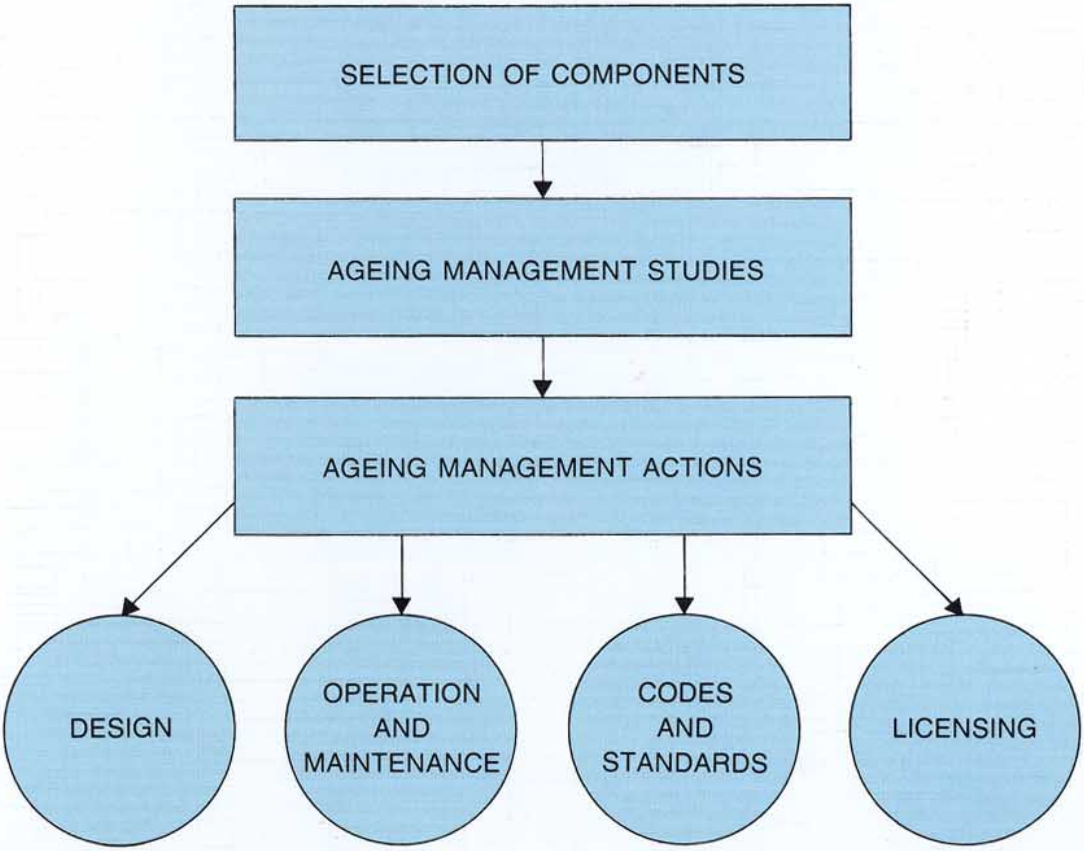

TECHNICAL REPORTS SERIES No. **338**

Methodology for the Management of Ageing of Nuclear Power Plant Components Important to Safety

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1992

METHODOLOGY FOR THE MANAGEMENT OF AGEING OF NUCLEAR POWER PLANT COMPONENTS IMPORTANT TO SAFETY

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FOREWORD

Ensuring the safety and reliability of ageing nuclear power plants is an important task facing both the nuclear industry and governmental bodies responsible for safety. It will grow in importance as the inventory of nuclear plants gets older. From a safety perspective, ageing in nuclear plants must be effectively managed to ensure that required safety margins are maintained throughout plant service life, including any extended life. In addition, from a power production perspective, ageing of components, structures and systems of nuclear power plants must be effectively managed to ensure the reliability and economic viability of older plants.

A number of organizations in Member States have active programmes to address safety and reliability issues arising as a result of the ageing of nuclear power plants. In 1989, the IAEA began a comprehensive programme on ageing which was recommended by the 1988 Advisory Group on Safety Aspects of Nuclear Power Plant Ageing and Life Extension. Its goal is to establish and maintain international co-operation to promote awareness and understanding of ageing degradation processes and to develop effective methods and guidelines for managing ageing.

This technical report, one of a series on the management of ageing of nuclear power plants, has been prepared under this programme. It presents methodologies both for selecting plant components important to safety whose ageing should be assessed and for performing ageing management studies. These methodologies are based on current practices of Member States leading in this field.

The intended readership of this report includes both management and technical staff of utilities, regulatory agencies and research institutes concerned with the evaluation and management of ageing. Although the report has been developed specifically for the management of ageing of plant components important to safety, the methodology for ageing management studies is also applicable for components important to plant life.

It is expected that the application of the guidance provided in the report in IAEA co-ordinated pilot studies on management of ageing of nuclear power plant components and in other Member States' projects will facilitate international co-operation in this field and will thus contribute to the safety and reliability of ageing NPPs.

The report was prepared by J. Pachner (Canada; IAEA since September 1990). The IAEA would like to acknowledge the contributions of R. Capel (France), D.H. Njo (Switzerland), J.W. Seddon and R.F. Cox (United Kingdom), and in particular of J.P. Vora (United States of America). Comments on the first draft received from representatives of 13 Member States and three international organizations at a Technical Committee Meeting in November 1989 were taken into account in the final report.

EDITORIAL NOTE

1. INTRODUCTION

Ageing[1] of nuclear power plant (NPP) components, systems and structures (referred to in the following as plant components) must be effectively managed to ensure that required safety margins are maintained throughout plant service life, including any extended life. In various programmes being conducted, many organizations in Member States are developing the necessary technical basis for managing ageing.

Managing the ageing of NPP components important to safety means predicting and/or detecting when a plant component has degraded to the point that the required safety margins are threatened and taking appropriate corrective or mitigatory actions. The ageing management process consists of three basic steps:

(1) selection of safety important plant components for which ageing should be evaluated;
(2) understanding dominant ageing mechanisms in the selected components and identifying or developing effective and practical methods for monitoring and mitigating ageing of the components (ageing management studies);
(3) managing the ageing degradation in the selected components by effective practices and initiatives in surveillance, maintenance and operations (proper design, manufacturing, storage and installation are also significant in the management of ageing).

This report focuses on documenting the methodologies used in Step 1 (selection of NPP components) and Step 2 (ageing management studies). It also provides recommendations for ageing management pilot studies of specific components.

1.1. BACKGROUND

Ageing of nuclear plant components, if unmitigated, reduces their safety margins provided in the design and thus increases risk to public health and safety. The term 'safety margin' is used in a broad sense meaning the safety state (i.e. integrity and functional capability) of both passive and active plant components in excess of their normal operational requirements (see Fig. 1). The safety state may be monitored by measuring and evaluating component specific functional parameters and condition indicators; this is discussed further in Section 4.2.2.

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[1] In this report, the term ageing is used to mean the process by which the physical characteristics of a system, structure or component change with time or use; this process may proceed by a single ageing mechanism or a combination of several ageing mechanisms. All materials in an NPP experience ageing degradation to a greater or lesser extent, which may lead to the functional degradation of plant components.

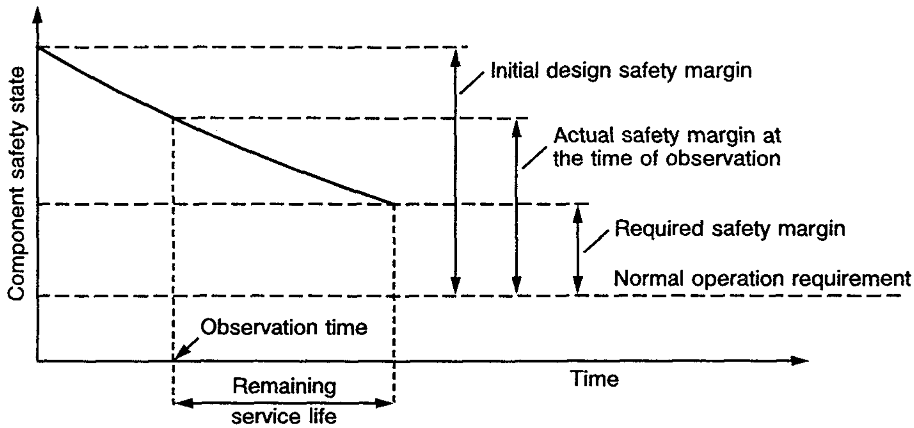


FIG. 1. Component safety state and safety margin as functions of time.

Operating experience shows that age related component failures[2] have occurred because of degradation processes, such as general and local corrosion, erosion, erosion–corrosion, radiation and thermally induced embrittlement, fatigue, corrosion fatigue, creep, binding and wear. The potential for failures and problems resulting from ageing may increase as more nuclear power plants of the first generation approach the end of their nominal design lives.

Examples of some significant ageing related component failures include:

— carbon steel feedwater line rupture caused by single phase erosion–corrosion;
— wall thinning (metal loss of 1–9 mm/a) of carbon steel bodies of boiler feed pumps and valves caused by single phase erosion-corrosion;
— Zircaloy pressure tube rupture caused by hydride blistering;
— failures of primary pump motors due to degradation of high voltage epoxy–mica insulation of stator windings caused by electrical stress (partial discharge);
— failures of solenoid values in dousing systems caused by degradation of elastomeric parts at high ambient temperature;
— failures of electrical cable insulation caused by thermal embrittlement.

More examples of ageing related component degradation and failures are given in Appendix I. Such ageing related failures may significantly reduce plant safety since they may impair one or more of the multiple levels of protection provided by the defence in depth concept. Ageing may lead to a large scale degradation of

[2] Failure is considered to have occurred when a component is unable to meet its minimum performance requirements, including required safety margins.

physical barriers and redundant components resulting in an increased probability of common cause failures. This could cause a reduction in component safety margins below limits provided in plant design bases or in regulatory requirements and thus could cause impairment of safety systems. It is then possible that degradation not revealed during normal operation and testing could lead to failure or even multiple common cause failures of redundant components under special loading and environmental stresses associated with an operational upset or accident.

In order to develop effective ageing management methods, many organizations in Member States are currently developing and implementing programmes and projects relating to NPP ageing. Since 1985, the IAEA has been sponsoring activities concerned with safety aspects of NPP ageing. In 1989, the Agency commenced implementation of a comprehensive programme recommended in 1988 by an Advisory Group [1]. Its overall objective is to establish and maintain, under the auspices of the IAEA, a programme of international co-operation for increased awareness and understanding of ageing degradation processes and the development of methods and guidelines to manage ageing for safe and reliable operation of NPPs. Activities carried out under this programme are sponsored by the IAEA's Division of Nuclear Safety, focusing on the evaluation and management of the safety aspects of ageing, and by the Division of Nuclear Power, focusing on managing ageing for long term plant reliability and economic aspects of plant life extension.

1.2. PURPOSE OF THE REPORT

The intent of the activities led by the Division of Nuclear Safety is to integrate information generated by Member State organizations into a common knowledge base, including the preparation of documents that will provide guidance on selected topics pertinent to the evaluation and management of the safety aspects of NPP ageing. Within this context, the purpose of this report is:

— to document a methodology for the selection of NPP components important to safety for which ageing should be evaluated;
— to document a methodology for performing ageing management studies of NPP components;
— to document recommendations for pilot studies on the management of ageing of a limited number of safety important components.

Looking further ahead, it is envisaged that the IAEA will collate the findings generated by organizations in Member States participating in these pilot studies and subsequently make arrangements for further development of ageing management strategies judged to be necessary to maintain required safety margins throughout the entire NPP service life.

1.3. TECHNICAL SAFETY ISSUES

Ageing affects all materials in NPPs to some degree and may lead to degradation of the safety state (i.e. integrity and functional capability) of plant components. Studies on the management of ageing, in general, are aimed at identifying problems that may result from plant ageing and the actions or initiatives that are available to manage ageing degradation of plant components. On attempting to define common technical issues to be addressed in these studies, a set of issues quickly emerged. Such issues, which are by no means exhaustive, are presented in the following:

(1) Which NPP components are susceptible to ageing degradation that could adversely affect plant safety? Which of these components are renewable (by maintenance, refurbishment or replacement)?
(2) What are the degradation processes of materials and components that could, if unchecked (i.e. if components are improperly maintained and/or not replaced), affect plant safety?
(3) Are current methods for testing, inspection, surveillance, maintenance and replacement adequate to detect and mitigate ageing problems before they significantly affect safety? If not, what additional measures are needed?
(4) Are current analytical models and criteria adequate to evaluate the residual life of key components and structures? If not, what additional criteria and supporting evidence (data, analyses, inspections) are needed?
(5) How should structures and components be selected for comprehensive assessments of ageing and evaluations of residual life?
(6) What kinds of records and other documentation are needed to support effective ageing management?

2. APPROACH TO THE MANAGEMENT OF NPP AGEING

The approach to the management of ageing that is presented in this report is applicable for all NPP components. However, the level of effort and the measures employed will differ depending on the significance of a component in terms of the potential impact of its failure on plant safety, plant life and operational economy. So, for example, while for a reactor pressure vessel (which is very significant in terms of both plant safety and plant life) comprehensive and rigorous measures are appropriate, for a potable water faucet (which has no impact on plant safety or plant life) a simple corrective maintenance would be appropriate. To determine appropriate ageing management measures for different plant components, a systematic approach should be employed.

2.1. GROUPING OF NPP COMPONENTS

Since there are thousands of components in an NPP, components should be carefully selected and prioritized to facilitate effective use of limited resources in the management of ageing. Figure 2 shows a general breakdown of NPP components into major subsets: components important to plant life, components important to safety and all other plant components. Safety important components recommended for ageing management studies are shown as a subset of the components important to safety.

As illustrated in Fig. 2, some of the components important to plant life, which are subject to plant life management considerations, are also important to plant safety and may be recommended for ageing management studies from the safety perspective (e.g. primary system piping). For such components, the safety related ageing management work and plant life management work should be co-ordinated to eliminate unnecessary duplication of effort. In general, components important to plant life are expensive or difficult to replace, while components important to safety include both large cost/difficult to replace items (e.g. the reactor pressure vessel) and routinely replaceable components (e.g. valves, motors or instruments).

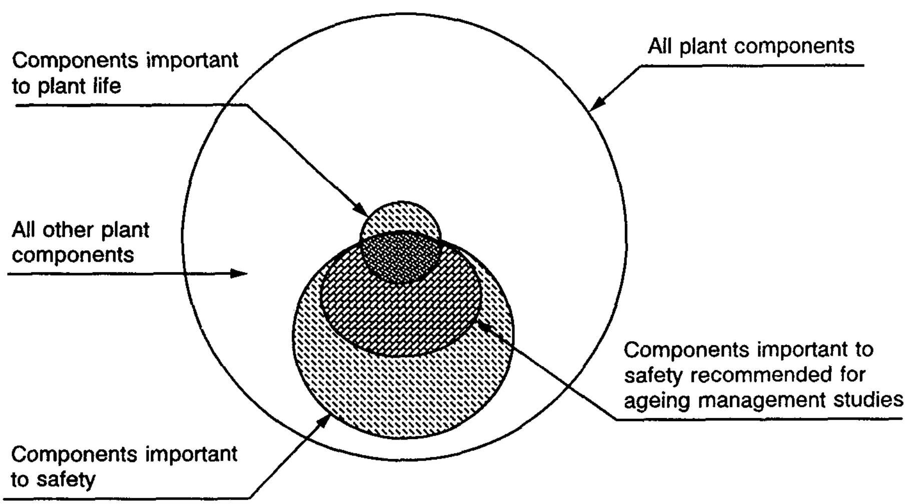


FIG. 2. Grouping of NPP components for ageing management.

2.2. GENERAL APPROACH TO THE MANAGEMENT OF NPP AGEING

The selection of plant components is the first step of the three step general approach to the management of NPP ageing. This approach is illustrated in Fig. 3. The second step involves performing the ageing management studies for the selected components, and the third step is the application of the results of these studies in appropriate ageing management actions or initiatives.

Section 4 of this report presents a recommended methodology for performing the ageing management studies. The objective of the studies is to have, for each of the selected NPP components, an understanding of dominant ageing processes and to identify or develop practical and effective methods for monitoring and mitigating ageing degradation of the components.

In general, utilities have in place some ageing management programmes. However, their scope and effectiveness may differ between the utilities and even between different plants of the same utility. Some of these ageing management programmes were developed in the plant design stage and may include, for example,

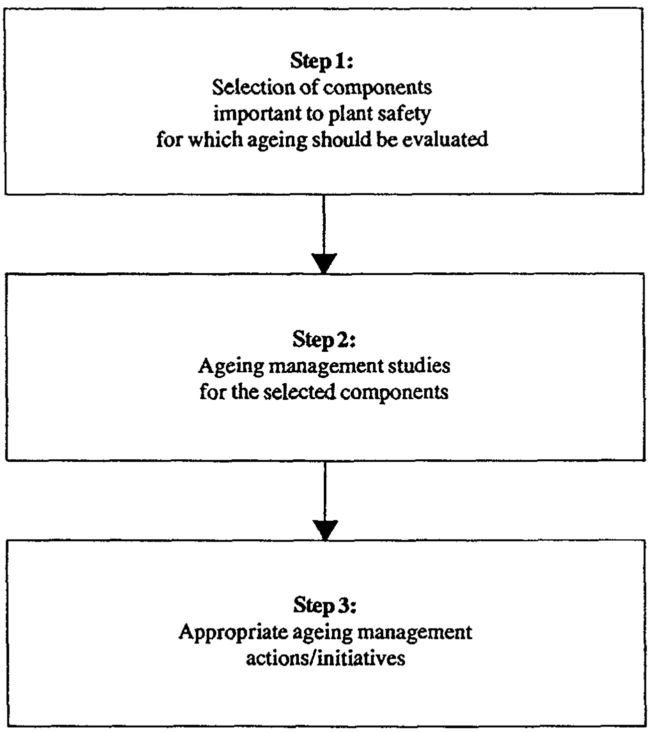


FIG. 3. General approach to the management of NPP ageing.

monitoring and mitigation of fatigue and irradiation embrittlement of the reactor pressure vessel wall. During NPP service life, it is prudent to re-evaluate periodically the safety state of key plant components and the effectiveness of ageing management methods employed in the light of current knowledge and practices in newer plants.

2.3. EQUIPMENT QUALIFICATION: AN EXAMPLE OF AN AGEING MANAGEMENT PROGRAMME

In general, NPP equipment[3] important to safety should be qualified to ensure its capability to perform designated safety functions on demand under postulated service conditions, including harsh accident and post-accident environments. Equipment qualification (EQ) programmes provide an example of a potentially effective strategy for managing ageing of NPP components important to safety covered by these programmes. The scope of the EQ programmes usually includes all equipment that performs safety functions or contributes towards the execution of the safety functions, but it may vary between Member States.

One objective of an EQ programme is to uncover deficiencies that could cause simultaneous failures of redundant NPP components. This objective should be achieved through a qualification process consisting of generating, documenting and maintaining evidence that equipment can perform its safety functions, whenever necessary, during its service life. Since ageing degradation followed by exposure to environmental extremes resulting from design basis events poses a potential hazard for common cause failures of safety important plant components, all significant ageing mechanisms should be evaluated and accounted for in the EQ programme.

The ageing degradation is usually taken into account by establishing a so-called 'qualified life' which is a maximum period that a component may be kept in normal service with a reasonable assurance that it would perform as required under design basis accident conditions. Routine maintenance, testing and calibration activities are part of normal service conditions and they, as well as the operational stresses, should be taken into account when establishing the qualified life. The qualified life may be dependent on the implementation of scheduled maintenance activities such as parts replacement, cleaning or lubrication, but these activities may also have an adverse effect if errors are made in their execution.

The assessment of equipment degradation due to ageing and appropriate simulation of ageing mechanisms remain among the most difficult areas of equipment qualification and a large measure of judgement enters into the analysis owing to the complexity of ageing processes. Therefore, the qualified life should be recognized

[3] The terms 'components' and 'equipment' are used interchangeably in this section.

as just an estimate with high uncertainty. As such, it should be subject to periodic review and re-evaluation based upon the actual service conditions, physical state and operational and maintenance histories of the equipment.

3. SELECTION OF NPP COMPONENTS IMPORTANT TO SAFETY FOR AGEING MANAGEMENT STUDIES

Ageing affects all materials in an NPP to some degree. While this report focuses on the management of ageing of safety important components, it should be recognized that ageing degradation should also be taken into account in connection with production reliability of NPPs and their overall economics. Consideration for safety must be an integral part of any reliability and economic evaluation. Safety aspects cannot be ignored.

An NPP has a large variety of components, many of which are essential for overall plant safety. Some of the safety related components contribute more than others towards ensuring plant safety and the extents to which these components are susceptible to ageing degradation also differ considerably.

At all NPPs there are maintenance, testing and inspection programmes in some form or another. These programmes all contribute to the detection and mitigation of ageing degradation. While many components have been designed to be replaced on a routine basis, there are others whose replacement is judged to be difficult owing to considerations of cost, plant outage or worker radiation dose. Also, there are a small number of NPP components whose replacement is judged not to be practicable.

It is not practicable nor is it necessary to evaluate and quantify the extent of ageing degradation of the many thousands of individual NPP components. A more rational and cost effective approach is required. The approach presented in this section is based on a systematic selection and prioritization of safety important NPP components for more detailed ageing management studies.

To enable safety important components to be selected for ageing management studies, a selection process is proposed which is based on a systematic examination of all systems and structures from a safety perspective. This examination is based on the following precepts:

— required safety margins of NPP components have to be maintained at all times;
— safety important components in an NPP have already been classified;
— the failure of safety important components can result in different degrees of loss of system safety functions, with or without severe consequences;
— current maintenance, testing and inspection programmes in NPPs include different strategies of varying effectiveness to deal with ageing effects;

— safety important components may experience varying degrees of degradation owing to ageing under different loading and environmental conditions;
— methods used for monitoring ageing effects in specific components and structures may vary significantly;
— existing databases pertaining to ageing effects in NPP components are not sufficiently comprehensive.

Although the selection process has been developed for application to thermal neutron reactors, the general method may well be applicable to other types of reactor systems such as fast reactors and research reactors.

The recommended selection process is described in Section 3.1. Section 3.2 presents a prioritization approach which may be used for assigning priorities for work programmes.

3.1. SELECTION PROCESS

There are two principal steps and four evaluation questions in the selection process, as shown in Fig. 4. Step 1 is at the system and structure level (Question 1.1) and Step 2 at the component level (Questions 2.1–2.3). Supporting guidance on how to answer each of the evaluation questions follows.

Question 1.1: Does the plant system or structure contribute to plant safety?

— A schedule of systems and structures that contribute to plant safety should be derived from a list of all plant systems and structures.
— To implement this step one can use a safety classification system developed by the Member State and/or a probabilistic safety assessment of a plant, if available.

The output of Step 1 is a shorter list of specific plant systems and structures, each of which now needs to be further evaluated at component level. There are three evaluation questions at the component level (Step 2).

Question 2.1: Would component failure result in a loss of system safety function?

— Failure is considered to occur when a component is unable to meet its minimum performance requirements, including required safety margins.
— At this step, the significance of component failure is to be assessed on the assumption that it could be caused by ageing degradation.
— It is to be expected that failure of some system components may be more significant to safety than failure of others. (a) Some systems include components which only provide information on system performance or status or

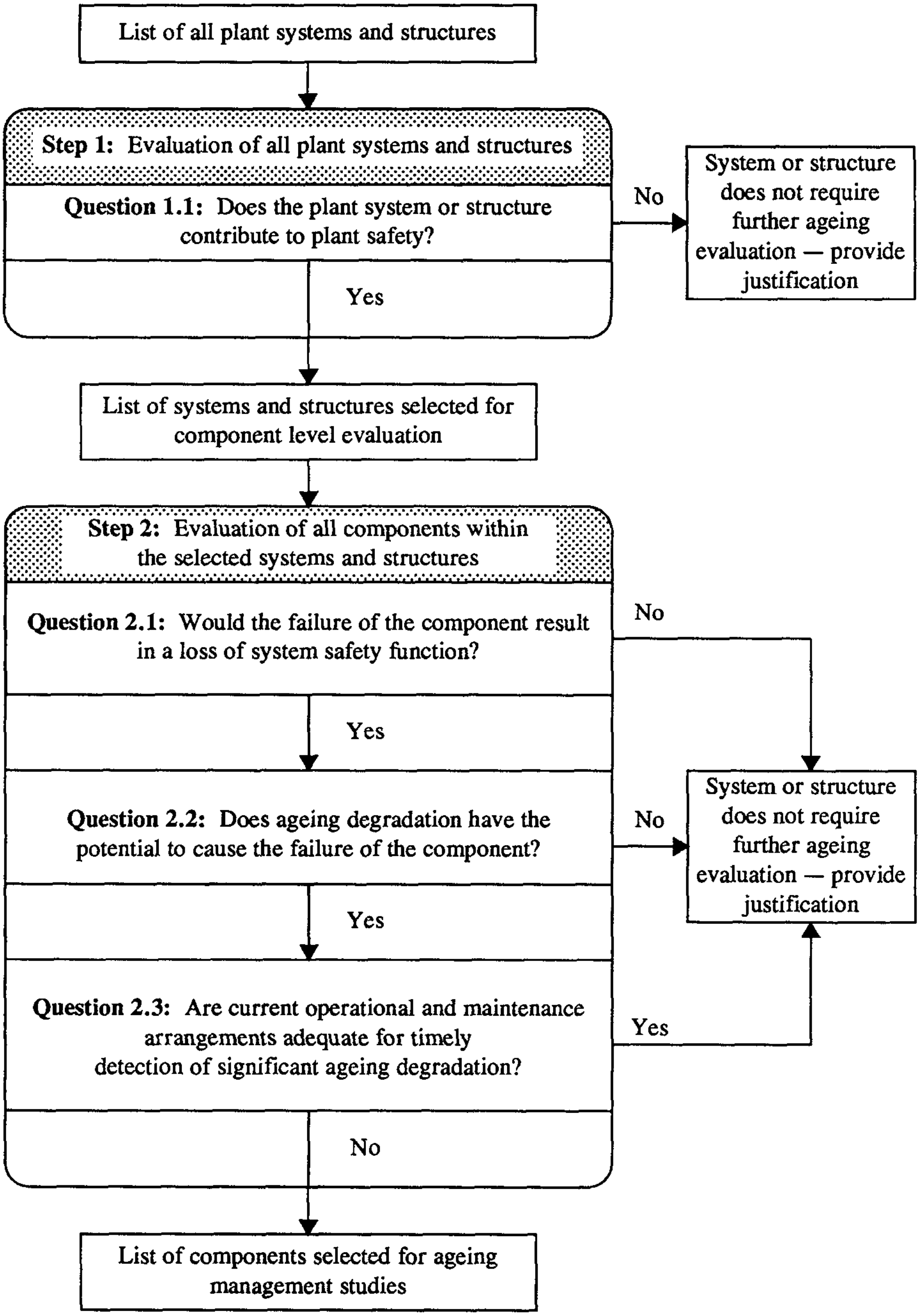


FIG. 4. Selection process for safety important NPP components for ageing management studies.

which only facilitate testing or maintenance activities. Similarly, structures may include components that are extraneous to the structure's safety function. Such components may be omitted from further ageing evaluation if they do not contribute to the performance of the safety function. (b) There may also be plant components without safety functions whose failure could prevent other components, systems or structures from performing their intended safety functions. Such components should be included in further ageing evaluation.
- No account should be taken of component redundancy or diversity, on the basis that ageing degradation should be regarded as a common cause failure mechanism and that the diversity may not provide protection against all potential failures caused by common ageing mechanisms. Therefore, both redundant and diverse components important to safety should be included in further ageing evaluation.

Question 2.2: Does ageing degradation have the potential to cause component failure?

- As the basis for evaluating this potential, consideration should be given to the component's design life.
- Current knowledge of component ageing mechanisms should be evaluated.
- Both industry wide and plant specific operating experience should be reviewed, including results of root cause analyses of relevant significant operating events and trend and performance analyses of routine maintenance data.

Question 2.3: Are current operational and maintenance arrangements adequate for the timely detection of significant ageing degradation?

- Are the existing component condition indicators adequate for monitoring and detection of ageing degradation?
- Are current techniques adequate for monitoring these condition indicators effectively?
- Are the scope and quality of current maintenance and operating practices adequate?

The resulting list of selected components may now be arranged into generic groups for the purposes of resource effective ageing management studies.

3.2. APPROACH TO PRIORITIZATION

A prioritization of selected components can be performed if there are limited resources and a desire to deal first with components of high safety significance. A deterministic approach should be used as a basic strategy for the prioritization.

However, a hybrid deterministic–probabilistic approach should be used if an applicable and appropriate probabilistic safety assessment (PSA) of a plant exists.

The IAEA Safety Guide 50-SG-D1 [2] provides guidance in the ranking of the various safety functions that can be used to prioritize plant components for ageing management studies. However, applying the IAEA classification may well result in all Class 1 components having the first priority. Other aspects also should therefore be taken into account in the prioritization, such as:

— component failures can have different degrees of severity in terms of their direct or indirect consequences;
— some components may not be allowed to fail (e.g. a reactor pressure vessel);
— components have different susceptibilities to ageing;
— the effectiveness of ageing management programmes differs;
— components can be categorized according to their replaceability;
— components can show substantial differences in their expected lifetimes.

The United States Nuclear Regulatory Commission (USNRC) has developed a prioritization approach which takes into account the effect on plant risk of component ageing and the effectiveness of current practices in the industry in mitigating that ageing [3]. This approach has been used to prioritize NPP components for further evaluation under the USNRC's Nuclear Plant Ageing Research (NPAR) Programme.

More recently the USNRC has developed a risk based prioritization approach which systematically prioritizes plant components on the basis of their contribution due to ageing to the core damage frequency and/or public health risk [4]. The ageing contributions to risk are composed of individual component ageing contributions and component ageing interaction contributions which are due to multiple components ageing simultaneously. This risk based prioritization approach can be used in conjunction with a deterministic approach where the deterministic approach covers those aspects or components not included in the risk based prioritization.

In the risk based approach the ageing contribution ΔR to risk from a set of n plant components (both active and/or passive components) is given as a sum of individual and interaction contributions:

$$\Delta R = \sum_{i} S_i \Delta A_i + \sum_{j>i} S_{ij} \Delta A_i \Delta A_j + \ldots + S_{12\ \ n} \Delta A_1 \ldots \Delta A_n$$

In this expression, which is exact when all terms are included, S_i, S_{ij}, etc., are the risk importance coefficients and $\Delta A_i, \ldots, \Delta A_n$ are the ageing effects of the components. With regard to the risk importance coefficients,

S_i is the risk importance of the individual component
S_{ij} is the risk importance of the interaction of components i and j
$S_{12\ \ n}$ is the risk importance of the interaction of the components 1, 2,...n.

These risk importances are calculated from the probabilistic risk assessment for the plant basically by determining the risk increase when a given subset of plant components is unavailable. Reference [4] provides algorithms for calculating the risk importances.

The ageing effects ΔA_i are increases in failure probability or unavailability of a component i due to ageing. The ageing effects are calculated using reliability models incorporating age dependent failure rates or age dependent degradation rates and effects of testing and maintenance on the component reliability.

This risk based formalism also provides a framework for integrating deterministic prioritization results with risk based prioritization results. In this general framework, S_i, S_{ij}, etc., can be interpreted as safety importances of the ageing components which also need to be determined in deterministic prioritizations, for example by relative rankings based on expert judgement. The ageing effects ΔA_i also need to be determined in deterministic prioritizations, again for example by relative rankings based on expert judgement taking into account component susceptibility to ageing and the effectiveness of relevant ageing management programmes. The safety importances and ageing effects for the deterministic prioritizations can then be combined to determine the overall impact on safety by using the foregoing formula for ΔR. In this way, the deterministic prioritizations can then be integrated with the risk based prioritization.

It is expected that in future the hybrid prioritization approach will be improved as applications of PSA to NPP ageing are further developed and more practical experience is gained.

4. METHODOLOGY FOR AGEING MANAGEMENT STUDIES

Section 3 of this report describes a deterministic method approach for the selection of components for ageing management studies; however, a hybrid approach with a deterministic method supplemented by a probabilistic method, when available, may also be used.

The purpose of Section 4 is to present a methodology for systematic ageing management studies that is applicable for any component selected in Section 3. The methodology can be used for ageing management studies of generic component types and also for ageing assessments of specific plant components (including the component's safety state and the effectiveness of methods for monitoring and mitigation of its ageing). Although this methodology was developed specifically for NPP components important to safety, it is also applicable to NPP components important to plant life.

It is recommended that results of the ageing management studies should be fed back into the process of component selection and prioritization where appropriate.

Similarly, a feedback process should be considered throughout all of the elements of the ageing management process.

In general, the ageing of a component is a complex process that begins as soon as it is produced and continues throughout its entire life, including the service life. Ageing of the component occurs owing to its use and the exposure of its constituent materials to service conditions, including the operating environment. It may proceed by a single ageing mechanism or by a combination of several ageing mechanisms. IAEA-TECDOC-540, Safety Aspects of Nuclear Power Plant Ageing [5], provides an extensive overview of ageing mechanisms.

To maintain the safety and reliability of NPPs throughout their service life requires the effective management of ageing degradation processes that affect the functional capabilities of plant components, systems and structures. The management of NPP ageing has technical as well as organizational aspects. The organizational and management aspects, such as the definition and division of responsibilities and the capability and availability of human resources, are essential to a successful programme for NPP ageing management; however, they are beyond the scope of this report, which deals only with the technical aspects of NPP ageing management.

Phased approach to ageing management studies for NPP components

Ageing management studies for selected NPP components should address the following three essential elements of an effective ageing management programme:

(a) understanding of the ageing degradation processes;
(b) monitoring of ageing that is capable of detecting component degradation before failure;
(c) timely mitigation of ageing and its effects (e.g. through maintenance, replacement or changes in operating conditions) to ensure that required safety margins are maintained.

The recommended methodology for the ageing management studies uses a well tried phased approach which allows efforts to be concentrated on the more significant tasks of the studies. Phase I, Interim Ageing Study, is focused on the review and evaluation of existing knowledge and technology relating to the understanding, monitoring and mitigation of ageing of the selected NPP component.

The purpose of Phase II, Comprehensive Ageing Study, is to fill or otherwise adequately deal with the knowledge and technology gaps identified in Phase I. This is accomplished through an in depth review of Phase I data, follow-up investigation of pertinent operating experience, research for better understanding of component ageing, and the identification and, if necessary, development of effective and practical technology for monitoring and mitigation of the component ageing.

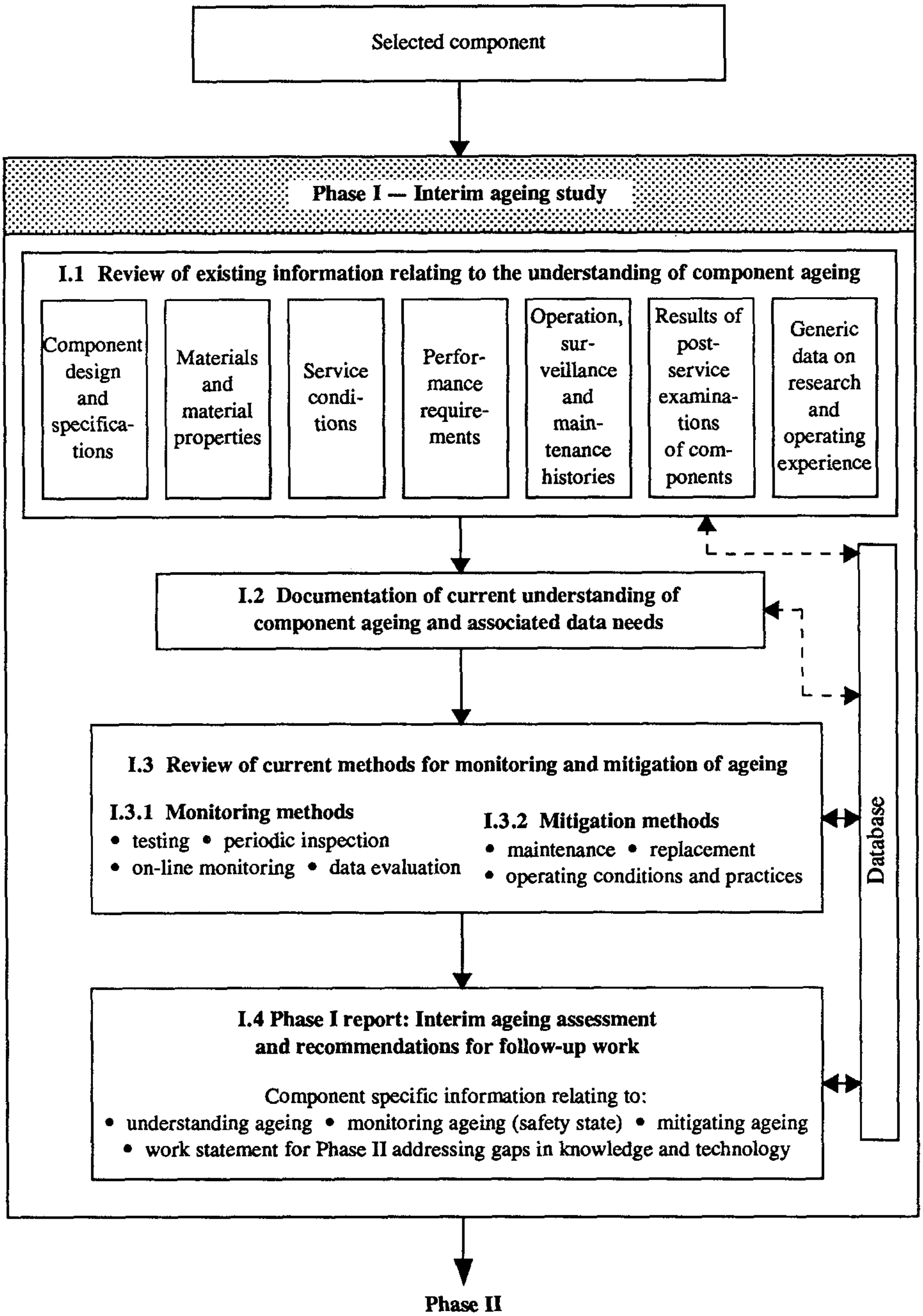


FIG. 5. Methodology for ageing management studies. Phase I: interim ageing study.

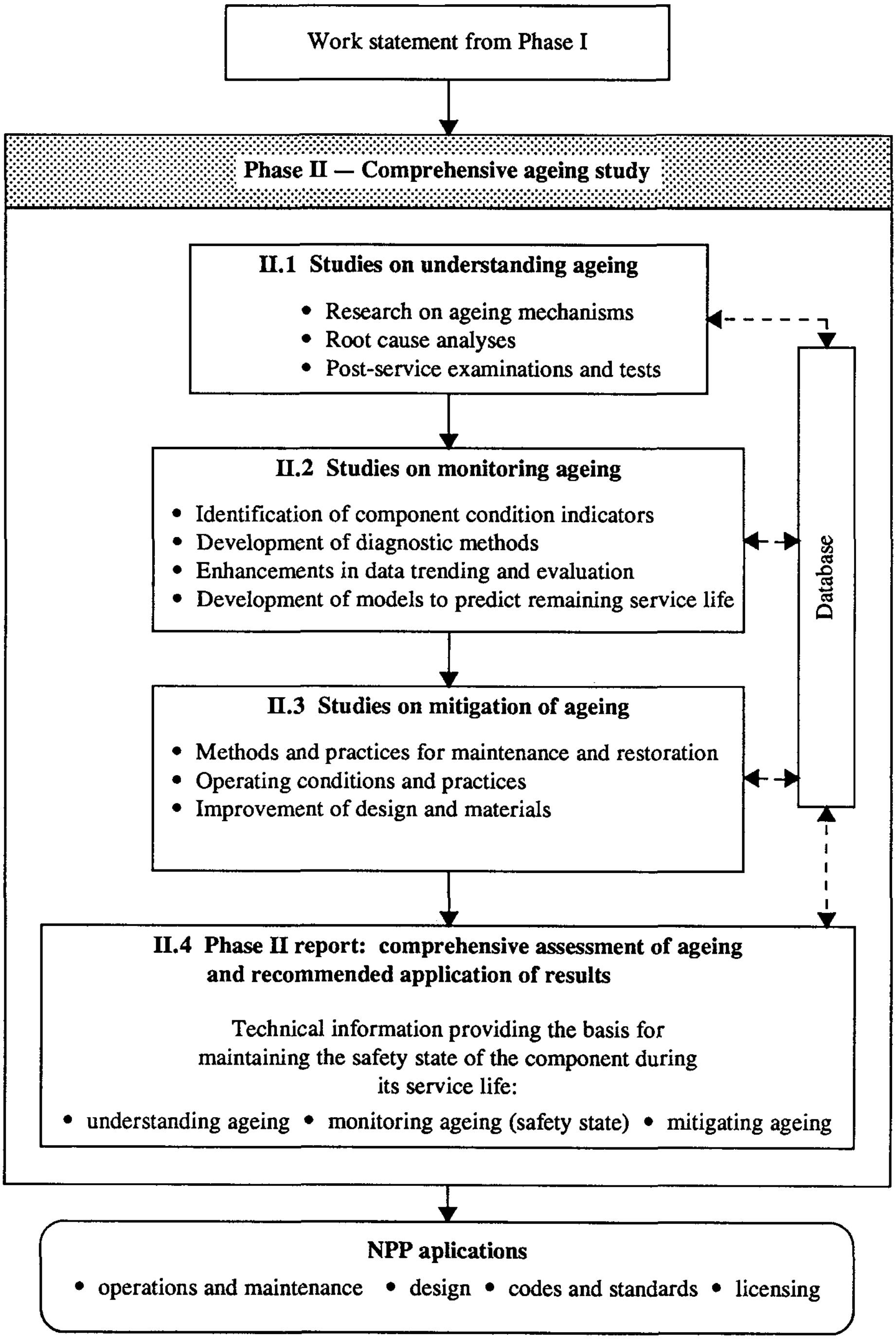


FIG. 6. Methodology for ageing management studies. Phase II: comprehensive ageing study.

The methodology is illustrated in flow charts shown in Figs 5 and 6. It is recommended to provide for a feedback, by means of a common database, of information generated by various tasks and study participants; this is an important aspect to increase the efficiency and effectiveness of the studies.

4.1. PHASE I: INTERIM AGEING STUDY

The Phase I study for a selected NPP component should consist of the review and assessment of relevant existing information and documentation of the findings. The recommended major steps of Phase I, described in the following sections and shown in Fig. 5, are as follows:

(1) review of existing information relating to the understanding of component ageing;
(2) documentation of current understanding of component ageing based on the findings of Step 1;
(3) review of current methods for monitoring and mitigation of component ageing and evaluation of their effectiveness;
(4) preparation of Phase I report to document findings of the interim ageing assessment and to make recommendations for follow-up work.

It should be recognized that it may not be technically or practically feasible to obtain all the desired information identified in the following text by means of the aforementioned reviews and evaluations. Nevertheless, an effort should be made to acquire as much of this information as possible for the selected component.

4.1.1. Review of existing information relating to the understanding of component ageing

Understanding of component ageing is necessary for the effective monitoring and mitigation of ageing effects. To understand the ageing degradation of an NPP component, it is first necessary to identify and understand its ageing processes. Since these processes involve constituent materials, parts and the service conditions of a component, it is necessary to know the design, materials, service conditions, performance requirements, operating experience and relevant research results for the component. The following paragraphs further detail these items and define expected outcomes of their review.

Component design and specifications

The required knowledge of the component design can be obtained from design documents and specifications. This part of the review should examine design data (including records of design changes made during service life), specifications, applicable standards and regulatory requirements, component certificates, final safety analysis reports, operating and maintenance manuals, and product literature. Additional information should be obtained, as appropriate, from vendor surveys, utilities, published reports and expert opinion.

Materials and material properties

A list of all significant parts and materials that make up the component should be drawn up, and the materials and parts judged most susceptible to ageing should be identified. For these materials and parts, the following information relating to material properties and conditions should be gathered, as appropriate:

- the as-built material composition;
- material properties in the as-built condition and the after-service condition, if affected by plant operation and maintenance;
- the manufacturing process and type of semi-finished product (e.g. casting, forging, coating, welded or seamless pipe);
- further processing of semi-finished products (hot or cold formed parts), appearance of constituent parts (e.g. root gap, root penetration, or misalignment of weld edges) and repairs;
- heat treatment received and heat treated conditions (e.g. as-welded, stress relieved);
- types of polymers, activation energies of age susceptible insulating materials;
- assessment of any defect that may pertain to the initial fabrication state and integrity assessment.

Service conditions

The age related degradation of a component is a time dependent phenomenon and depends, among other things, on service conditions, including the operating environment, and the operating history.

The service conditions considered in the ageing management studies are also referred to as 'stressors' because they impose stresses on a component which lead to its degradation through various physical and chemical processes. Examples of these stressors are temperature, electrical and mechanical loadings, radiation, chemicals, contaminants, atmospheric humidity and, where appropriate, the system chemistry (e.g. in the case of the primary system components, the primary coolant chemistry).

The service conditions that should be investigated and identified include environmental, loading and power conditions resulting from normal operating requirements, including expected operational transients, and also those conditions that prevail during testing, shutdowns and storage. Accident and post-accident conditions should be considered for those components credited in plant accident analysis and those whose failure could prevent the performance of required safety functions.

Performance requirements

The performance requirements of the component should be reviewed to assess whether or not ageing may degrade its ability to perform the required safety function in normal, abnormal and, where applicable, accident conditions. An attempt should be made to identify functional and condition indicators that could be practically monitored to provide an indication of age related degradation and future performance of the component.

Operation, surveillance and maintenance histories

A review should be made of available operation, surveillance and maintenance histories of the components. The review is intended to provide information on failure rate history, identified failure mechanisms and degradation sites, and age related failure modes and causes that have been experienced.

The sources of information that should be reviewed to obtain this information include plant surveillance, maintenance, in-service inspection (ISI), design change and reliability records, and significant event and reliability databases maintained by various national and international organizations.

When the desired information is not directly available from the existing records, limited analyses of the available records and interrogation of plant personnel may be performed to uncover missing information. For example: an unknown ageing/failure mechanism might be determined by evaluating component design, materials, specified versus actual service conditions and component applications and loadings. Component degradation sites may be identified from failure descriptions, or surveillance, maintenance and ISI records.

With reference to the degradation sites, it should be noted that most components are not uniformly susceptible to ageing degradation. Certain locations within the component boundary exhibit more deterioration than others and, for many components, degradation is limited to a specific site only. An understanding of the ageing degradation of a specific component requires knowledge of the sites where degradation occurs, its mechanisms and its rate. This information is fundamental to the evaluation, selection and application of monitoring and mitigation methods.

Appendix II lists some known ageing mechanisms and susceptible components and materials and likely degradation sites. Reference [5] describes some ageing mechanisms in more detail.

Results of post-service examinations of components

Results of tests and examinations of components removed from service or from decommissioned plants should be reviewed to supplement or confirm information on failure mechanisms and other factors obtained or deduced from historical records. These results may also be helpful in identifying condition indicators that could be monitored to determine the ongoing effects of ageing.

If such results are not available, some screening type tests and examination should be performed in Phase I. In general, they should involve visual inspection, in situ or on-site (after the component has been removed) tests and examinations, and possibly some laboratory tests.

Generic data on research and operating experience

There are ongoing national and international research programmes aimed at understanding ageing phenomena of various plant components. Various organizations (e.g. the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA), the World Association of Nuclear Operators (WANO) and the IAEA) are also compiling operational experience, and are analysing significant events to improve operational safety and reliability. Information from these programmes should be reviewed to provide additional insight into ageing processes affecting the investigated component.

4.1.2. Documentation of current understanding of component ageing

Information obtained in these reviews should now be synthesized and interpreted to arrive at an understanding of the component's ageing. This is needed as a basis for a meaningful review of the effectiveness of current methods for monitoring and mitigation of ageing of the component which is discussed in Section 4.1.3.

There are three expected outcomes of this task:

- A data set containing results of the component specific reviews described in the foregoing. (It should be consistent with the categories of data identified in Section 4.1.1. However, the content of each category may vary according to the type of component.)
- A summary of information describing current understanding of ageing of the component. (This is a condensation of information derived from the aforementioned data set. It should contain important information on component materials, stressors and environment, degradation sites and ageing mechanisms of concern; any explanatory notes and references should be included as needed. Examples of such a summary of information are presented in Appendix III for several NPP components; the relevant information is at the top of each summary sheet and under the subtitle Understanding Ageing.)

— A component specific list of data needs relating to the evaluation and management of the component's ageing. (In addition to the component data needs list, deficiencies in the quality and availability of the necessary data in the existing records and data sources should be identified to facilitate improvements in data collection and record keeping practices in support of the understanding of component ageing. The IAEA report on data collection and record keeping [6] should be consulted for guidance on the preparation of the data needs list and for help in identifying gaps or weaknesses in the existing data.)

4.1.3. Review of current methods for monitoring and mitigation of component ageing

The third step of Phase I is the review and evaluation of current methods for the monitoring and mitigation of ageing for the investigated component. This evaluation should be carried out in the light of the current understanding of ageing of the component documented in the preceding step of this study (see Section 4.1.2).

Monitoring methods

Existing methods for inspection, surveillance and monitoring should be evaluated to determine whether they are effective for timely detection of ageing degradation before loss of safety function. Methods to be reviewed include periodic inspections (both visual and instrument aided), testing, on-line monitoring techniques (by instruments) and data evaluation methods. The review should also seek to identify new functional parameters and condition indicators that are capable of detecting component degradation before failure. The results of this review should provide:

(a) an assessment of the effectiveness of currently used functional parameters and condition indicators for monitoring and trending ageing degradation of the component;
(b) an assessment of the capability and practicability of existing monitoring techniques to measure these parameters and indicators with sufficient sensitivity, reliability and accuracy;
(c) an assessment of existing data evaluation techniques and criteria for detecting degradation and predicting future performance of the component (i.e. for assessing the safety state and residual lifetime of the component).

Mitigation methods

The purpose of this part of the Phase I ageing management study is to evaluate the effectiveness of existing methods and practices for mitigating ageing degradation of the component. Methods to be evaluated include maintenance, refurbishment and periodic replacement of components, and altering of operating conditions and practices affecting the rate of component degradation. Significant ageing mechanisms, service conditions (including the operating environment) and degradation sites identified in the review of current understanding of ageing of the component should be taken into account in the evaluation.

4.1.4. Phase I report: Interim ageing assessment and recommendations for follow-up work

Results of the reviews and evaluations conducted in the Phase I study (both for generic component type studies and for specific plant component ageing assessments) should be integrated into a coherent report providing an interim ageing assessment of the component under study. This assessment should include significant ageing mechanisms of concern, defect characterization, and an evaluation of the safety significance of the probable failure modes. In the case of a study of a specific plant component, an assessment of the current safety state of the component should also be included. An interim evaluation of current technology for the monitoring and mitigation of ageing of the component should be documented. The report should also include a listing of effective and potentially effective functional parameters and condition indicators.

The Phase I report should make clear the current understanding of ageing of the component, the parameters and indicators that should be monitored and the recommended monitoring methods or techniques, and the ageing mitigation methods that should be used. Any gaps in knowledge and technology relating to the understanding, monitoring and mitigation of ageing should be identified.

The Phase I report should also make recommendations for Phase II studies to address the identified gaps in knowledge and technology. These recommendations should be in the form of a work statement for the Phase II studies, clearly stating the objectives, scope of work and tasks to be performed in the Phase II study for the selected NPP component.

If the results of Phase I show that there are adequate understanding and technology for managing the ageing of the component, recommendations should be given, as appropriate, for the application of the Phase I results in codes, standards and regulatory requirements and in plant design, operation and maintenance.

4.2. PHASE II: COMPREHENSIVE AGEING STUDY

The Phase II study on the selected NPP component is a comprehensive and systematic effort to verify the interim ageing assessment of the Phase I study and to address associated gaps in knowledge and technology or weaknesses relating to maintaining the required safety state of the component during its service life. The work statement contained in the Phase I report should be used as a basis for the implementation of the Phase II study.

The scope of work of Phase II consists, in general, of the following major tasks:

(1) studies on understanding of ageing to enhance or refine current understanding of significant ageing mechanisms and to determine root causes of ageing degradation of the component;
(2) studies on monitoring of ageing to verify existing diagnostic and data evaluation techniques or develop new techniques capable of timely detection of ageing degradation of the component;
(3) studies on mitigation of ageing to improve existing or develop new methods and practices for operation and maintenance or new designs needed to control ageing degradation of the component;
(4) preparation of a Phase II report documenting the findings of the comprehensive ageing assessment with recommendations for their application.

Although these tasks should ideally be performed sequentially, in practice they are usually done in parallel to a certain extent. This requires an exchange and feedback of information among key participants in the Phase II study. Each of these major tasks is depicted in Fig. 6 and discussed in the following.

4.2.1. Studies on understanding ageing

Studies on comprehensive understanding of ageing of the selected component should include research on ageing mechanisms, root cause analyses of degradation or failures experienced and post-service examinations of naturally or artificially aged components. These tasks are described in the following paragraphs.

Research on ageing mechanisms

Research on ageing mechanisms of the selected component should focus on determining the ageing mechanisms causing significant degradation of the component (if the mechanisms or their significance are unknown or uncertain) and quantifying the effect of relevant factors (such as ambient environment, operating requirements and conditions) on the rate of degradation. Specific research objectives and scope of work should be derived from the results of the Phase I study. Typical research on component ageing mechanisms includes an in depth review and analysis of operating experience, in situ and laboratory tests of naturally aged components, and artificial ageing of components or their parts.

Root cause analysis

Root cause analysis of an observed component failure or degradation is conducted to discover its underlying reason, i.e. root cause. Once the root cause is known, actions can be taken to control, minimize or prevent future component deterioration and failure due to this root cause.

Root cause analysis is a systematic method of collecting and analysing information relating to a failure of a specific component, in order to determine, with a high degree of confidence, the fundamental cause or failure mechanism (and the contributing factors or conditions) responsible. It should be noted here that, in addition to ageing degradation, there are several broad categories of root causes; they include design error, manufacturing flaws and improper procedures.

Experience shows that a successful root cause analysis requires knowledge to be acquired from plant personnel to support the often incomplete and inaccurate information available in plant records. When a root cause has been determined, the lessons learned should also be applied to other similar components in similar applications.

Post-service examinations and tests

An additional insight into and confidence in the understanding of component ageing can be acquired by undertaking a programme of post-service examination and tests on plant components withdrawn from service, with particular emphasis on ageing evaluation of components that have either failed in service or experienced long service life.

Components that have experienced significant operating and environmental stresses should be determined from commercial operating plants, decommissioned facilities and research reactors. A major thrust of this research should be to evaluate performance of naturally aged equipment before and after it is subjected to the stresses and environmental conditions expected under accident conditions. The evaluation should quantify ageing degradation of the equipment and determine whether adequate safety margins exist; it should be based on following the dynamics of functional parameters and condition indicators that were identified in Phase I.

Depending on the origin and size of a component, the examinations and tests may be undertaken in situ or at a research laboratory.

The findings of the post-service examinations should be compared with predictions of ageing degradation for additional confidence in the operational readiness of safety related components to function, as required, under fault and design basis accident conditions.

4.2.2. Studies on monitoring of ageing

Studies to improve monitoring of component ageing degradation should include efforts to identify appropriate condition indicators, and to improve methods of diagnosis, data trending and evaluation and methods for assessing the remaining service life of components.

Identification of component condition indicators

Effective monitoring of ageing degradation of a component requires knowledge of one or more measurable parameters, called condition indicators, which indicate the performance and physical state of the component at the time of observation, and can be used to assess a component's ability to perform its specified functions during a period following the time of observation. The first of the studies on monitoring component ageing should therefore identify candidates for appropriate component specific condition indicators.

An appropriate condition indicator is a measurable parameter providing a warning of impending functional degradation that may not yet be apparent. Such a parameter must therefore undergo a change which is detectable before component failure. Ideally, monitoring a single condition indicator would be sufficient to determine physical conditions and the safety state of a component. However, for some components more than one condition indicator may be needed.

Examples of common condition indicators include parameters such as voltage, current, response time and set point drift for instrumentation and control components, vibrations for rotating equipment, and a shift in critical brittle temperature for the reactor pressure vessel. For other examples of condition indicators and related information, see Appendix IV and also Section 7.2.1 of Ref. [5].

Development of diagnostic methods

Diagnostic methods used for monitoring component ageing degradation may take the form of measurements or periodic tests or inspections designed to produce consistent, repeatable results by which the current performance and the physical condition of the component are determined.

Research and development studies for the development of diagnostic methods for monitoring the ageing degradation of a component require an assessment of the practicability of the component specific candidates for condition indicators identified earlier. This means assessing whether the condition indicator/parameter is measurable with sufficient sensitivity, accuracy and reliability and at acceptable cost. In this effort, advanced techniques and technologies, either in use or under development, are investigated. When available, sources of technology both within and outside the nuclear industry are used. The sources outside the nuclear industry include fossil fuel power plants, the petrochemical industry, the aerospace industry, national laboratories and other government agencies. Also, the practical feasibility of applying these technologies to nuclear plant components is explored.

Laboratory and field application and verification tests of candidate technologies are carried out. The objectives of the tests are to demonstrate that methods are appropriate to follow the dynamics of the condition indicators of interest; that methods have adequate selectivity (will not give false indications) and sensitivity (will detect degradation in the incipient stage); and that suitable acceptance/rejection criteria are available so that maintenance needs can be correctly identified.

The laboratory tests simulate defects of varying degrees of intensity in prototype hardware to determine sensitivity and detection criteria. Various combinations of defects and environments are used to determine selectivity. These laboratory tests are carried out to verify that the methods are applicable for in situ use at power plants. The field tests at power plants are recommended in order to confirm the laboratory results, and to provide information about the frequency and method of data collection and analysis and the practicability of application.

Data trending and evaluation

Monitoring of ageing degradation of a specific component consists of a continuous or periodic measurement of appropriate condition indicators followed up by trending and evaluation of measured data. The data trending and evaluation involve comparisons of the measured data with results of previous measurements on the same component and with minimum acceptance criteria.

In this study on monitoring ageing it should be established which condition indicators should be monitored and trended, and how they should be evaluated to determine present, and predict future, performance and physical condition of the monitored component, and to define the type and timing of maintenance.

Three examples of condition indicator trending for a reactor pressure vessel, containment isolation valve and power transformer are presented in Appendix IV of this report.

Development of remaining service life prediction models

Assessment of remaining service life is of primary importance to NPP components that are either very expensive or very difficult to replace. The development and verification of the prediction models for the remaining life of these major plant components is the subject of this element of the studies on monitoring of ageing.

The knowledge of relevant ageing mechanisms and of ageing effects and their rate of change are important inputs for developing the residual service life models. The models should correlate values of condition indicators for the component with its functional parameters, safety state and expected residual lifetime. These correlations are not well established and, as a consequence, the techniques for predicting remaining service life are not well developed.

The effort under this element should include: a compilation of currently used methods and an evaluation of their applicability; testing and examination of naturally aged components; and comparison of their results with the service life predictions based on actual service history. Additional information that should be considered includes information on design, required safety margins, significant degradation mechanisms and the actual state of the component.

4.2.3. Studies on mitigation of ageing

Comprehensive studies on mitigation of component ageing degradation include a development or refinement of appropriate maintenance and restoration methods and practices, an assessment of modifications and identification of appropriate operating conditions and practices, and an evaluation of possible changes in design and materials of the component under study.

Maintenance and restoration methods and practices

The role of plant preventive maintenance programmes is to preserve the required functional capability of NPP components for operational and emergency use. It is therefore also a primary means of detection and mitigation of ageing effects in NPP components.

Preventive maintenance is effected by two kinds of maintenance: scheduled or time directed maintenance and predictive or condition directed maintenance [5]. The corrective or breakdown maintenance approach may be preferred for NPP components whose failure does not have significant consequences for safety. Components important to safety should be covered either by predictive maintenance or by scheduled maintenance.

Preventive maintenance programmes should be periodically reviewed and modified on the basis of operating experience and new knowledge to ensure their effectiveness. Such a review, focused on a selected plant component, should also be conducted within the framework of comprehensive studies on the mitigation of ageing, and the information generated in the relevant Phase I and Phase II studies should be taken into account. The review should identify reliable techniques for the prediction of component degradation and performance, and criteria for deciding the timing and kind of maintenance work. Consideration should be given to the application in this review of reliability centred maintenance (RCM) methodology, which has been shown to be effective in optimizing NPP maintenance programmes on a system level [7, 8].

On the basis of the review results, in order to mitigate component ageing effectively, it may be appropriate to improve technologies and procedures, or develop new ones, for maintenance and restoration. In such a case, this effort should also be a part of the scope of this study on the mitigation of ageing.

Operating conditions and practices

Operating conditions and practices may have a substantial effect on the rate of component ageing degradation. Studies on mitigation of ageing should therefore include a consideration of possible modifications of the operating conditions and practices, and an assessment of their impact on the component ageing. In all cases of proposed changes in component operating conditions or practices, their potentially harmful side effects on other ageing mechanisms of the component or its parent system should be evaluated.

Some general examples of possible changes in operating conditions and practices to mitigate ageing would be:

— to reduce local stresses due to thermal or mechanical loads;
— to improve operational procedures, e.g. change the loading scheme of the fuel assemblies to reduce the neutron flux density with respect to the reactor pressure vessel (RPV) wall;
— to reduce ambient temperatures for electrical equipment and for materials subject to thermal ageing;
— to modify testing and optimize the test frequency.

Design and materials

Another option that should be considered to mitigate ageing is to make appropriate changes in the design of a component or the materials that are used in its fabrication. The utilization of new and innovative designs to minimize the costs of maintenance should always be considered.

4.2.4. Phase II report: Comprehensive ageing assessment and recommended application of results

At the end of Phase II, a comprehensive assessment of results of all Phase II studies should be conducted to demonstrate that the knowledge and technology gaps that were identified in the Phase I study have been adequately dealt with, and that the basis is provided for maintaining the safety state of the component during continued plant operation. The Phase II results should be incorporated into an integrated plan for managing ageing of the component investigated.

The Phase II report should address in a comprehensive and coherent manner the topics of:

— understanding ageing of the component
— monitoring its ageing (safety state)
— mitigating its ageing.

The report should also present clear recommendations for the application of Phase II results in plant operation, maintenance and design as well as in relevant codes, standards and regulatory requirements. Recommendations for the collection of data and record keeping needed to monitor ageing of the component and to provide evidence that required safety margins are maintained throughout the component's service life should also be included.

Follow-up actions should include: dissemination of the report to appropriate organizations designing and operating NPPs, safety authorities, standards writing bodies and research institutes, and the use of Phase II results in system level evaluations and in risk evaluations of ageing. Furthermore, ageing management should include ongoing feedback of plant operating experience and pertinent research and development results. On the basis of this feedback, ageing assessments should be updated to identify where additional changes in design, operation and maintenance might be advantageous.

5. RECOMMENDATIONS FOR AGEING MANAGEMENT PILOT STUDIES

Various organizations in the IAEA's Member States are devoting a significant effort to better understanding and managing the effects of ageing in NPPs. It is recognized that a greater exchange of information and co-operative work amongst Member States would enhance the understanding of NPP ageing and the effectiveness of ageing management measures. The recommended ageing management pilot studies are intended to facilitate such international co-operation.

The main objectives of these component specific pilot studies for each component are the identification and understanding of dominant ageing mechanisms, and the identification or development of an effective strategy for managing the ageing effects that they cause. The plant components proposed for the pilot studies have been chosen on the basis of their safety significance and their susceptibility to a wide range of ageing phenomena. They also represent a cross-section of NPP components and structures.

In the pilot studies it is planned to use the methodology for ageing management studies presented in Section 4. The results and experience gained from the pilot studies will have practical applications, notably in monitoring and preventive maintenance and also in the further development of relevant codes and safety criteria. Organizations in Member States should adopt this methodology if they wish to participate in these pilot studies.

5.1. TOPICAL AREAS PROPOSED FOR PILOT STUDIES

Four topical areas representing different types of safety functions and materials are proposed:

(1) Pressure boundary components of the reactor circuit: for example, reactor vessels, pressurized water reactor recirculation loops and piping.
(2) Electromechanical components of fluid systems: for example, pumps and valves in residual heat removal/shutdown cooling systems and emergency core cooling systems.
(3) Containment structures: for example, containment structures and buildings.
(4) Electrical system components: for example, electrical cables inside the containment.

5.2. SELECTION OF NPP COMPONENTS FOR PILOT STUDIES

Specific plant components were selected to satisfy the following requirements:

— one component to be from each of the four topical areas mentioned;
— each component to be important to safety;
— each component to be susceptible to a different type of ageing degradation;
— some results from previous ageing management studies to be available.

The intent of the last criterion is to keep the exercise within reasonable bounds and to enable each pilot study to make some immediate headway.

Components selected

The components selected for pilot studies were:

Topic 1: Pressure boundary components of the reactor circuit: The primary nozzle of a reactor pressure vessel.
Topic 2: Electromechanical components of fluid systems: A motor operated isolating valve as used in an emergency core cooling system or residual heat removal system.
Topic 3: Containment structures: A concrete containment building (which may incorporate such features as prestressed cable anchorages or reinforcement bars).
Topic 4: Electrical system components: Reactor instrumentation and control cables within the reactor containment.

Other international groups are already studying ageing degradation of reactor pressure vessels in general, including vessel internals and supports. However, the proposed pilot study of the primary nozzle of a reactor pressure vessel is intended to complement rather than to duplicate other work.

5.3. TECHNICAL ISSUES RELATING TO THE PILOT STUDIES

There are a number of technical issues which should be dealt with in the recommended pilot studies. They can be conveniently divided into common issues and issues specific to the selected topical areas.

Common issues

(1) What is the current understanding of relevant ageing phenomena and how are research results and operating experience being fed back and used in operational plants?

(2) What are the potential safety impacts of the ageing mechanisms identified if they are not adequately mitigated by maintenance, operating practices or replacement?

(3) What and how effective are the existing techniques used to monitor and to mitigate component ageing degradation?

(4) How effective are current procedures for predicting future component performance based on the evaluation and trending of data on component operation, maintenance, testing and inspection?

(5) At present, in-service monitoring often provides assurance only that the component will function under normal service conditions. What is being done to demonstrate (with confidence) that these components will function as required under abnormal and accident conditions?

(6) What methods and criteria have been developed to enable the remaining service lives (including required safety margins) of these components to be predicted?

Topical area specific issues

Topic 1: Primary nozzle of a reactor pressure vessel

- What are the current methods for assessing the integrity of the primary nozzle, with regard to the effects of ageing mechanisms such as thermal ageing, stress corrosion, corrosion fatigue and high cycle fatigue and their interactions?
- What are the capabilities and limitations of the assessment methods used?

- Are currently used techniques for surveillance of reactor operating conditions such as temperature, pressure and water chemistry adequate and representative for monitoring actual nozzle loading conditions?
- How effective are current in-service inspection programmes for the timely detection of ageing degradation in primary nozzles of RPVs? Are the associated evaluation methods capable of determining ageing degradation rates?
- What research is proceeding to develop or improve effective and practical testing and inspection procedures to better assess ageing degradation rates?
- Does this research deal adequately with all the identified shortcomings of the existing diagnostic methods?

Topic 2: Motor operated isolating valve

- Are existing in situ diagnostic techniques and maintenance practices capable of detecting significant ageing degradation of motor operated isolating valves, including valve bodies (for example, caused by erosion, corrosion, wear, vibration/fatigue and thermal embrittlement of electrical insulation) before failure?

Topic 3: Containment structures

- To what extent have effective procedures been developed for leak rate testing in order to evaluate containment performance throughout the service life of the plant?
- To what extent have methods been developed for monitoring any degradation of the containment function that could result from ageing degradation, e.g. of concrete to steel interfaces (including liners and penetrations), concrete to soil interfaces, prestressed tendons, rebars, corrosion, bursting forces or degradation of foundation supports?

Topic 4: Reactor instrumentation and control cables

- What are current practices for in situ monitoring of cables and are they capable of detecting significant ageing degradation of cable insulation?
- To what extent have methods and procedures been developed to assess ageing of cables and the evaluation of safe residual life?

Appendix I

EXAMPLES OF AGEING RELATED COMPONENT DEGRADATION AND FAILURE

— Failures of control rods to scram due to degradation of BUNA-N disc material of the scram pilot valve solenoids.
— Failures of cables, attributable to temperature induced accelerated ageing and degradation of cable insulation, resulting in loss of off-site power.
— Degradation of insulation of instrument cables due to oxidation and thermal embrittlement.
— Failures of inverters due to thermal degradation of capacitors, fuses and solid state devices.
— Degradation of bodies of motor operated valves due to cavitation induced erosion.
— Thimble tube thinning due to flow induced vibration and wear.
— Boric acid induced corrosion of the high pressure injection nozzle of the reactor coolant system.
— Fatigue cracks in pressurized surge lines induced by thermal stratification.
— Failure of steam generator tubes due to intergranular stress corrosion cracking, pitting, denting, fretting and wastage.
— Degradation of station batteries due to erosion of plate to bus bar connections.
— Failures of check valves due to wear, vibration and stress corrosion cracking.
— Erosion and vibration induced failures of emergency service water pumps.
— Damage to pipe supports due to vibration.
— Corrosion/erosion fouling reducing the heat transfer capability of service water system heat exchangers.
— Rupture of the carbon steel feedwater line caused by single phase erosion–corrosion.
— Wall thinning (metal loss of 1–9 mm per year) of carbon steel bodies of the boiler feed pump and valve caused by single phase erosion–corrosion.
— Rupture of Zircaloy pressure tubes caused by hydride blistering.
— Failures of primary pump motors due to degradation of high voltage epoxy mica insulation of stator windings caused by electrical stress (partial discharge).
— Failures of dousing system solenoid valves caused by degradation of elastomeric parts at high ambient temperature.
— Failures of electrical cable insulation caused by thermal embrittlement.

Appendix II

AGEING DEGRADATION MECHANISMS AND SUSCEPTIBLE MATERIALS AND COMPONENTS

Table I lists typical ageing degradation mechanisms and susceptible materials and components. The information is derived from the discussion of the American Society of Mechanical Engineers' Section XI Special Working Group Meeting on Plant Life Extension in 1987.

TABLE I. AGEING DEGRADATION MECHANISMS AND SUSCEPTIBLE MATERIALS AND COMPONENTS

Degradation mechanism	Susceptible materials and components
General corrosion, pitting, and wastage (low and high temperature)	Crevices and hideout regions, low and no flow components, safety injection systems, service water systems
Stress corrosion cracking on internal surfaces (low and high temperature)	Weld vicinity in components (off-normal chemistry conditions)
Stress corrosion cracking on external surfaces (chloride related; low and high temperature)	Components near leaking valves and in coastal plants (e.g. insulation)
Irradiation assisted stress corrosion	Reactor pressure vessels and internals
Erosion-corrosion (high temperature)	Steam piping and steam separation, heat exchanger (i.e. moisture separator reheaters), turbine blades
Crevice corrosion (low and high temperature)	Stagnant regions, weld vicinity, sleeved regions, welds with backing rings
Microbial influenced corrosion (low temperature)	Service water, heat exchangers, equipment where pressure tests are performed, equipment laid up, anchor bolts, diesel generators
Corrosion fatigue (low and high temperature)	Thermal mixing regions, especially carbon and alloy steels

TABLE I. (cont.)

Degradation mechanism	Susceptible materials and components
Fatigue (low and high temperature)	Rotating equipment supports and piping attached to large components
Weld related cracking (lack of fusion, hot ductility, ferrite depletion, crevice formation; high or low temperature)	Similar metal welds, wrought materials to castings, low ferrite filler joints, seam welds
Dilution zone cracking (high or low temperature)	Dissimilar metal welds, vessel to clad interface, nozzle to safe-ends, valves or pumps to pipe (carbon steel to stainless steel)
Low temperature sensitization (high temperature)	Stainless steel components, cast components
Thermal embrittlement (high temperature)	Ferritic stainless steels, cast stainless steels
Irradiation embrittlement	Reactor pressure vessel, internals and support structures
Hydrogen embrittlement (low temperature)	High strength, low alloy components, vessel cladding (ferrite phase), interface between vessel cladding and vessel, anchor bolts, vessel and pressurizer supports
Mechanical wear, fretting (low and high temperature)	Rotating equipment
Binding and wear	Components within pumps and valves
Creep and swelling (high temperature)	Vessel internals (radiation assisted)
Insulation embrittlement and degradation	Cables, motor windings, transformers
Thermal runaway (dielectric materials)	Capacitors, solid state devices
Partial discharges	Transformers, inductors, medium and high voltage equipment
Oxidation	Relay and breaker contacts, lubricants, insulation materials associated with electrical components

Appendix III

EXAMPLES OF SUMMARY RESULTS OF AGEING MANAGEMENT STUDIES FROM THE USNRC's NUCLEAR PLANT AGEING RESEARCH PROGRAMME

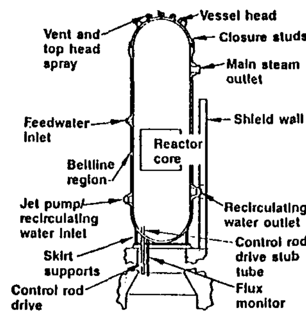
Figures 7–10 show summary sheets of results, requirements and recommendations from ageing management studies conducted under the USNRC's Nuclear Plant Ageing Research (NPAR) Programme for the following NPP components:

— boiling water reactor pressure vessels;
— light water reactor coolant pumps;
— motor operated valves.

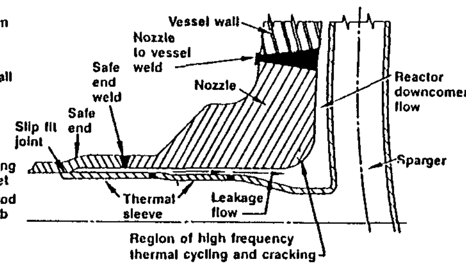
Note. *These examples are included for illustration and discussion purposes only. It is recommended that the Member State organizations participating in the pilot studies contribute more comprehensive data.*

Understanding and managing aging of BWR pressure vessels

Materials	Vessel	- Low alloy carbon steel SA-533B-1, SA-302B
	Cladding	- Type 308 SS and 309 SS
	Nozzles	- SA-508-2
	Safe Ends	- Type 304 SS, Type 316 SS, Inconel SB-166, Inconel SB-167, SA-508-1
	Thermal Sleeves	- Type 304 SS
	Closure Studs	- SA-540 Gr. B22 or B23
	Weldments	- SA-193 Gr. B7
Stressors and Environment	Operational transients, neutron flux and fluence, temperature, reactor coolant and preloads	



Typical BWR pressure vessel



Cross section of feedwater nozzle with cracking location

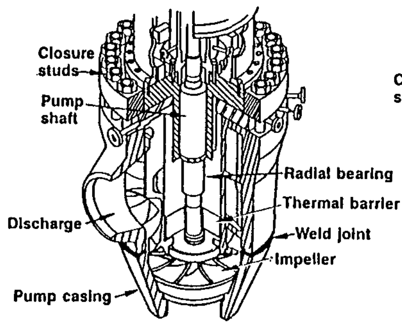
UNDERSTANDING AGING (Materials, Stressors, and Environmental Interactions)		MANAGING AGING		
Sites	**Aging Concerns**	**Inservice Inspection, Surveillance, and Monitoring**		**Mitigation**
		NRC Requirements	Recommendations	
Feedwater nozzles and safe end welds	High-cycle thermal fatigue caused by feedwater leakage Environmental fatigue	Volumetric examination of all nozzle-to-vessel welds and nozzle inside radius sections during each inspection interval (IWB-2500)	Use on-line fatigue monitoring (monitoring of pipe wall temperatures and coolant flows, temperatures, and pressures) Develop criteria for assessing high-cycle fatigue damage	Modify design, revise operating procedures, and remove feedwater nozzle cladding to prevent fatigue cracking
Recirculation inlet/outlet nozzles and dissimilar metal welds	IGSCC crack initiated in HAZ may propagate into base metal Environmental fatigue	Volumetric and surface examination of all dissimilar metal welds during each inspection interval (IWB-2500)	Develop on-line corrosion monitoring Evaluate long-term effects of hydrogen water chemistry	Implement hydrogen water chemistry to reduce IGSCC damage
Welds - Control rod drive stub tubes - Interior attachments	IGSCC crack initiated in HAZ may propagate into base metal by corrosion and/or environmental fatigue	Visual examination of all accessible interior attachment welds during each inspection interval (IWB-2500)	Develop robotics system for remote inspection probe positioning and scanning	

Beltline Region	Irradiation embrittlement - Chemical composition of vessel materials (Cu, Ni, P) - Drop in upper shelf energy (USE) - Shift in reference nil-ductility-transition-temperature (RT_{NDT}) - Welds are more susceptible than base metal - Flux is lower than that in PWR vessel Environmental fatigue	Surveillance program to assess shift in RT_{NDT} and drop in USE (10 CFR 50 App. H, Reg. Guide 1.99, Rev. 2) Damage evaluation (10 CFR 50 App. G) Pressure-temperature (P-T) limits during heatup, cooldown, criticality, and inservice leakage and hydrostatic pressure tests to prevent nonductile fracture (Tech. spec. requirement, 10 CFR 50 App. G.) [P-T limits are also applied to non-beltline region] Volumetric examination of all shell welds during each inspection interval (10 CFR 50.55a, IWB-2500, Reg. Guide 1.150, Rev. 1) Flaw evaluation (10 CFR 50.55a, IWB-3000) Leakage and hydrostatic pressure tests (10 CFR 50.55a, IWA-5000, IWB-5000)	Revise Reg. Guide 1.99, Rev. 2 to account for phosphorous when copper content is low Use state-of-the-art inspection techniques for improved reliability of defect detection, sizing, and characterization Develop robotics system for remote inspection probe positioning and scanning Include fracture toughness and tensile test specimens in surveillance program* Develop use of reconstituted and miniature specimens and accelerated irradiation of reconstitued specimens Use fatigue crack growth curves (ASME Section XI, Appendix A) Develop acoustic emission monitoring to detect crack growth (nonmandatory appendix is being developed by ASME Section XI)	Inservice annealing (ASTM E 509-86) Determine effects of annealing and reembrittlement rate Implement neutron flux reduction program
Closure Studs	Environmental fatigue - Preload cycles during head replacement Fretting	Volumetric and surface examination of all studs and threads in flange stud holes during each inspection interval (IWB-2500)		
External attachment welds such as skirt supports	Low-cycle thermal and mechanical fatigue	Volumetric or surface examination (IWB-2500)		

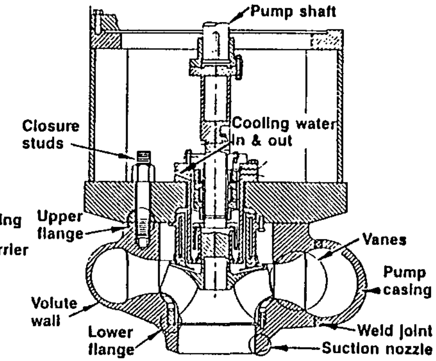
FIG. 7. The USNRC Nuclear Plant Ageing Research (NPAR) Programme: summary sheet on understanding and managing ageing of boiling water reactor pressure vessels.

Understanding and managing aging of LWR coolant pumps

Materials	Casing	- Statically cast SS Gr. CF8, CF8A, CF8M, or SA-508 with austenitic SS clad
	Closure Studs	- SA-193 Gr. B7 or SA-540 Gr. B23
	Cover Gasket	- Type 304 SS flexitallic (stainless steel-graphite-asbestos material)
	Shaft	- Type 304 or 316 SS
Pump Types	Westinghouse	- Type F
	Babcock & Wilcox	- Type F, Type E
	Combustion Engineering	- Type F, Type E
	General Electric	- Type C
Stressors and Environment	Temperature, operating transients, residual stresses, gasket leakage, alternating bending stresses, turbulent mixing of hot and cold coolant, and vibration	



PWR Type F coolant pump



Vertical cross section

PWR Type E coolant pump (locations of maximum stress intensity are circled)

Understanding Aging (Materials, Stressors, and Environmental Interactions)			Managing Aging		
	Sites	Aging Concerns	Inservice Inspection, Surveillance, and Monitoring		Mitigation
			NRC Requirements	Recommendations	
Casing	Cast SS base metal	Thermal embrittlement - Coolant temperature - Ferrite content and spacing - Chemical composition Fatigue at high stress intensity locations	Volumetric examination of all welds and visual examination of internal surfaces, in at least one pump casing during each inspection interval (10 CFR 50.55a, IWB-2500) Visual examination of external surfaces during system leakage tests and hydrostatic tests; these tests are performed during each refueling outage and each inspection interval, respectively	Characterize ferrite distribution and existing flaws in pump casing and welds Develop standards for allowable flaw sizes for pump casing base metal Develop techniques for monitoring actual degree of thermal embrittlement in pump casing Perform examinations of high stress regions	Use improved cover gaskets with better spring-back characteristics, proper gasket installation, and cleanliness control to prevent boric acid corrosion of closure studs Leave leak-off lines between inner and outer gaskets unplugged Install instruments on leak-off lines to detect leakage of reactor coolant Remove chrome plating on pump shafts
	Low-alloy base metal	Fatigue at high stress intensity locations			
	Welds	Fatigue at welds having high residual stresses or high stress intensities Thermal embrittlement			
	Welds with low ferrite content	IGSCC if sensitized and lower fatigue strength if microfissures are present			

Closure Studs		Boric acid corrosion caused by gasket leakage	Volumetric examination of all closure studs (on pump being examined) during each inspection interval (10 CFR 50.55a, IWB-2500)	Include visual examinations in inservice inspection requirements to detect corrosion wastage Use cylindrically guided wave technique to detect both corrosion wastage and cracks	
Shaft	Sites with high stress concentrations or residual stresses	High-cycle mechanical fatigue caused by alternating bending stresses		Evaluate use of modified cylindrically guided wave technique for shaft inspection	
	Near thermal barrier	High-cycle thermal fatigue caused by turbulent mixing			
	Chrome-plated shafts	Cracks in chrome plating may propagate in shaft by high-cycle mechanical fatigue			

FIG. 8. The USNRC NPAR Programme: summary sheet on understanding and managing ageing of light water reactor coolant pumps.

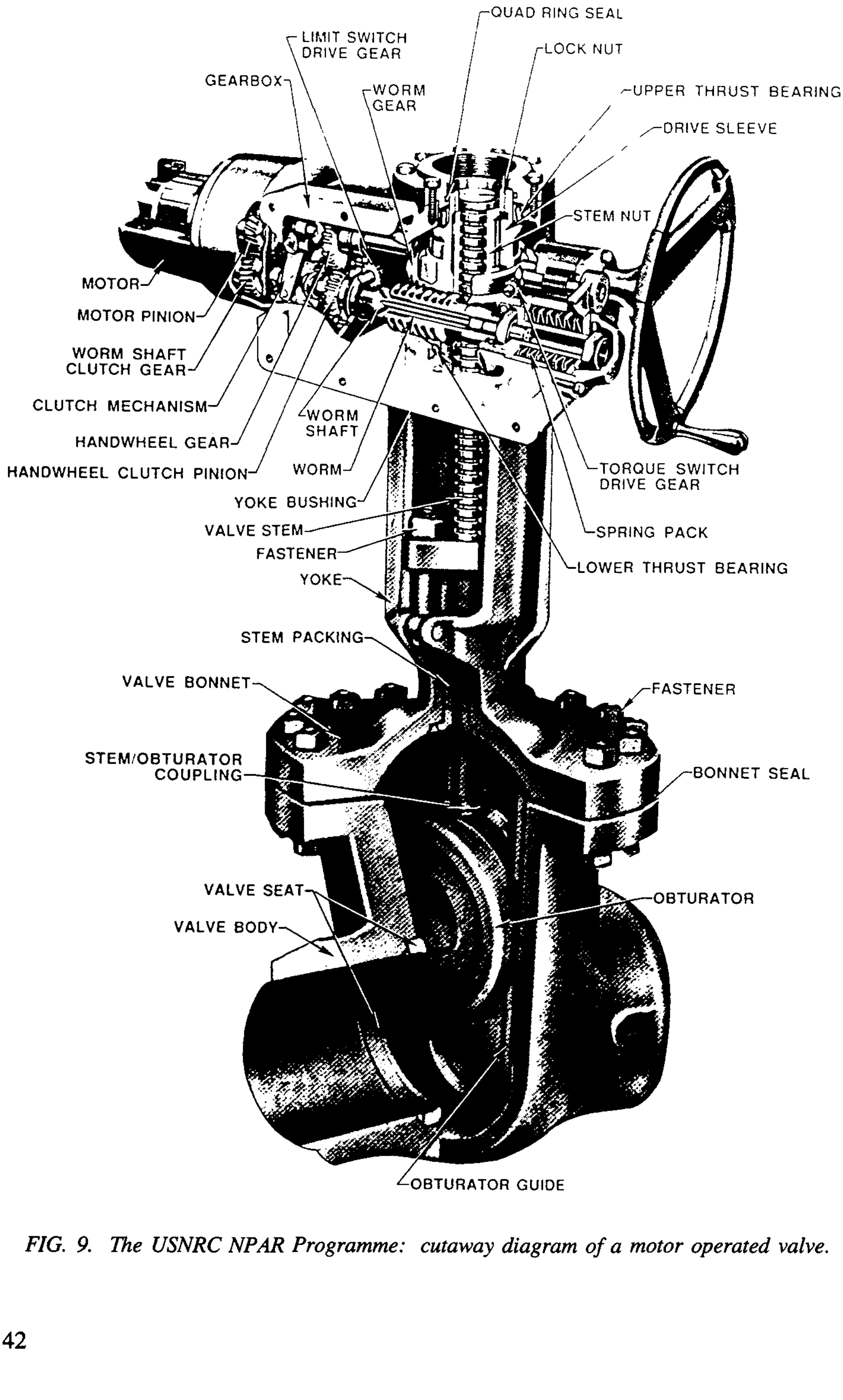


FIG. 9. The USNRC NPAR Programme: cutaway diagram of a motor operated valve.

UNDERSTANDING AGING (Materials, Stressors, and Environment Interactions)		MANAGING AGING	
Sites	**Aging Concerns**	**Inservice Inspection and Monitoring**	**Mitigation**
Motor Operator		NRC Requirements	
Gearbox assembly	Gear wear Shaft wear, distortion Fastener loosening Stem nut wear Stem lock nut loosening Spring pack response change Drive sleeve wear Clutch mechanism wear Seal wear,deterioration Bearing wear, corrosion Lubricant degradation, hardening	ASME Boiler and Pressure Vessel Code, Section XI, Subsection IWV A. Verify valve obturator position B. Measure stroke time C. Measure seat leakage	Implementation of improved condition monitoring methods, predictive and corrective maintenance programs, and replacement strategies
Electric motor assembly	Bearing wear, corrosion Insulation (electrical) breakdown	IE Bulletin 85-03	
Switches	Contact pitting, corrosion Gear/cam wear Insulation (electrical) breakdown Fastener loosening Grease hardening (limit switch)	Requests that utilities develop a program to ensure that MOV switch settings are selected, set, and maintained correctly to accomodate normal and abnormal events	
Valve (Gate valve)	Obturator wear, corrosion Obturator guide wear, corrosion Yoke bushing wear Valve stem wear, distortion Fastener loosening Valve seat wear, corrosion Bonnet seal deterioration Stem packing wear, deterioration		

FIG. 10. The USNRC NPAR Programme: summary sheet on understanding and managing ageing of motor operated valves.

Appendix IV

EXAMPLES OF CONDITION INDICATOR TRENDING AS A BASIS FOR MITIGATING COMPONENT AGEING

Figures 11–13 show illustrative examples of condition indicator trending for three representative NPP components:

— reactor pressure vessel;
— containment isolation valve;
— power transformer.

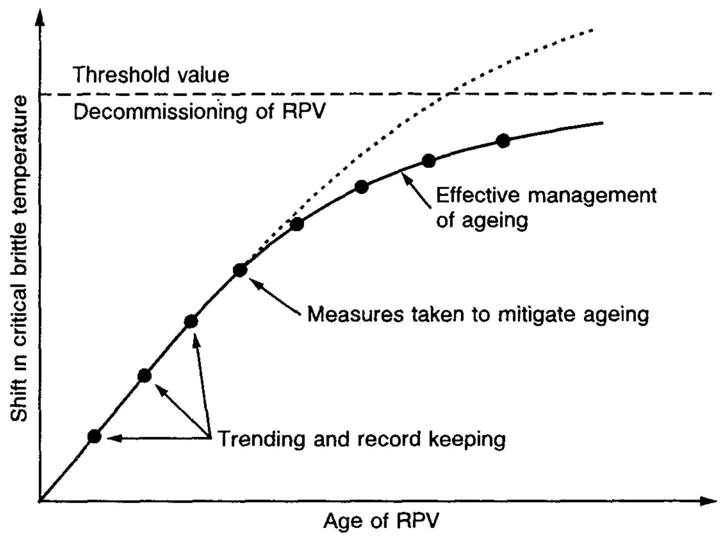


FIG. 11. Condition indicator trending for the reactor pressure vessel. The ageing mechanism is radiation embrittlement. The condition indicator is the shift in critical brittle temperature (determined by test results from surveillance specimens). Ageing can be mitigated by decreasing the neutron flux impinging on the reactor pressure vessel wall by fuel management and the installation of screens.

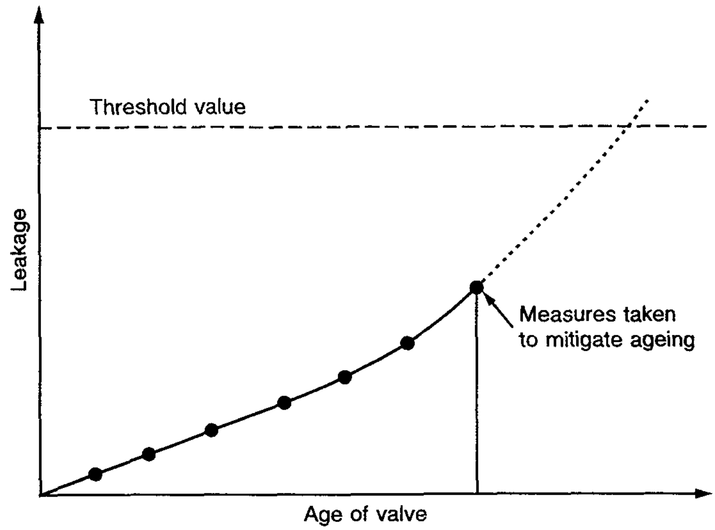


FIG. 12. Condition indicator trending for the containment isolation valve. The ageing mechanism is wear. The condition indicator is leakage in tightness tests. Ageing can be mitigated by repairing the sealing.

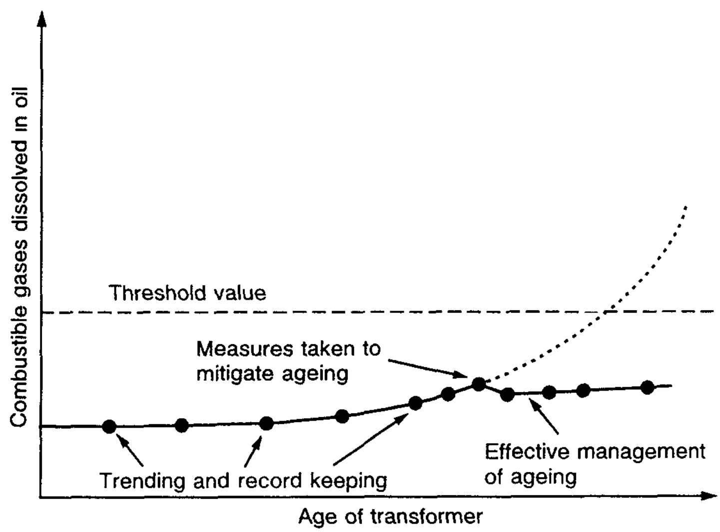


FIG. 13. Condition indicator trending for the power transformer. The ageing mechanism is thermal embrittlement. The condition indicator is dissolved gases in the mineral oil. Ageing can be mitigated by improving the cooling of the windings and reducing the transformer loads.

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