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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

SURVEY ON ORGANIC COMPONENTS IN NPPs

January 1999

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article I of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral. non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996) and the Republic of Korea (12th December 1996). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of all OECD Member countries except New Zealant and Poland. The Commission of the European Communities takes part in the work of the Agency.

The primary objective of the NEA is to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

This is achieved by:

- *encouraging harmonization of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;*
- *assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;*
- *developing exchanges of scientific and technical information particularly through participation in common services;*
- *setting up international research and development programmes and joint undertakings.*

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded a Co-operation Agreement, as well as with other international organisations in the nuclear field.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of scientists and engineers. It was set up in 1973 to develop and co-ordinate the activities of the Nuclear Energy Agency concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations. The Committee's purpose is to foster international co-operation in nuclear safety amongst the OECD Member countries.

CSNI constitutes a forum for the exchange of technical information and for collaboration between organisations which can contribute, from their respective backgrounds in research, development, engineering or regulation, to these activities and to the definition of its programme of work. It also reviews the state of knowledge on selected topics of nuclear safety technology and safety assessment, including operating experience. It initiates and conducts programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach international consensus in different projects and International Standard Problems, and assists in the feedback of the results to participating organisations. Full use is also made of traditional methods of co-operation, such as information exchanges, establishment of working groups and organisation of conferences and specialist meeting.

The greater part of CSNI's current programme of work is concerned with safety technology of water reactors. The principal areas covered are operating experience and the human factor, reactor coolant system behaviour, various aspects of reactor component integrity, the phenomenology of radioactive releases in reactor accidents and their confinement, containment performance, risk assessment and severe accidents. The Committee also studies the safety of the fuel cycle, conducts periodic surveys of reactor safety research programmes and operates an international mechanism for exchanging reports on nuclear power plant incidents.

In implementing its programme, CSNI establishes co-operative mechanisms with NEA's Committee on Nuclear Regulatory Activities (CNRA), responsible for the activities of the Agency concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with NEA's Committee on Radiation Protection and Public Health and NEA's Radioactive Waste Management Committee on matters of common interest.

Foreword

PWG-3 deals with the integrity of structures and components, and has three sub-groups, dealing with the integrity of metal structures and components, the ageing of concrete structures, and the seismic behaviour of structures. Ageing is also a primary consideration of the group.

Organic components (mainly cables, but also seals etc), do not fall into the remits of any of the sub groups, so this report was prepared by the main PWG3. The authors of this report include participants in the recent IAEA Co-ordinated Research Programme on cables, so co-ordination has been ensured..

Executive Summary

The survey covers all types of components which use organic materials within nuclear power plant, including electrical insulation, elastomeric seals, gaskets, lubricants, coatings and adhesives. Because of the limited information available on other components, much of the survey is focused on electrical cable materials and seals.

The technical background to ageing of organic materials is included in the survey, together with operating experience and current research programmes in this area.

A number of areas have been identified which could be considered for future work. These are:

- **Further development of condition monitoring methods**, particularly those that are non-destructive and can be used in-situ in NPP. For cable materials, this should concentrate on demonstration of the practicality of using condition monitoring in plant. For other components, suitable methods need to be developed.

- **Methods for assessment of residual life** from condition monitoring data and accelerated ageing. Practical guidelines need to be developed on how to apply condition monitoring and lifetime prediction methods to real plant situations.

- **Comparison of lifetime prediction models with real-time ageing**, using predictions based on actual service conditions not design basis data. There are many data available on accelerated ageing of organic materials. Where these same materials are used in plant, their predicted degradation could be compared with the real-time ageing.

- **Realistic failure criteria** that relate to loss of functionality. If condition monitoring and lifetime prediction methods are to be used for ageing management, it will be necessary to determine what failure criteria should be used to determine the end of life, bearing in mind the requirement of some components to survive a DBE.

Contents

1 INTRODUCTION

1.1 Background

Within the mandate of the Principal Working Group 3 of the OECD/Nuclear Energy Agency (PWG-3) specific attention is given to ageing related effects. Ageing of nuclear power plant systems, structures or components may reduce, if unmitigated, the safety margins provided in the design. With respect to the functional capability of systems, structures or components, the problems are very complex and multi-faceted. Significant efforts have been undertaken in several countries and international organisations to study the influence of ageing phenomena. There is a further need for an assessment of approaches taken to ageing issues, aimed at developing and reviewing general principles, promoting technical consensus and identifying areas where further work is required.

At the 19th meeting of the PWG-3 in April 1996, a decision was made to examine the ageing of organic materials in nuclear power plants (NPP). It was agreed that IPSN (France), NII (UK) and GRS (Germany) would take the lead on preparing a report on this matter. As a first step in this work a questionnaire was prepared and sent to people identified as working on this field. The response was used as an initial basis for this report, with the addition of other information from the literature and from databases on reportable events in NPP.

1.2 Objective

The objective of this report is to survey ageing problems, ageing management practices and research with regard to organic materials in NPP and to identify areas where further work is required.

1.3 Scope

The scope of the report basically covers all organic materials used for a range of components and working fluids of safety significance in NPP, such as electrical insulation and dielectric materials, elastomeric seals and gaskets, lubricants, adhesives and coatings. The survey of methods, experience and current research (section 3 and 4) is primarily focused on electric insulation, seals and lubricants under normal operation. This is because of the limited information available on the other component types, both from the replies to the questionnaires and in the literature.

1.4 Structure Of The Report

Section 2 covers the technical background of ageing of organic materials, including an overview of the types of organic materials used in NPP, a discussion of safety aspects of ageing, a characterisation of stressors and main ageing mechanisms, as well as a brief review of international operating experience.

Section 3 provides a survey of the range of ageing management methods which are currently in use. This includes qualification procedures, environmental monitoring, lifetime assessment, in-service inspections and maintenance.

Section 4 covers a survey of national and international research programmes with regard to their objectives, the methodology for ageing testing and prediction, the compilation of data and co-operative programmes.

Conclusions are presented in section 5 and recommendations for further work in section 6.

2 TECHNICAL BACKGROUND

Organic materials serve vital functions in NPP equipment. In general, the reliability of components containing organic materials has been high. However, operating experience indicates that organic materials are subject to some form of ageing degradation.

The following sections deal with safety aspects of ageing, the application of organic materials in NPP, ageing mechanisms and effects, as well as operating experience with organic materials.

2.1 Safety Aspects Of Ageing

Ageing is a general process in which the characteristics of a system, structure or component gradually change with time or use. The effects of ageing are taken into account in design and qualification as far as they are known. However, the evaluation of operating experience shows that nuclear power plant systems, structures and components still exhibit some form of unexpected ageing degradation (see section 2.4).

Ageing effects may reduce design safety margins and cause failures of both operational and safety systems. A particular concern relating to ageing degradation is the potential wide-scale degradation of physical barriers and redundant components which leads to a higher probability of common cause failures. For example, age-degraded redundant components of safety systems could fail simultaneously when exposed to abnormal conditions associated with a transient or an accident. If ageing degradation is not correspondingly monitored or timely corrective action is not taken before a loss of functional capability occurs, plant safety could be impaired.

2.2 Application Of Organic Materials In NPP

Organic materials are used virtually everywhere in NPP and serve vital functions in electrical and mechanical equipment, including safety-related functions. Table 1 gives an overview of their application and important properties.

There are many parts in electrical and mechanical equipment which are polymer-based. Polymers are organic materials which consist of long macromolecules built up by small molecules (monomers) or groups of molecules as repeated units. They may be broadly grouped into thermoplastics, elastomers and thermo-setting materials. More detailed information is given in the IAEA-TECDOC-540 [(1)]. A wide variety of different organic materials is used in NPP. Table 2 contains a summary of the polymer types in use, taken from the response to our questionnaire.

Lubricants and organic hydraulic fluids represent a further unique class of engineering organic materials used in NPP. Lubricating oils and greases are used in essential motors, pumps, valves, gearboxes, slideways and pivoting devices. The proper functioning of the machinery is dependent on proper lubrication. The choice of ingredients used in lubricants governs their functional properties (ability to reduce friction, transfer heat, scavenge contaminants), as well as their physical and chemical properties (viscosity, bulk modulus, oxidation stability, flammability, etc.).

Paints and coatings protect various structures and components and facilitate their decontamination.

In addition, some NPP utilise organic ion-exchange resins for radionuclide removal from coolant and waste water. These resins are usually based on co-polymers of styrene with divinylbenzene.

2.3 Ageing Mechanisms And Effects

Several environmental and operating stressors such as irradiation, temperature, chemical stress and mechanical stress may cause degradation. The degradation depends on the properties of the material, the stress level, time, changes in stress level, and the sequence of such changes. Defining the service stresses as a function of real time presents a problem because it is difficult to predict the stress history that a material or component will experience in service. Environmental monitoring (particularly of temperature and radiation dose as a function of time) will help to provide an estimate of realistic stress histories.

2.3.1 Stressors and ageing mechanisms

The main stressors causing age-related degradation of polymer-based components, such as cable materials and their ageing mechanisms are described in IAEA-TECDOC 932 [(2)]. These are:

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

Of these, temperature, radiation dose rate and the presence of oxygen are considered to be the dominant environmental ageing stressors for polymeric components used in the majority of reactor systems. For BWR systems, moisture may also be significant. Mechanical stress may accelerate ageing degradation in vibrating equipment. Real service conditions usually involve synergistic effects between two or more of the stressors listed.

The detailed degradation behaviour of a polymeric component will be determined by the specific formulation used. Within a generic class of polymers, eg. PVC, there will be significant variability in response for materials obtained from different manufacturers, and for materials from different formulations from the same manufacturer.

For many of the polymers of interest, oxidation is the dominant ageing mechanism and is initiated both thermally and by irradiation. In PVC, which was widely used in cables in older NPP, loss of plasticiser from thermal ageing is also an important degradation mechanism.

2.3.2 Cable materials

Both oxidation and plasticiser loss can result in embrittlement of cable materials, increasing the probability of cracking of the insulation under mechanical stresses. Such stress can arise in the plant from handling, vibration, thermal cycling or from the way in which the cable is routed. In practice it is this loss of mechanical integrity which is the prime cause of failure of low voltage cable, resulting in the loss of electrical integrity.

2.3.3 Elastomers

Typical ageing effects on elastomers are [(3)]:

- extrusion
- chemical attack
- mechanical wear
- tensile cracking
- load relaxation
- compression set.

There are also thousands of elastomer compounds to choose from, many specifically designed to avoid a certain mode of failure under set service conditions. However, while some material properties are closely related to failure modes (e.g., tensile stress to tensile cracking), other commonly quoted properties such as hardness, elongation, permeability and thermal expansion have only a tenuous association.

2.3.4 Lubricants

The normal operating environment for lubricants is essentially the same as in any other industry, with the addition of a radiation environment. The radiation dose is usually well below any levels that could be damaging during normal service, with a few exceptions such as control rod mechanisms or fuel handling devices [(1)]. The primary causes of lubricant ageing are contamination of the lubricant and thermal ageing due to oxidation. These phenomena are well understood.

Radiation can influence the properties of the two principal components of a grease, the fluid and the thickener. Of the properties of a fluid (oil) which change when it is subjected to radiation, changes in base oil viscosity and oxidation of the base oil have the most significant effects on grease performance.

Viscosity may either increase as a result of polymerisation (cross-linking) or, in case of certain synthetic products, chain breaking reactions (scission) may cause a decrease in viscosity. Increasing viscosity becomes a significant effect when the increase becomes 2 - 4 times the original value. At this level of increased viscosity, the lubricated bearing is being required to operate with an unsuitable fluid. This can result in an increased operating temperature and hence accelerated deterioration of the grease. Conversely, in the case of a decrease in viscosity, the bearing could be operating with a fluid affording insufficient film thickness for correct lubrication and hence undergo rapid lubrication failure.

The effect of thermal oxidation of the base oil is generally to increase the base oil viscosity. In this case, however, the viscosity increase is due to the products of oxidation (sludge), which usually accelerate further oxidation, and reduce the service life of the lubricated component owing to their normally acidic nature.

The principal effect of radiation on thickeners is to reduce their efficiency and, as a result, to soften the grease.

2.3.5 Paints and Coatings

Failure can occur as a result of ageing embrittlement, which occurs when the coating dries and hardens, causing shrinkage and cracking. Coating degradation may also be caused by radiation. Typical effects are a loss of elasticity caused by embrittlement, high temperatures, condensation and immersion, physical damage, and damage caused by substrate corrosion [(4)]. The extent of degradation depends somewhat on the type and quality of the initial coatings.

Physical damage, eg. gouge marks, cracks, or pinholes on coated surfaces permit moisture to reach the substrate surface (metal or concrete) through the coating. With time, substrate corrosion spreads and lifts the coating, which in turns exposes a larger substrate surface to the moisture and accelerates coating delamination.

In some applications, the ease of decontamination of a painted or coated surface is of prime importance. Ageing degradation of the coating will tend to make decontamination more difficult.

2.4 Operating Experience

In this section, operating experience with organic materials in NPP is reviewed. This includes information from the OECD / IAEA Incident Reporting System (IRS) and the corresponding German database, as well as information about U.S. experience with NPP cables and information about specific examples of recent problems with organic components.

2.4.1 OECD / IAEA - IRS-Database

The IRS-database was investigated to get a broad estimate of the safety significance of ageing of organic materials in NPP. For the majority of organic materials used in NPP, there has been little evidence of significant degradation. However, some safety-related incidents were reported which demonstrate the safety significance of ageing management with regard to organic materials in NPP. Different equipment was affected and different countries were involved such as Canada, France, Switzerland and the USA. In order of increasing frequency, cases of ageing degradation concerned the following components

- seals
- lubrication
- cable insulation
- valve seats
- valve diaphragms
- contacts
- expansion joints

According to the reports, the degradation was primarily caused by thermal ageing rather than radiation ageing.

2.4.2 German Operating Experience

German operating experience with organic materials in NPP for the period from 1977 till 1995 was investigated, based on the German incident reporting system database. Of a total of about 4600 incidents that have been reported, about 2 per cent relate to ageing of organic materials. About one third of these incidents pertain to the emergency power supply including diesel generators.

The lion's share of about 63 per cent of the incidents which were identified on organic materials relate to mechanical equipment such as seals (31%), fasteners (19%) and hoses (13%). Of the remaining incidents, 22% of the events were detected in electrical equipment and 15% pertain to oil and greases.

Many of the incidents that have been reported were caused by premature thermal ageing. Typical examples are [5]:

- blocking of control magnets of safety relief valves due to hardening of collars
- malfunction of relief valves due to hardening of greases
- jamming of valves due to shrinking of coil bodies of contacts

- malfunction of micro-switches due to shrinking of the polymer-based casings
- obstruction of valve actuation due to shrinking of bearing rings.

All plants have been affected, albeit to different extents. All ageing effects were detected in time and could be eliminated by repair, upgrading and replacement measures. Therefore, they basically had only minor significance with regard to plant safety.

Some cases of common cause events or potential common cause events were identified, in particular in connection with the ageing of lubricants. For example, ageing of a lubricant led to too high a contact resistance on contacts of a selector switch, which caused a failure of a circuit breaker of an emergency diesel. As a result, the emergency diesel could not be connected to the corresponding emergency busbar. The failure was detected within the framework of a regular monthly inspection of the emergency diesels. Further examinations showed that there were also increased contact resistances on two other switches of the same type. However, these switches were still functioning.

2.4.3 U.S. Experience with Cables

The historical performance of low voltage, medium voltage and neutron detecting cables in U.S. commercial nuclear power plants was reviewed in reference 6, based on the evaluation of the NRC Licensee Event Reports (LER), the Nuclear Plant Reliability Data System (NPRDS) and other sources. A summary of the stressors and ageing mechanisms that have been identified is given in Table 3. The following conclusions were drawn:

- The number of cable failures of all voltage classes that have occurred throughout the industry was extremely low in proportion to the amount of installed cable. However, the data which supports this conclusion is limited in two ways: (1) there is little or no data to quantify performance under accident conditions, and (2) only a few plants have operated for more than twenty years, which is only about one-third of the total expected period of operation of these systems (i.e., 60 years assuming life extension).

- Thermal embrittlement of insulation is one of the most significant ageing mechanisms for low-voltage cable. Mechanical stress (vibration, etc.) was also frequently cited as a cause for failure. These thermal and mechanical ageing mechanisms occur predominantly near end devices or connected loads. Thermal ageing results largely from localised hot spots; ageing due to the ambient environment or ohmic heating may also be present.

- As evidenced in all of the data sources examined, localised radiolytic degradation (i.e., degradation induced by ionising radiation) affects low-voltage cables to a lesser degree than thermal and mechanical degradation. Degradation resulting from exposure to external chemical substances occurs infrequently.

- Localised thermal, radiolytic, and incidental mechanical damage appear to be the most significant ageing mechanism for cables located near the reactor pressure vessel, especially neutron monitor circuits.

- Wetting concurrent with operating voltage stress appears to produce significant ageing effects on medium-voltage power cables.

- Damage to cable insulation during or prior to installation may be crucial to the cable’s longevity, particularly for medium voltage-systems.

- Based on the high reliability demonstrated by cable systems and assuming that their reliability remains high, continued reliance on visual inspection techniques for the assessment of low-voltage cable ageing appears warranted since these techniques are effective at identifying degraded cables.

2.4.4 Recent problems with organic components

Recent events illustrate the safety-related and economical significance of ageing of organic materials in NPP. The specific components affected were

- marshalling rack wires in the Netherlands and
- ‘silentblocs’ in France.

In the Dutch Borssele NPP, insulation damage was identified during a periodic visual examination of the marshalling racks. Marshalling racks in power plants are the termination interfaces between the power plant signal and control cabling and the main cabling going to the main control room. The inspections revealed that the polyvinyl chloride (PVC) insulation of a few dozen red-coloured single-core 0,8 mm I&C wires had been broken. It was further noticed that, if these wires were bent, parts of their insulation would break and chip off. The cause of this premature ageing was connected with a catalytic process, which was due to inferior quality, causing plasticiser loss. The results of tests showed that the red wires were far from meeting the specified requirements and the quality of wire of four other colours was just about at the acceptance criteria. In total, some 37000 marshalling rack wires were replaced within the framework of backfitting measures [(7)].

An inspection of the French Bugey-4 NPP in May 1997 revealed that three so-called ‘silentblocs’ were broken. These are antivibration studs in the upper part of the structure that houses the relays connected to the reactor's control system and are designed to protect the relays from damage in an earthquake. A defect in the silentblocs could, in an earthquake, prevent the correct operation of the relay circuitry. The ruptures were caused by ageing of the elastomer of which the silentblocs were made. Since that incident, EDF has inspected silentblocs at the other Bugey PWRs and found similar degradation on silentblocs in units 2 and 5 [(8)].

These experiences highlight the need for ‘near miss’ reporting to encourage staff working in NPP to report unusual degradation, even if it is not initially related to safety systems. In these two examples, reporting of an initial fault resulted in more extensive inspection of similar components and the finding of further degradation.

3 AGEING MANAGEMENT METHODS

Most of the work that has been carried out on the management of ageing in organic materials has been aimed at electrical cable insulation materials. This is therefore the area which is most developed at the current time. There is less information available on other component types. In general, the reliability of cables and other components containing organic materials have been high, as shown by operating experience. Databases in USA which cover operational failures of components such as the LER (Licensee Event Report) and NPRDS (Nuclear Plant Reliability Data System) support this.

The following sections deal with qualification of components containing organic materials, environmental monitoring in plant and the specific ageing management methods being used for different types of components.

3.1 Qualification Of Components

Components using organic materials which are used in safety related equipment in nuclear power plant are normally required to undertake a formal qualification process. This process identifies the timescale over which the equipment would be expected to continue to function after in-service ageing. In some cases (eg. class 1E equipment - essential to safe shutdown and isolation of the reactor), this would also include a requirement to survive an accident scenario after in-service ageing. For more details of the qualification process see reference 8.

Many countries use the IEEE-323 and IEEE-383 standards as the basis for their qualification procedures [(9)]. The testing carried out under these procedures aims to simulate the ageing which would occur in service, encompassing the worst case environmental conditions, and normally include a margin above these levels. This is then followed by simulation of a design basis event. At the end of the qualification process, the specific equipment type will have a qualified life which may be as long as 40 or 60 years, eg. most cable types. Use of such equipment beyond its qualified life requires on-going qualification or some form of re-evaluation of the qualification tests based on actual service conditions, rather than worst case conditions.

Since the IEEE standards were written, a better understanding has been developed of the degradation behaviour of organic materials. In particular, it is now realised that the high acceleration factors (elevated temperature, high radiation dose rates) typically used in qualification programmes may not adequately simulate the degradation seen in-service.

A qualified life of 40 years based on the qualification procedures in IEEE standards is not now accepted by some countries. A shift towards more on-going tests is occurring, either via formal on-going qualification or by additional testing or condition monitoring, particularly in Europe. For example, in Germany the draft KTA 3706 rule has been introduced, requiring the demonstration of accident resistance of electrical equipment at regular intervals through the plant life [(10)]. In Sweden, a more formal on-going qualification is now required, with the maximum qualified life being limited to about 15 years. This can be achieved in a number of ways including installation of a component deposit in the plant, removal of real-time aged samples, and accelerated ageing in the laboratory.

A recent literature review on environmental qualification of electrical cables has highlighted some of the concerns that have not yet been resolved in this area [11].

3.2 Environmental Monitoring

Since the ageing rate of organics is determined by their environment, an important prerequisite for ageing management is a knowledge of the environmental conditions to which the components are exposed. The temperature and radiation dose are probably the most important factors for organic components, but in some cases information on humidity and any chemical contaminants will also be important.

Temperature monitoring within the plant is the form of environmental monitoring which is most frequently in place. Some power utilities have well established monitoring programmes of this type [12], which are used to re-evaluate the qualified life of components based on their actual service temperatures rather than the design temperatures used in their initial qualification tests. In this way considerable savings can be made on replacement components.

The radiation dosimetry used for personnel dosimetry may not be appropriate for monitoring long-term dose exposures to components. For this type of environmental monitoring, dosimeters based on alanine are very useful since they are insensitive to temperature and the effects of long term fading [13]. Since radiation fields can be quite variable within a plant, dosimetry at the location of the organic component is necessary, not just in the general vicinity. Radiation monitoring of the type suitable for ageing management is not often utilised in nuclear power plant.

3.3 Ageing Management Of Components

There have been considerable advances in the understanding of ageing degradation of organic materials under conditions appropriate to nuclear power plant. The development of ageing management methods for components containing organic materials has been slower, but has made considerable progress over the last few years. Most of the work has concentrated on electrical cable insulation materials because of their widespread use in safety related circuits, but there has been some consideration also made to other organics. Each of the main groups of components containing organic materials is considered in section 3.4.

Several different approaches to the management of ageing of organic components in NPP have been developed over the last few years. These are described in a series of documents from the IEC (International Electrotechnical Commission) [14, 15], from the IAEA (International Atomic Energy Agency) [2] and from the Sandia Laboratories, USA [6]. These documents cover the following main areas -

- radiation testing
- condition monitoring
- on-going qualification
- lifetime prediction
- cable deposits
- ageing reviews

3.3.1 Radiation testing

Recommendations for methods for radiation testing are included in a series of standards and technical reports from the IEC [14, 15]. These methods take into account factors which are now known to affect the radiation degradation behaviour, eg. radiation dose rate, synergy between temperature and radiation, oxygen diffusion limitations. These methods are generic to polymeric materials, but many of the examples quoted are specifically for cable and seal materials.

3.3.2 Condition monitoring

Condition monitoring is intended to provide information on the current state of degradation of a component and, with trending, to provide some indication of future performance. This area has been widely researched over the last ten years, particularly for methods for cable condition monitoring. A summary of the methods which have been examined for cables, their limitations and the current state of research is provided by a recent IEC technical report [15]. There is currently no single method which can be used for all types of cable material, but there are a small number which are looking promising for practical use in plant. The most developed of the methods available are -

- cable indenter
- oxidation induction methods (OIT and OITP)
- thermogravimetric analysis (TGA)
- density
- dielectric loss
- time domain reflectometry (TDR)

Some of these methods could be adapted for condition monitoring of other organic components. This is a topic which is still subject to on-going research and is likely to develop still further.

3.3.3 On-going qualification

This is a formal method of re-qualifying aged components after a limited qualified life, typically 10 to 15 years [2]. The main intention is to remove some of the uncertainties in qualification testing relating to the use of high acceleration factors for radiation and thermal ageing. Representative samples of the components which have been subjected to realistic environmental ageing, either in plant or via long term accelerated ageing, are put through a series of qualification tests (including accident conditions) to demonstrate an extension of the qualified life. This procedure is repeated at the end of the extended qualified life until the tests show that the qualified life cannot be extended further.

On-going qualification can be applied to a wide range of components. The main requirement is for the samples to be representative of those used in the most severe conditions in-plant. This type of formal requalification is currently being used in Sweden.

3.3.4 Lifetime prediction

There has been a considerable amount of work carried out on methods of lifetime prediction for organic materials, with most of the work concentrating on cable and seal materials. The most developed methods for lifetime prediction are summarised in a recent IEC technical report [(15)]. Each of these methods are based on laboratory tests on accelerated aged samples, but take into account much of what has been learnt on the degradation behaviour of these materials. The methods available vary in the amount of data required for predictive modelling and each method has its limitations. However, they are sufficiently well developed for their practical use to be recognised for predictive work in plant.

The approaches used for lifetime prediction are generic and can be applied in principle to any organic component used in NPP. The examples given in reference 15 are for seal and cable materials, where most of the work on lifetime prediction has been carried out.

3.3.5 Component deposits

The use of deposits of components placed in a severe environment position in plant has been utilised by quite a number of utilities and research organisations [(2)]. Some examples include the long term ageing programme on cables carried out by Siemens, Germany [(16)], the cable deposit at Perry nuclear power plant, USA [(17)], and the EPRI long term programme on cables and other components [(18)].

A well-designed deposit, with samples of many types of components used in the plant, can be a very useful method for obtaining early information on degradation. It is very important that the deposit is placed in the plant so that its environment is well defined and monitored. Samples are usually removed for testing during normal outage periods. Depending on its position within the plant, the conditions in the deposit will give a significant lead time over most of the components in their normal positions.

The use of deposits is most practical for relatively new plant, < 5 years old. However, a deposit can be set up in older plant if accelerated ageing is used to bring the components in the deposit to an aged state equivalent to their worst case condition in the plant. Provided that the accelerated ageing is carried out with consideration of factors like dose rate effects and diffusion limited oxidation, such a deposit will give a useful lead time for the plant.

3.3.6 Ageing reviews

Since the rate of ageing of organic materials is dependent on the environment to which they are exposed, an important part of any ageing management is to identify those components which are most vulnerable to degradation under plant conditions. A formal ageing review will systematically examine the environmental conditions in plant, compared with the organic materials in use. Such a review enables any further testing or condition monitoring to be focused on those components which are most at risk. The ageing management guideline on cables produced by Sandia Laboratories provides the background for such a formal review and suggestions as to an appropriate methodology [(6)]. This type of approach could be applied to any organic components used in NPP.

3.4 Components

3.4.1 Electrical cable insulation and sheath materials

The development of ageing management methods has mainly been concentrated on the material types used in electrical cables. All of the ageing management methods described in section 3.3 have been applied to cable materials. On-going programmes to develop these methods into practical guidelines are currently in progress, eg. the second phase of the IAEA co-ordinated research programme on management of ageing in electrical cables (2). Compilations of data on degradation of cable materials under conditions appropriate to NPP are also available (19).

3.4.2 Electrical components (other than cables)

Apart from cable insulation and jacketing, there are many components based on organic materials used in electrical circuits. These include electrical connectors and terminations, splices, relays, switches, insulation in motors and transformers, terminal boards, insulation sleeving and tapes. These types of components have generally been put through formal EQ tests based on the IEEE standards (9). Compilations of data on ageing degradation cover some of these components (19, 20). Condition monitoring using thermal imaging is being used for some electrical components, eg. terminals of power transformers (21). Electrical testing using TDR has proved to be a useful method for condition monitoring of connectors, terminations and penetrations (22).

3.4.3 Seals and gaskets

This group of components have been reasonably well studied, like cables, and there are useful data available on their degradation behaviour and on methods for management of ageing (2, 15). However, unlike cable materials, these components are usually relatively easy to replace. Ageing management in practice tends to be based on the planned replacement of such materials on a routine maintenance basis (20). There are exceptions where seal replacement is not straight forward, eg. in AGR refuelling machines. For these specific applications there is a need for condition monitoring and lifetime prediction.

3.4.4 Hoses

There has been little specific work on these components although there are some data available on their degradation behaviour. These types of components have generally been put through formal EQ tests based on the IEEE standards (9). In practice, ageing management is based on routine replacement during maintenance (20).

3.4.5 Lubricants

There has been little specific work on these components although there are some data available on their degradation. These types of components have generally been put through formal EQ tests based on the IEEE standards [9]. In practice, ageing management is based on routine replacement during maintenance [20].

3.4.6 Paints and coatings

There has been little specific work on these components although there are some data available on their degradation [19]. These types of components have generally been put through formal EQ tests based on the IEEE standards [9].

4 RESEARCH PROGRAMMES

This section summarises some of the research programmes on ageing degradation of organics which are known to be in progress around the world. The following sections look at the objectives and scope of these programmes, the methodology used, lifetime prediction methods, data compilations and some of the collaborative international programmes.

4.1 Objectives Of Research Programmes

The main objectives of research programmes devoted to the ageing of organic materials, carried out by the countries concerned with nuclear safety, are:

- lifetime prediction of the components (cables, seals)
- the definition of representative accelerated ageing tests
- the development of reliable condition monitoring methods

Research programmes on lifetime prediction and definition of representative ageing tests have been carried out for insulation components, mainly cables, and to a lesser extent to sealing components. Such programmes have been initiated both by the operators of NPP and their corresponding safety authorities. Monitoring methods have been developed for cables in order to get information on their ability to continue to function.

4.2 Scope Of Research Programmes

The possibility of predicting the lifetime of equipment containing organic materials, the definition of realistic accelerated ageing tests and the development of condition monitoring methods has been, and still is, the subject of extensive research. These studies rely on irradiation experiments under various ageing conditions (temperature, doses, dose rates), and also on modelling, and characterisation experiments. The following summaries have been taken from the replies to the questionnaire and from published information on current research programmes.

- The NRC programme in the USA focuses on cable ageing (lifetime prediction, revision of current rules) and condition monitoring, with the following approach:
  - to develop a thorough data base of environmental qualifications, and identify which issues require further research
  - application of the Arrhenius ageing model
  - application of the material activation energies
  - multiple conductor vs. single conductor cable qualifications
  - bonded jacket cable failure mechanisms
  - to check the effectiveness of cable condition monitoring methods

   - to study the correlation of cable condition monitoring data to DBE survivability.

  The NRC research is being conducted on three cable types: XLPE insulation with Neoprene jackets, EPR with CSPE jacket, and EPR with CSPE jacket (bonded). Some cables have been naturally aged.

- Brookhaven National Laboratory (BNL) in USA has recently performed a careful literature review on the ageing of I&C cables which highlights some of the outstanding issues in cable ageing [11].

- Electric Power Research Institute (EPRI) in USA has performed ageing tests in order to select insulation materials (magnet wire enamels, resins, and several motor lead wire types) to be used in a motor insulation rewinding system for motors used in harsh environments [23].

- EPRI is currently conducting a project to develop baseline condition monitoring data for environmentally qualified equipment (solenoid valves) to determine which material and operational parameters trend with equipment ageing [24]. The baseline data will be compared to that for devices in service to re-evaluate the established qualified life of the equipment. EPRI has also supported development of several condition monitoring techniques for cable materials in particular [25-28].

- VEIKI (Hungary) has performed some ageing experiments on cables in normal and severe condition.

- The CANDU Owner Group (COG-Canada) has funded at AECL a programme aimed at the lifetime prediction of seals. Long-term (up to 2 years) thermal ageing tests were carried out on identified superior O-ring compounds. Tests were done in air, oil and water at a minimum of four temperatures and to several degrees of degradation. Materials properties relevant to O-ring applications were measured. The resulting material database allows improved life prediction for the compounds studied. Radiological ageing and synergism tests as well as studies on the effects of compression on ageing complete the knowledge base. Furthermore superior elastomer compounds have been developed and well characterised for use in O-ring, diaphragms and other elastomer seals. An elastodynamic spot tester has been developed to track the visco-elastic properties of elastomers in service or in storage.

- Ontario Hydro, DJS Associates (Canada): They have studied a range of cable condition monitoring techniques (oxidation induction time, solubility/gel content, plasticiser content, Fourier Transform Spectroscopy) to measure degradation using micro samples removed from operational cables of the plant, and in-situ techniques such as the cable indenter [29].

- The objectives of the IPSN and Cis-Bio (France) research programme was motivated by concern about the accelerated ageing procedures used in qualification procedures. They have performed numerous ageing tests at various temperatures and dose rates, even very low dose rates, both on the constitutive materials of cables and on complete cables [30]. Ageing evaluation was based on measurements of absorbed oxygen, density and elongation tests.

- SKI and DNV Ingemansson AB (Sweden) have performed a comprehensive experimental study on ageing which comprises [31]:
   - methodology aspects of accelerated ageing tests (evaluation of the quality of using Arrhénius technique, evaluation of the margins to account for differences between component samples, quality of data extrapolation, benefits of using on-going qualification techniques)

- evaluation of the influence of an inert atmosphere, influence of humidity, vibration and of ionising radiation

- The research programme developed for many years by Siemens/KWU [16] includes a thorough comparison of cables that have been aged on site (in the power plant) and artificially (laboratory), and their resistance to LOCA tests. In the framework of this programme they have studied the parameters influencing the artificial ageing such as the dose rate effect, the test sequence, and acceleration factors. Careful measurements were performed of the environmental parameters to which equipment are exposed (temperature, dose rates) according to their location in the plant.

- AEA Technology (UK) has developed lifetime prediction models based on data obtained during experimental ageing of various materials used in cables and seals. Validation tests of the model have been in progress for more than 7 years for some of these materials [32]. They have also been active in developing condition monitoring methods for cable materials. These experimental programmes on cables and seals have been funded by the UK nuclear industry (BNFL, Nuclear Electric). AEA Technology has developed a combined approach of cable life management based on accelerated ageing tests and on the use of a range of condition monitoring techniques, including dielectric loss measurements and oxidation induction measurements.

- CERN (Switzerland) has acquired an experience on polymer ageing over the last 30 years. Their objectives were to determine the lifetime (or replacement frequency) of equipment used in the CERN accelerators. They have tested a wide range of polymers, cables, seals, lubricants, and various equipment containing organic materials, both in high dose rate conditions and with moderate dose rate to simulate long term ageing [33, 34]. Part of those ageing experiment were done in situ, i.e. on some selected spots close to the particle accelerators, others were accelerated ageing tests in the laboratory. Careful dosimetry measurements were performed to validate the ageing acceleration procedures.

- Bhabha Atomic Research Centre (BARC) - Accelerated ageing tests have been performed on a variety of cables to determine lifetime (through Arrhenius method) and threshold radiation dose levels. Five performance parameters were used as indicators of cable ageing: insulation resistance, breaking load, elongation, flexibility, cracking on bending.

- IAEA has supported a Co-ordinated Research Programme (CRP) on the management of ageing of in-containment I&C cables. Phase 1 included participants from Canada, Germany, India, Russia, Sweden, U.K., and observers from CERN, and France. The objectives of this phase 1 CRP (1993 - 1995) were

  - to carry out validation checks of the predictive models on two cables (XLPE with EVA jacket and EPR with an other EVA jacket),
  - to create a database (IAEABASE) on cable ageing with data supplied by the participants
  - to provide guidelines for the management of cable ageing.

Details of this CRP are given in section 4.6. A second phase of the CRP started in Dec 1996 to resolve some of the outstanding technical issues raised in the first phase. The first phase identified some of the current cable condition monitoring techniques. The reproducibility of some of these methods will be explored further in the second phase of the CRP.

- Research Inst. NPP Operation (Russia): They have developed a mathematical approach to the indentation method which makes it possible to obtain the standard strain-stress curve out of a dynamic hardness diagram.

- RISI programme

- NRI Rez (Czech Republic): a procedure for the assessment of cable lifetime based measurements of OIT and elongation at break has been developed by NRIR and applied to the Dukovany NPP. The synergistic effects resulting from different sequences of radiation and thermal ageing have been demonstrated for EPR, EVA, XLPE, PE and PVC based cable materials. For the majority of cable materials tested, the radiation ageing followed by thermal ageing was more severe than thermal followed by radiation.

4.3 Materials & Irradiation Conditions Used

The methodology used in the various research programmes appears, through the answers to the questionnaire, to be rather similar. Most organisations have used gamma irradiation for their ageing experiments, with various temperature, doses and dose rate. Air is the most usual environment. Few have performed electron irradiations.

A summary of the materials which have been tested (Table 4) and their irradiation ageing conditions (Table 5) are listed, mainly using the answers supplied in the replies to the questionnaire.

4.4 Predictive Models

At least four basic approaches for the lifetime prediction of cable materials have been developed; these have been discussed in a recent IAEA report. The four predictive models which have been described are:

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

The detailed methodology for using these techniques is described in the references [15, 35]. All of the methods utilise data on changes in elongation at break as a function of ageing time under accelerated test conditions, by applying higher dose rates and/or higher temperatures than are normally seen under service conditions. In each of the methods, it is emphasised that care must be taken to ensure homogeneous oxidation conditions when assessing the results. The methods differ mainly in the amount of data required for predicting the behaviour of cable materials and in the way the test data are extrapolated to the service conditions.

The power law extrapolation method utilises data obtained at a single temperature over several dose rates[15]. The DED (Dose for Equivalent Damage) values are assessed at each of the test conditions and plotted as a function of log DED against log dose rate. Typical DED values for evaluation could be e/e_o =

0.5 or e = 50% absolute. This plot is linear in a number of polymers, particularly polyolefins, enabling an extrapolation to be made of the predicted DED at lower dose rates. Note that the IEC 544 standard for radiation testing recommends the use of e/e_o = 0.5 as the failure criterion [(14)].

The method based on superposition of time dependent data uses data on elongation obtained as a function of time in a range of combined temperature/dose rate conditions [(15)]. The method relies on superposition of the elongation against log time data at each of the test conditions to yield a master curve. The shift parameters required to form this master curve are found to be related to the test temperature and dose rate by a semi-empirical equation which has been verified for a number of cable materials. The equation can then be used to calculate the shift factors for the master curve of elongation against time at temperatures and dose rates appropriate to service conditions.

The method based on superposition of DED data also utilises data on elongation obtained at different temperatures and dose rates but calculated the DED values, for e/e_o =0.5 typically, for each of the test conditions. These DED values are then plotted as log DED against log dose rate and the data superposed by using a shift factor determined by the Arrhenius relationship. In many cable materials, a single value of activation energy can be used in the Arrhenius equation to superpose all of the DED data.

The kinetic modelling method [(35)] based on Dakin's law also utilises elongation data obtained in a range of temperature and dose rate conditions. Superposition of the data is obtained using equations based on the chemical kinetics of the degradation. The analysis of the different rate constants (radiation, thermal, pressure etc.) allows to draw up a predominance diagram for the material. The combination of these approaches is useful in defining accelerated test procedures.

Limitations of the methods.

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

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

The superposition of time dependent data is only possible where the general shape of the elongation versus log time curve does no vary with changes in temperature and dose rate. This implies that all of the degradation mechanisms are equally accelerated by an increase in temperature or dose rate. This is generally the case when the degradation is dominated by a single mechanism (e.g. oxidation), as is the case with many of the commonly used cable and seal materials. If more than one degradation process is significant in the temperature and dose rate range tested, then the curve shapes will not be the same and the data cannot be superposed. The method has been successfully applied to a range of polymers, including EVA, EPR, PEEK, nitrile rubbers, fluoroelastomers and silicones. It does not work for XLPE materials at temperatures <100°C because of recrystallisation effects.

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

The kinetic model can be applied to a range of materials, including EPR and EVA. The main limitation in its wider application is the extensive matrix of test data required [(36)].

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

4.5 Compilations Of Data

A few compilations of data on the ageing of polymers, lubricants and components have been produced. Some of those that are available are listed below.

- One result of the first phase of the IAEA CRP was the development of a database (IAEABASE), collecting data from the different participants to this CRP. This database collected information specifically on the ageing behaviour of three specific polymer types widely used as cable materials - XLPE, EPR/EPDM and EVA [(37)].

- EPRI, BNL and NUS Information Services, Inc. have developed the Equipment Qualification Data Bank (EQDB). This EQDB was intended to serve as a comprehensive source of information related to environmental qualification. EQDB contains individual databases which address electrical and mechanical EQ equipment used primarily in US designed plants, thermal and radiation data on non-metallic materials, and operating experience for various equipment and non-metallic components. The more robust materials data published in references 38 and 39 represent a part of the information represented in the EQDB materials databases.

- Several commercial material property databases and materials evaluation tools have been compiled by consultants serving the nuclear industry including Fulcrum Group, Inc (System 1000); GLS Entreprises, Inc (EMA+); Science Applications International, and Wyle Labs. FGI and GLS offer the most current material ageing databases and software.

- The data on ageing of organic materials obtained at CERN are presented in a series of reports (CERN 79-04, 79-08, 82-10, 85-02, 89-12, 96-05, 98-01), which can be obtained from the CERN Library, 1211 Geneva 23, Switzerland [(19)].

- Ontario Hydro is developing a database of the materials addressed in their equipment environmental qualification assessments.

4.6 Co-Operative And International Programmes

4.6.1 IAEA co-ordinated research programmes on cable ageing

The most important international programme in terms of the number of organisations and countries involved is the International Atomic Energy Agency Co-ordinated Research Programme (CRP) on ageing of in-containment cables. This programme first developed from 1989 as one of 4 pilot studies on the management of ageing of nuclear power plant components. The first phase of the CRP ran from 1993 up to 1995 (2), and is now being followed by a second phase which started in Dec 1996.

The participants to the first phase of the CRP were:

CERN (Switzerland), Bhabha Atomic Research Centre (India), AEA Technology (UK), IPSN (F), Cis-Bio International (F), Siemens-KWU (Germany), Research Institute for NPP Operations (Russia), DNV Ingemansson (Sweden), DJS Associates/Ontario Hydro (Canada)

The main objectives of the first CRP were to

- validate predictive cable ageing models accounting for synergistic effects (radiation and temperature) over the NPP lifetime and in real plant environment
- provide guidelines and procedures for the management of ageing of instrumentation and control (I&C) and low voltage power cables. A database of ageing data on XLPE, EPR/EPDM and EVA cable material was also put together within this CRP (IAEABASE).

The participants to the second CRP (1996-1999) are:

CERN (Switzerland), Bhabha Atomic Research Centre (India), AEA Technology (UK), CEA/IPSN (F), Cis-Bio International (F), EdF (F), Siemens-KWU (Germany, DNV Ingemansson (Sweden), Ontario Hydro (Canada), DJS Associates (Canada), EPRI (USA), NRIR (Czech Republic), BNL(USA), JAERI (Japan), Eurotest (Romania), Research Institute of Scientific Inst. (Russia)

The main objectives of this second CRP involve:

- review and improvement of initial qualification procedures
- collection of practical experience on using cable condition monitoring (CM) techniques in-plant
- validation of the promising CM techniques and correlation with survivability of a Design Basis Event (DBE)
- application of additional practical experience in on-going qualification to make specific recommendations on optimum procedures for ageing management

4.6.2 Other collaborative programmes

EPRI has also worked with Electricité de France with regard to the suitability of use of the cable indenter to evaluate the condition of cables used in EDF nuclear plants.

Ontario Hydro Technologies has performed extensive studies on behalf of EPRI with regard to cable ageing for both low and medium voltage cables.

The US NRC (Sandia Lab.) has recently completed a joint study with CEA/IPSN in France to conduct long term ageing (very low dose rates) and LOCA testing of electrical cables [(40)].

IEC (International Electrotechnical Commission) SC15E WG2 produces standards and technical reports relating to the radiation ageing of organic materials. The participants in this working group include experts from France, Germany, Switzerland, UK, USA, Canada and Japan. They are currently working on a technical report on guidelines for the management of ageing of organic materials, building on the work of the IAEA CRP programme.

5 CONCLUSIONS

The following general points have come out of this survey on the ageing of organic materials used in nuclear power plant.

- Most research and international collaborative programmes in the area of ageing and degradation studies have been on cable materials, and to a lesser extent, on sealing materials. Information on the ageing of other organic components is fairly limited and mainly arises from formal qualification procedures rather than any study of degradation mechanisms.

- Ageing behaviour is strongly dependent on the specific formulations used in the organic components. In many commercially available organic components, the formulations will include a high proportion of additives and fillers which will affect the ageing behaviour of the base organic material.

- Realistic accelerated ageing is complicated by a number of factors which need to be understood, both for research work on ageing degradation and for qualification of components for use in NPP. These factors include
  - dose rate effects (which are known to be significant in some polymeric materials used in seals and cables)
  - synergy between thermal and radiation ageing (the ageing observed is not always simply additive)
  - interaction between different organic materials within the same component (eg. jacket and insulation materials in cables are often of different materials). The degradation products from one polymer can affect the ageing behaviour of the other.
  - synergy between mechanical stress and radiation (tends to increase the degradation rate)

- The development of practical condition monitoring methods for cables has made considerable progress over the last few years and work is on going. There is still a need for in-plant assessment of these methods and work on their use in assessing residual life. Very little is currently available for condition monitoring of organic components used in NPP other than cables.

- Despite the large body of research carried out on organic materials, there are still no definition of end of life criteria that are realistic in terms of the functionality of a component and survivability of a design basis event.

6 RECOMMENDATIONS

There are several recurrent themes on requirements for future work in the replies to the questionnaire and in reports on research work on ageing of organics. These are -

- **Further development of condition monitoring methods**, particularly those that are non-destructive and can be used in-situ in NPP. For cable materials, this should concentrate on demonstration of the practicality of using condition monitoring in plant. For other components, suitable methods need to be developed.

- **Methods for assessment of residual life** from condition monitoring data and accelerated ageing. Practical guidelines need to be developed on how to apply condition monitoring and lifetime prediction methods to real plant situations.

- **Comparison of lifetime prediction models with real-time ageing**, using predictions based on actual service conditions not design basis data. There are many data available on accelerated ageing of organic materials. Where these same materials are used in plant, their predicted degradation could be compared with the real-time ageing.

- **Realistic failure criteria** that relate to loss of functionality. If condition monitoring and lifetime prediction methods are to be used for ageing management, it will be necessary to determine what failure criteria should be used to determine the end of life, bearing in mind the requirement of some components to survive a DBE.

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Table 1: Application of organic materials in NPP and important properties

Category	Examples of application	Important properties
Cables	Electric cable insulation, Sheath materials	Dielectric insulation, Strength/ Flexibility
Electrical Equipment (other than cables)	Connectors, Terminations, Switches, Insulation in motors and transformers, Terminal boards	Dielectric insulation, Strength/ flexibility, Dimensional stability
Mechanical Equipment	Seals and gaskets, Fasteners, Hoses, Diaphragms, Expansion joints, Penetrations, Silentblocks	Leakage rate, Compressibility, Strength/ Flexibility
Lubricants	Oil, Greases	Viscosity, Friction coefficient
Paints and Coatings	Corrosion protection, Fire protection, Facilitation of decontamination	Adhesive strength, Elasticity
Ion exchange resins	Water treatment	Exchange capacity

Table 2: Polymer-based materials which are in use in NPP

Type of equipment	Type of organic material
Electric insulation	
Cables	EPR
	EPDM
	CSPE (jacket)
	PVC
	PEEK
	XLPE
	EVA
	CPE
	silicone rubber
	chloroprene (Neoprene jacketing)
	ETFE (Tefzel)
	polyimide (Kapton)
Insulation in electrical equipment (other than cables)	epoxide resins (epoxy)
	silicone rubber
	PTFE
	EPDM
	VAMAC
	glass-filled polyester
	Polyurethane
	Polysulfone
	nitrile butadiene rubber (Buna.N)
	Polyphenylene oxide
	PVC
	Phenolic
Seals	
door, porthole, airlock	PTFE
	other fluoropolymers
	VAMAC
	Silicone
	EPR
	epoxide
filter, pump, ...	EPR
	EPDM
	PTFE
	other fluoropolymers (VITON, Kalrez)
	Silicone
	nitrile butadiene rubber (Buna-N)

Table 3: Summary of the most important stressors and ageing mechanisms of low voltage, medium voltage and neutron detecting cables according to reference 6

Voltage Category	Sub-component	Applicable Stressors	Ageing Mechanisms	Ageing Effects
Low	Insulation and Jacketing	Heat (environment and ohmic)	Thermooxidative degradation	Embrittlement, cracking
		Radiation	Radiolysis and photolysis	Hardening, cracking, crazing, swelling
		External mechanical stress	Wear or low-cycle fatigue	Cuts, cracking, abrasion, tearing
Medium	Insulation	Moisture and voltage stress	Moisture intrusion; water treeing	Dielectric break down and fault to ground
Neutron Detecting	Insulation	Heat (environment)	Thermooxidative degradation	Embrittlement, cracking
		Radiation	Radiolysis	Hardening, cracking, crazing, swelling
		External mechanical stress	Wear or low-cycle fatigue	Cuts, cracking, abrasion, tearing

Table 4: The materials studied by various organisations

	EPR EPDM	CSPE	PVC	PEEK	XLPE	EVA	Nitr. Rub.	Neop Rub.	PE	VAM-AC	epoxy resins	silicone Rub.	PTFE	PUR	Fluo Sil.	Div	Lubr.
AEAT	X	X	X	X	X	X	X					X					X
AECL	X		X	X	X		X					X	X				X
BNL	X	X			X			X									
CERN	X		X	X	X	X	X		X	X	X	X	X	X		A	X
EDF	X	X	X		X	X											
EPRI	X	X	X		X		X	X			X	X	X	X		B	X
IPSN	X	X				X				X							
JAERI	X	X	X	X	X	X	X	X	X	X	X	X	X			C	X
NRIR	X		X		X	X			X		X	X					
Ontario Hydro	X		X	X	X							X					X
Siemens KWU	X		X		X	X						X	X				
VEIKI			X		X						X	X	X				

Abbreviations : CSPE=Chloro-sulfonated Polyethylene, XLPE=cross-linked PE, EVA= ethylene-vinyl-acetate, Nitr. Rub= nitryl rubber, Neop. Rub.= neoprene rubber, Silico. Rub= silicone rubber, Fl.Si.= fluoro-silicone, Lubr.= lubricants, Div.= diverse polymers

A) CERN: PI, PEI, XLPE, PS, PPO, PPS,...
B) EPRI: PPO, PS, PI, CLPE (chlorinated PE), phenolic,...
C) JAERI: PA, PI, PS, PES, PP,...

Table 5: Irradiation conditions used by those organisations

	radiation	dose	dose rate	environ^t	Temp.	References
AECL	gamma	up to 400 kGy	0.078-2.5 kGy/h	air	several	
AEA Techn.	^{60}Co	up to 10 MGy	0.001 - 1 kGy/h	air, carbon dioxide	20°C to 275°C	
BNL	gamma	up to 750 kGy	0.009-5 kGy/h	air	208-302°F	
CERN	^{60}Co	0.5-1MGy	0.1-4 kGy/h	air	20, 50°C	CERN 89.12, 83.08, TIS.RP.191
CERN	High energy particles	up to 100 kGy	1-10 Gy/h	air	20°C	CERN.EF.Beam 82.6, 83-08, CERN.TIS.RP.191
CERN	reactor	up to 100MGy	200 kGy/h	air	50°C	CERN 79.04, 89.12, 83.08, 79-08, 98-01
EDF	^{60}Co					
EPRI						
IPSN	^{60}Co	20-200 kGy	0.005-1kGy/h	air	20, 40, 60, 70, 80, 115°C	
IPSN	electrons	50-600 kGy				
JAERI	^{60}Co	1- 100 MGy	1 up to 30 kGy/h	air, vacuum, water, O2, N2	20, 50, 120,250°C 4.2, 77 K	RPC
JAERI	electrons 2 MeV	1- 300 MGy	1 up to 50 kGy/s	He, vacuum	20, 150, 350°C	Polymer
JAERI	various ion beams	20k-2MGy	0.1-1kGy/s	vacuum	20°C	RPC
JAERI	reactor	1-300 MGy	2MGy/h	air	20°C	
NRIR	^{60}Co	up to 750 kGy	0.003-0.8 kGy/h	air	20-120°C	NRI.9966 CH,T/ NRI Z-110
NRIR	electrons 4 MeV	<900 kGy		air	20°C	
Ontario Hydro	gamma	660 kGy	< 10 kGy/hr	air	50-54°C, 120-163°C	
Siemens KWU	gamma	1-1000 kGy	0.7Gy/h-10kGy/h	air		
VEIKI	^{60}Co	100-1000 kGy	0.4-10 Gy/s	air	30-70-80°C	47.91-189/82, 47;98-147/79
VEIKI	electrons	100 kGy		air	20°C	