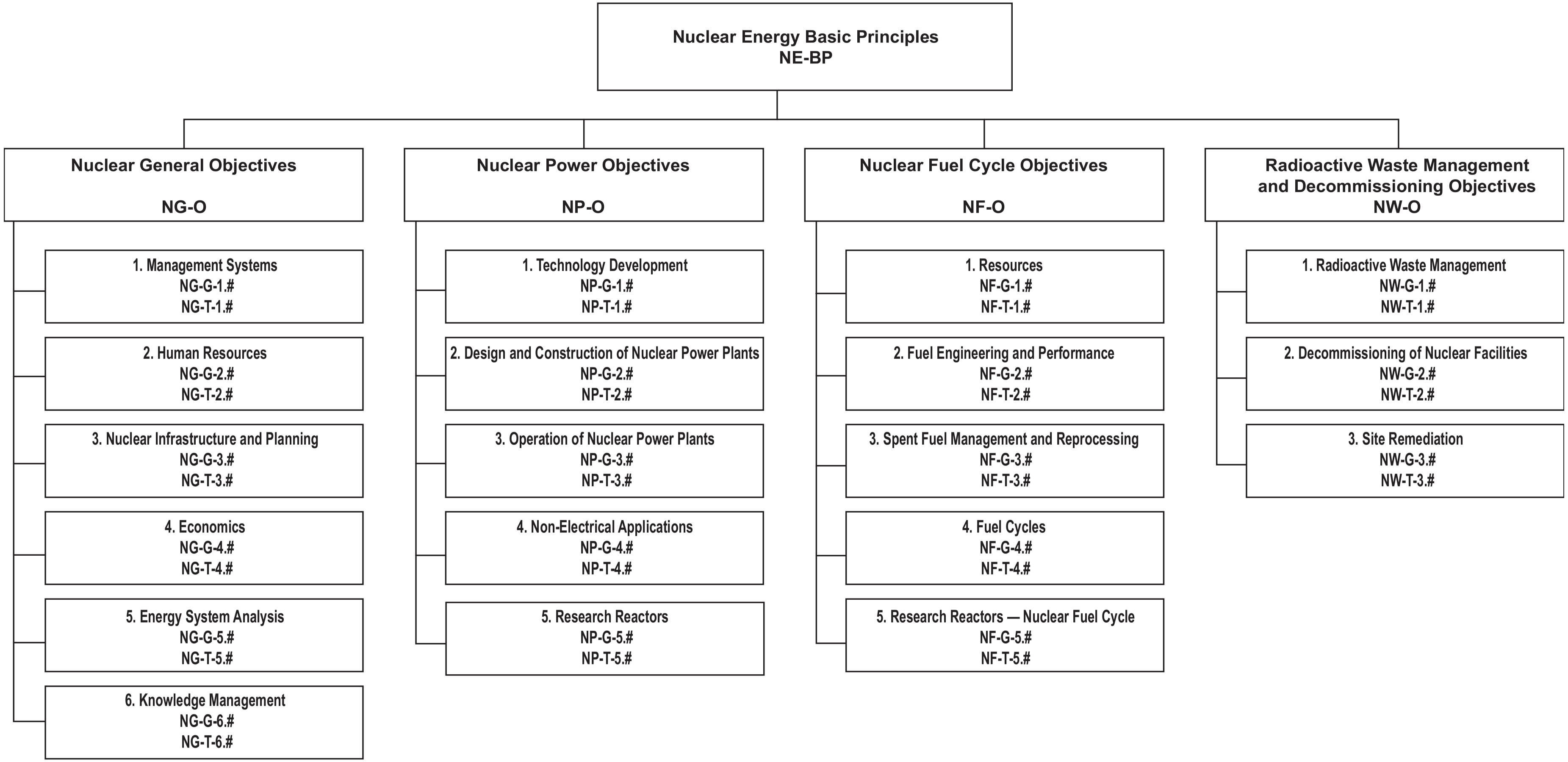

Key

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