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No. NR-G-5.2

Guidelines for Ageing Management, Modernization and Refurbishment Programmes for Research Reactors

GUIDES

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GUIDELINES FOR AGEING MANAGEMENT, MODERNIZATION AND REFURBISHMENT PROGRAMMES FOR RESEARCH REACTORS

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IAEA NUCLEAR ENERGY SERIES No. NR-G-5.2

GUIDELINES FOR AGEING MANAGEMENT, MODERNIZATION AND REFURBISHMENT PROGRAMMES FOR RESEARCH REACTORS

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FOREWORD

The IAEA's statutory role is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". Among other functions, the IAEA is authorized to "foster the exchange of scientific and technical information on peaceful uses of atomic energy". One way this is achieved is through a range of technical publications including the IAEA Nuclear Energy Series.

The IAEA Nuclear Energy Series comprises publications designed to further the use of nuclear technologies in support of sustainable development, to advance nuclear science and technology, catalyse innovation and build capacity to support the existing and expanded use of nuclear power and nuclear science applications. The publications include information covering all policy, technological and management aspects of the definition and implementation of activities involving the peaceful use of nuclear technology. While the guidance provided in IAEA Nuclear Energy Series publications does not constitute Member States' consensus, it has undergone internal peer review and been made available to Member States for comment prior to publication.

The IAEA safety standards establish fundamental principles, requirements and recommendations to ensure nuclear safety and serve as a global reference for protecting people and the environment from harmful effects of ionizing radiation.

When IAEA Nuclear Energy Series publications address safety, it is ensured that the IAEA safety standards are referred to as the current boundary conditions for the application of nuclear technology.

Research reactors have played an important role in the development and application of nuclear technology in various fields of science and technology for over seven decades. Approximately 70% of the operating research reactors in the world are more than 40 years old. Although the operating lifetime of such facilities could reach 60 years or more, it is of paramount importance that adequate life management programmes addressing ageing management, modernization and refurbishment be established and implemented during the lifetime of the reactors. Considering the general trend of funding reductions for research reactors and limited replacement planning, the development and implementation of sound life management and operation and maintenance programmes are vital for optimizing the operational performance of existing research reactors and ensuring the cost effective completion of assigned missions. Many Member States are looking to the IAEA for guidance and information exchange on these topics.

This publication provides detailed information on methodologies to manage existing and potential ageing effects and degradation of the structures, systems and components of research reactors. It provides practical guidance on managing the effects of ageing on civil structures, on mechanical, electrical and instrumentation and control systems, and on components of research reactors that are important for safety and operation. It also provides information on how to establish an effective and systematic ageing management programme for research reactors. Research reactors often undergo modifications, modernizations and refurbishments during their lifetime. The publication also addresses the management of such activities. Several practical examples of successful ageing management programmes executed in operating research reactors are included as annexes to assist operating organizations in the establishment or implementation of similar programmes.

The IAEA thanks all the participants and their Member States for their valuable contributions, in particular D. Jinchuk (Argentina), D.V. Rao (India) and A. McIvor (Canada). The IAEA officers responsible for this publication were R. Sharma and R. Mazzi of the Division of Nuclear Fuel Cycle and Waste Technology and A. Shokr of the Division of Nuclear Installation Safety.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

For over seven decades, research reactors have played an important role in several fields of basic sciences; in the development of nuclear science and technology; in the production of radioisotopes for various applications; and in the development of human resources and skills for nuclear fields. According to the IAEA Research Reactor Database (RRDB)[1], by June 2023 a total of 223 research reactors were operational in 54 countries, of which almost half were more than 50 years old and approximately 20% were more than 60 years old.

Most of the operating research reactors are challenged by the negative impacts of ageing of structures, systems and components (SSCs). Ageing is a process in which the characteristics of SSCs change with use or time. Ageing management includes engineering, operations and maintenance actions such as detection, monitoring and mitigation of the ageing related degradation of SSCs. The information collected in the IAEA's Research Reactor Ageing Database (RRADB)[2] and in the Incident Reporting System for Research Reactors (IRSRR)[3] shows that ageing is one of the root causes of many events that have occurred at research reactor facilities.

Requirement 86 of IAEA Safety Standards Series No. SSR-3, Safety of Research Reactors [1], states in para. 7.120 that "A systematic approach shall be taken to provide for the development, implementation and continuous improvement of ageing management programmes."

As a result, many research reactor facilities have established, or are in the process of establishing, a proactive strategy and a systematic programme to manage ageing and to mitigate its impact on the safety and availability of the facilities. Overall, a large body of knowledge on ageing issues exists in many Member States. Collecting and sharing this information within the research reactor community helps to improve ageing management programmes (AMPs) by preventing the negative consequences of ageing for the safety, operability and lifetime of research reactors. It also can help operating organizations managing research reactors that have been in an extended shutdown state by ensuring that the required SSCs are maintained in a safe manner while awaiting a decision to bring these facilities back into operation or to proceed with decommissioning.

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1 See https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx

2 See https://nucleus.iaea.org/sites/rramp/Pages/Home.aspx

3 See https://www.iaea.org/resources/databases/irsni

Among the safety guides supporting the implementation of SSR-3 [1], the IAEA has published IAEA Safety Standards Series No. SSG-10 (Rev. 1), Ageing Management for Research Reactors [2], in which detailed information is presented on what has to be included in an effective AMP.

Considering ageing effects on the research reactor facility in general, and the materials of the core support structures in particular, information may be found in the IAEA's Research Reactor Material Properties Database (RRMPDB).[4] Moreover, a repository of global experience in managing ageing of SSCs is available in the RRADB, which contains ~300 reports with examples of affected systems, ageing issues, degradation mechanisms and remedial actions, and allows searching and filtering of the list of reports. Both databases are updated on a biennial basis.

In accordance with IAEA safety standards, in recent years Member States have adopted various approaches to prepare and implement an AMP for their facilities. Many operating organizations of research reactors have completed or are planning large capital projects at their facilities to address issues related to ageing, to fulfil new safety and regulatory requirements to improve performance, or to provide new products and services. Such projects can pose unique challenges to the operating organizations of research reactors, including the following:

— Resource mobilization (internal or external) to complete the various work stages of a refurbishment project (e.g. design, fabrication, procurement, installation);
— Implementation during shutdown periods to complete project activities, including decisions on whether to complete the work during one major shutdown or in stages over several outages;
— Planning and prioritization of the work to minimize required outage time;
— Management of the interruption of services for extended periods;
— Involvement of regulatory or other oversight bodies.

To address these issues, the IAEA has issued several publications, for example on the management of research reactor ageing [3], on recommended practices for the optimization of research reactor availability and reliability [4], on research reactor modernization and refurbishment [5], and on the implementation of specific ageing management, modernization and refurbishment projects performed by Member States [6]. The IAEA has also held several technical meetings on ageing management, refurbishment and modernization activities, for example in Daejeon, Republic of Korea (2013), in Brewster, Massachusetts,

[4] See https://www.iaea.org/resources/databases/research-reactor-material-properties-database

United States of America (2015), in Vienna, Austria (2017 and 2022) and on-line, in a virtual meeting organized jointly with the International Group on Research Reactors (IGORR)[5] (2021). The meeting participants presented their completed or ongoing projects in relation to ageing management for research reactors and recognized the need for a specific publication that would provide practical guidance on how to establish and implement an AMP and that would reflect good practices and provide examples of programmes that have been successfully implemented in different Member States.

1.2. OBJECTIVE

The objective of this publication is to provide practical guidance on establishing, implementing and improving ageing management, refurbishment and modernization programmes for a research reactor that is planned, under construction or in operation, taking into consideration the requirements established in SSR-3 [1] and the accompanying guidance in SSG-10 (Rev. 1) [2]. The publication also focuses on guidelines for addressing associated challenges, such as old designs and obsolete components and the retirement of experts in the design, manufacturing, maintenance and operation of research reactors. The publication employs a methodological approach, including distinct examples of how to establish and implement an AMP for research reactors. The information in this publication is intended to assist operating organizations responsible for research reactors, support organizations specializing in design or maintenance, and regulatory bodies.

Guidance and recommendations provided here in relation to identified good practices represent expert opinion but are not made on the basis of a consensus of all Member States.

1.3. SCOPE

This publication provides comprehensive guidance for those interested in establishing and implementing a systematic AMP for their research reactors, whether planned or under construction, in operation or under permanent shutdown, or awaiting a decision to resume operation or to undergo decommissioning. It presents the views of contributors regarding ageing management for research reactors, together with examples of successful execution of projects for ageing management, refurbishment and modernization, and is expected to be of interest

[5] See https://www.igorr.com/

to organizations and stakeholders involved in the safety, operation and utilization of research reactors.

1.4. STRUCTURE

This publication has five sections, one appendix and four annexes. This section provides an introduction to and background for AMPs for research reactors and describes the objective and scope of the publication. Section 2 provides information on factors to be considered as applicable to ageing management for research reactors. Section 3 provides information on establishing and implementing an AMP following the guidance in SSG-10 (Rev. 1) [2]. Section 4 provides information on ageing management for specific SSCs commonly used in research reactors. Section 5 provides information on the management of modification, modernization and refurbishment projects. The appendix contains detailed information on the maintenance, testing and inspection of several electrical and mechanical components commonly used in research reactors. The four annexes provide examples of the successful implementation of AMPs for research reactors in Member States. The text and figures in the annexes were provided by the respective contributors.

2. FACTORS TO BE CONSIDERED FOR AN AGEING MANAGEMENT PROGRAMME

2.1. GENERAL

The probability of an SSC failure resulting from ageing effects normally increases with the time of exposure to service conditions, unless appropriate countermeasures are taken. The objective of an AMP is to determine and implement the appropriate countermeasures. The programme has to include activities such as identification of applicable degradation mechanisms, detection and trending of ageing effects, assessment of remaining life, and protection, repair, refurbishment and replacement, all of which are very similar to other activities carried out during routine maintenance and testing or when a modification project takes place (see IAEA Safety Standards Series Nos SSG-81, Maintenance, Periodic Testing and Inspection of Research Reactors [7] and SSG-24 (Rev. 1), Safety in the Utilization and Modification of Research Reactors [8]). However, it is paramount to distinguish between these similar activities, because ageing management necessitates a methodology that can be used in the detection and evaluation of SSC degradation observed under service conditions and leads to the application of countermeasures for the minimization and mitigation of the ageing effects. One approach to this methodology is a determination that the SSCs can perform their intended functions during their service life and under the service conditions. This can be achieved by appropriately selecting the SSCs that have to be subjected to surveillance activities and included in a long term AMP through data collection and evaluation of the potential ageing effects. Those activities will be accompanied by countermeasures for the minimization and mitigation of the ageing effects to ensure an adequate level of safety, availability and reliability for the reactor facility.

To manage ageing, it is necessary to understand how ageing affects the components and materials that are used to achieve the overall safety and operability of the reactor. This topic is discussed in detail in the following sections, along with an overview of current trends and future activities in research on ageing.

2.2. DEFINITION OF AGEING

Ageing is defined as a "General *process* in which characteristics of a *structure*, *system* or *component* gradually change with time or use" [9]. This process eventually leads to degradation of the characteristics of materials subjected to normal service conditions, including normal operation and anticipated operational occurrences under which the SSCs are required to operate. In a research reactor facility, the effects of ageing may result in the reduction or loss of the ability of SSCs to function as intended by the design. The safety, operation and utilization of the facility may be affected unless corrective measures have been taken to control the ageing process.

2.3. DEGRADATION MECHANISMS AND AGEING EFFECTS

Consideration of operating conditions and obsolescence, as well as the deterioration of material properties, is essential for an understanding of the degradation mechanisms and ageing effects.

2.3.1. Operating conditions and obsolescence

The following factors that contribute to ageing through physical and chemical processes (degradation mechanisms) [10] affect material properties and/or functional capabilities:

(a) Stress and/or strain;
(b) Fatigue;
(c) Temperature;
(d) Radiation;
(e) Humidity;
(f) Wear;
(g) Corrosion or erosion;
(h) Changes in the dimensions or position of individual parts of assemblies;
(i) Vibration.

In addition to these service conditions, the following factors that are unrelated to physical or chemical processes can lead to ageing effects and affect the safe and reliable operation of the research reactor:

(1) Technology changes;
(2) Safety requirements changes;
(3) Obsolescence of components;
(4) Out of date documentation;
(5) Inadequacies of design;
(6) Improper maintenance or testing.

Distinct categories of operating conditions and obsolescence are further discussed in Sections 2.5 and 2.6.

2.3.2. Degradation of material characteristics

The main impact of the ageing process is the degradation of material characteristics. The degradation may be reflected by the following:

(a) Changes in physical properties (e.g. ductility, strength, density, dimensions, colour, thermal conductivity, electrical conductivity);
(b) Changes in chemical properties (e.g. ionization caused by irradiation, reaction with contacting fluids);
(c) Material damage (e.g. breakage, cracks, surface deterioration);

(d) Performance deterioration of SSCs (e.g. calibration change of instruments, equipment not delivering design parameters).

2.4. SAFETY REQUIREMENTS AND AGEING

The safety of a research reactor requires that provisions be made from the design stage and throughout the lifetime of the reactor, including decommissioning, to facilitate the ageing management of its SSCs to ensure (i) continued adequacy of the safety level, (ii) reliable operation of the reactor and (iii) compliance with the operational limits and conditions.

2.4.1. Safety objective

Paragraph 2.1 of IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles [11], states:

> "This fundamental safety objective of protecting people — individually and collectively — and the environment has to be achieved without unduly limiting the operation of facilities or the conduct of activities that give rise to radiation risks. To ensure that facilities are operated and activities conducted so as to achieve the highest standards of safety that can reasonably be achieved, measures have to be taken:
>
> (a) To control the radiation exposure of people and the release of radioactive material to the environment;
> (b) To restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation;
> (c) To mitigate the consequences of such events if they were to occur."

To achieve this objective, several safety principles and requirements are utilized in the design stage, and these, as well as additional measures, are utilized during reactor operation. These are, inter alia, defence in depth, reliability, safety analysis, quality assurance and regulatory supervision, including the review and assessment of the relevant associated safety documentation prepared by the operating organization, as defined in SSR-3 [1].

The examples provided in Sections 2.4.2–2.4.4 from Ref. [3] elaborate on some of the areas where compliance with safety principles and requirements might be compromised owing to the effects of ageing.

2.4.2. Ageing and defence in depth

Defence in depth is usually achieved by a system of multiple barriers (see SSR-3 [1] and SSG-10 (Rev. 1) [2]). The integrity of such a system can be impaired by the failure of one or more of these barriers. The ageing process may lead to an increase in the probability of failure of a barrier component and ultimately to the failure of the barrier. An example of the effect of ageing on defence in depth is as follows. A release of fission products from the fuel to the environment is prevented by the fuel matrix, the fuel cladding, the reactor pool and the reactor (confinement) building. Cracking of the concrete of a confinement building as a result of environmental conditions over a long period of time could reduce the ability of the building to prevent a release of radioactive material.

2.4.3. Ageing and reliability

The ageing of components may lead to an increase in the failure probability of these components and a decline in the availability of the reactor. In most instances, redundancy in safety related systems will help to prevent the safety of the system being compromised. However, even those systems that incorporate redundancy may, of course, age, affecting reliability. For example the reactor nuclear instrumentation system, which is designed to shut down the reactor, may be a three channel system that requires the simultaneous action of two channels for shutdown, with a required reliability of 1×10^{-4} failures per demand. Ageing of the components may reduce the reliability of the system to 1×10^{-3} failures per demand.

2.4.4. Ageing and advances in technology and safety requirements

During the lifetime of a research reactor, obsolescence or the lack of vendor support, including the unavailability of spare parts, or the development of new technologies and products may lead to the replacement of old technologies and components with new ones. Advances in safety concepts might require changes in hardware or software and might interfere with the routine operation of the reactor. Sometimes remedial activities related to the above changes are identified as backfitting activities (for further details, see Refs [5, 6]). Therefore, modernization and refurbishment processes are often implemented. The management of such programmes is addressed in Section 5.

2.5. SERVICE CONDITIONS AND AGEING

Ageing effects are normally discussed in terms of undesirable effects or failures. The basic causes of ageing effects are often service conditions, including operating conditions that support the actuation of the degradation mechanisms leading to these effects. Service conditions and degradation mechanisms lead to undesirable phenomena or failures due to ageing. Sections 2.5.1–2.5.3 present general considerations associated with three main categories of service conditions, as presented in Refs [2, 3].

2.5.1. Normal operation

The levels of various parameters such as radiation, temperature or pressure in normal operating conditions will affect the physical properties of a material. Radiation affects components in and outside the reactor core. Other components may be affected by radiation from radioactive materials circulating with the coolant. While the effects of temperature and pressure are more pronounced in power reactors, they are also present in research reactors in components such as sealing gaskets. Cycling temperature or pressure variations may accelerate deterioration. Table 1 in Section 2.6 provides a summary of information on specific degradation mechanisms.

2.5.2. Anticipated operational occurrences

Following anticipated operational occurrences (e.g. fire, flooding, overheating, power excursions), an acceleration of ageing effects may occur. It is advisable to investigate and take corrective actions to prevent or mitigate accelerated ageing following such occurrences. Table 2 in Section 2.6 summarizes information on these conditions and induced degradation mechanisms.

2.5.3. External conditions

External environmental conditions include meteorological related conditions, such as humidity, excessive rain, frost and wind, as well as site conditions, such as salinity, sand, dust or the presence of chemical agents. The general effects of these conditions on the equipment exposed to them are corrosion, erosion or the occurrence of undesirable chemical reactions. Table 3 in Section 2.6 summarizes information on these ageing mechanisms and conditions.

2.6. PHYSICAL FACTORS OF AGEING

Sections 2.6.1–2.6.6 provide an overview of the general effects (physical changes) of ageing (consequence/failure) by several mechanisms, which may be induced by specific service conditions on the materials, components and systems of a research reactor [3]. These sections deal with several ageing related problems that would be expected for different service conditions. If several of these service conditions or mechanisms exist simultaneously, the ageing process may be accelerated. The RRADB and the RRMPDB provide specific case studies on the physical ageing of research reactor SSCs. Tables 1–3 provide a summary of the ageing effects with respect to the service conditions — see also SSG-10 (Rev. 1) [2].

TABLE 1. EFFECTS OF AGEING FOR SEVERAL NORMAL OPERATING CONDITIONS

Condition	Degradation mechanism	Consequence/effect/failure
Radiation	Change of properties	— Chemical decomposition — Strength change — Ductility change — Swelling — Resistivity change — Burnup
Temperature	Change of properties	— Strength change — Resistivity change — Ductility change — Colour change — Change in form of structure
Stress (pressure)	Creep	Changes of geometry (e.g. breakage or collapse) of structure
Cycling of temperature, flow and/or load	Motion	— Displacement — Change of position or set point — Loose connection — Material damage (cracks)
Flow induced vibrations	Fatigue (low or high cycle)	— Break, collapse — Deformation — Material damage (cracks)

TABLE 1. EFFECTS OF AGEING FOR SEVERAL NORMAL OPERATING CONDITIONS (cont.)

Condition	Degradation mechanism	Consequence/effect/failure
	Wear	— Deterioration of surface — Change of dimensions
Flow	Erosion	— Strength change
Fluids chemistry	Corrosion or galvanic action	— Release of radioactive material — Strength change — Deposition of particles — Short circuits — Leakage

TABLE 2. EFFECTS OF AGEING FOR ANTICIPATED OPERATIONAL OCCURRENCES

Condition	Degradation mechanism	Consequence/effect/failure
Power excursion	Thermal and/or mechanical stresses	— Deterioration of fuel and core components — Accelerated ageing of core components
Unbalanced control rod positions	Thermal stresses	— Reduction of strength — Accelerated ageing
Power–flow mismatch (error in fuel loading)	Thermal stresses	— Reduction of strength — Accelerated ageing
Primary pump failure	Thermal and mechanical stresses	— Accelerated ageing
Erroneous maintenance or operation	Mechanical damage and adverse chemical conditions	— Deterioration of systems — Corrosion — Accelerated ageing

TABLE 3. EFFECTS OF AGEING FOR SEVERAL EXTERNAL/ ENVIRONMENTAL CONDITIONS

Condition	Degradation mechanism	Consequence/failure
Humidity, salinity	Corrosion/ galvanic cells	— Leakage — Release of radioactive material — Strength reduction — Short circuits
Chemical agents	Chemical reactions	— Corrosion — Deterioration of SSCs
Wind, dust, sand	Erosion and deposition	— Strength reduction — Deterioration of surface — Malfunction of mechanical and electrical components — Short circuits
Fire	Excessive heat, smoke and reactive gases	— Reduction of strength — Corrosion
Flooding	Deposition and chemical contamination	— Corrosion

2.6.1. Radiation effects

The effect of neutron irradiation on metals is mainly an increase in the yield and in the ultimate tensile strength and a reduction in toughness, resulting in embrittlement. Such effects can lead to a brittle fracture of the material under high stress conditions [12, 13]. A common example in research reactors is the transmutation of aluminium to silica under neutron irradiation and the resultant changes in the properties of the aluminium. In commonly used materials, such as boron or beryllium, the generation of helium within the metal matrix leads to changes in material properties and swelling [14]. Swelling is particularly important in reactor control devices made of boron compounds or beryllium, used mainly as reflector material. Fast neutron irradiation of graphite causes displacement of lattice atoms and leads to graphite growth and distortion [14]. The Wigner effect in graphite is also a problem in some high power research reactors, potentially releasing sudden energy under given circumstances. The crosslinking of polymers and elastomers is affected by radiation effects (gamma, neutrons), resulting in a change in properties.

Concrete is traditionally used as a shielding material. The effect of neutron irradiation on concrete is mainly seen on the reinforcement metals and aggregates used in it [15]. Gamma heating could lead to loss of moisture, resulting in undesirable changes in concrete properties. However, severe damage from radiation is not expected under most research reactor operating conditions because the concrete is not usually in a high level radiation field.

Electrical and electronic equipment (e.g. coaxial or other cables) is generally located in low level radiation fields. Some of the detectors could be located in higher level radiation fields. The effect of ionizing radiation may generally lead to a deterioration of the insulation of cables beyond a threshold value. The AMP needs to take this into account and plan suitable inspection, testing and replacement [16, 17].

All organic materials and glass are sensitive to radiation and need to be carefully selected and monitored during use. More information on materials specific to research reactors is available in the RRMPDB and the RRADB.

2.6.2. Temperature and pressure

Temperature affects all SSCs to some extent. Attention needs to be paid to the proper cooling of experimental facilities and reactor structures, such as thermal shields, thermal columns, irradiation facilities and concrete shields, as well as to electrical and instrumentation cables, which may be in unventilated hot areas. A temperature above 60°C may cause degradation of concrete by dehydration, with a corresponding loss of integrity and neutron shielding effectiveness. Elevated temperature in polymers results in hardening or a loss in tensile strength and elasticity, even at the temperatures associated with research reactors.

High pressure and high temperature irradiation loops in research reactors have the same ageing effects as those of nuclear power plants and need to be treated accordingly. With cold neutron sources in research reactors, effects such as nil ductility transition in the metals, in particular in stainless steels, need to be considered.

Research reactors operate at much lower pressure than power reactors. Therefore, pressure alone does not usually impose high stress on components in these reactors. Local high stress areas are to be considered separately. Special care has to be taken with experimental devices operated at high temperature and/or pressure.

2.6.3. Vibration and cyclic loading

Vibrations and cycling of pressure, flow or temperature develop loading stresses that may cause cracking of material and eventually a fatigue fracture [18]. Vibrations may cause degradation of electronic components and instrumentation, and vibration associated with the integrity of bonds and seals may be an important factor in their premature failure. A change of position or of a set point in instruments is another phenomenon connected to vibration. Repeated relative motion of adjacent parts may result in fretting or wear.

2.6.4. Corrosion

Corrosion is the reaction of base material with its environment, leading to material loss with surface degradation and loss of strength. Some types of corrosion (e.g. intergranular corrosion, stress/strain corrosion, corrosion fatigue) lead to loss of strength through crack propagation and growth. Another effect of corrosion is the deposition of particles (corrosion products) in vulnerable places (e.g. valve seats) that impair the function of a component. These particles may contain radioisotopes, which increase the radiation dose to operating personnel. As corrosion products occupy a larger volume than that of the metal itself, filling of crevices and narrowing of passages can also occur. Corrosion of reinforcing bars in concrete causes them to swell and can result in cracks or spalling. The following are common types of corrosion that research reactor SSCs are likely to encounter:

— Uniform corrosion attack;
— Local corrosion attack (galvanic cells);
— Selective corrosion attack, especially intergranular corrosion;
— Stress/strain corrosion cracking;
— Corrosion fatigue;
— Corrosion erosion.

2.6.5. Erosion

Operational conditions such as the high velocity of coolant fluid and of dissolved and suspended matter may cause erosion in equipment such as pipes and heat exchangers. Erosion results in the deterioration of surfaces and loss of material and a consequent reduction in thickness. Changes in the environment (e.g. an increase in silt level) and service conditions (e.g. an increase in velocity caused by a reduction in the flow area) may lead to increased erosion of SSCs.

Environmental conditions such as high winds and sandstorms may cause erosion in outside structures.

2.6.6. Other chemical reactions

Some environmental conditions, such as an increase in the concentration of gaseous impurities like ozone, nitrogen oxides and sulphur oxides in air, may lead to chemical reactions with structural materials, causing a deterioration of SSCs. The use of chemicals, such as the acids or alkalis typically used in research reactors in water purification systems, may cause damage to equipment. Special care has to be taken when irradiating capsules containing materials such as copper or mercury, which may cause strong corrosion or the formation of amalgamates, respectively, in aluminium alloys. Sea water is highly corrosive and causes biofouling. Suitable measures, such as the periodic chlorination of sea water to prevent biogrowth, have to be in place.

2.7. NON-PHYSICAL FACTORS OF AGEING

Non-physical ageing occurs when SSCs become out of date in comparison with current technology, knowledge, standards and regulations, or when documentation needs updating (see Sections 2.7.1–2.7.5) [3]. Table 4 summarizes information on the various aspects of non-physical ageing.

TABLE 4. EFFECTS OF AGEING FOR SEVERAL NON-PHYSICAL CONDITIONS

Condition	Effect	Consequence/failure
Technology progress	Shortage of spare parts, disappearance of suppliers	— Maintenance difficulties
Change of safety standards	Obsolescence of existing safety components and systems	— Interference with operation — Modification of safety related components and systems
Out of date documentation	Incomplete updating	— Incomplete information

2.7.1. Changes in technology

Research reactors are built in accordance with the standards and with the equipment available at the time of construction. For some older research reactors, technology, especially of electronics, has progressed since their design and construction. Even if the original instrumentation and control systems of the reactor still function well, obtaining spare parts may become difficult. This may make it necessary to modernize the entire instrumentation and control system in order to facilitate a proper maintenance programme. IAEA Safety Standards Series No. SSG-37 (Rev. 1), Instrumentation and Control Systems and Software Important to Safety for Research Reactors [19], provides guidance on this matter.

2.7.2. Changes in safety requirements

Considering the time that has elapsed since the construction of most of the fleet of research reactors, many safety standards have been revised and include new safety requirements (see, for example, SSR-3 [1]). Therefore, modification of the hardware and updating of the documentation for the reactor have to be considered. Such modifications are usually called backfitting activities. Moreover, lessons identified from accidents and incidents that have occurred over many decades of operation also contribute to safety requirement changes. The AMP needs to take this into account.

2.7.3. Out of date documentation

The utilization of the reactor demands modifications and changes of experimental devices that have to be reflected in any relevant documentation. The integrated management system for a research reactor needs to include a process to ensure that any design changes include revisions to the documentation. A good AMP includes a comprehensive review of documentation with safety significance, and supports the updating of safety and operational documents, drawings, specifications and other documentation.

Engineering drawings are sometimes available only as whiteprints or blueprints. As they are sensitive to sunlight, these print forms fade over time even if properly stored. In addition, the substrate (paper) degrades with use. A good practice is therefore to store all engineering information as electronic media, keeping in mind their technological evolution.

2.7.4. Inadequacies in design

Inadequate design, such as the selection of improper materials or inaccessibility for inspection and repair, could also contribute to accelerated ageing effects. To overcome the effects of inadequate design, an AMP has to include measures such as changes in the operating conditions, for example a decrease of reactor power to lower the rate of ageing, or more frequent inspections, tests and analyses.

2.7.5. Improper maintenance and testing

Improper maintenance and testing may add to the severity or rate of ageing effects. For example, increased pressure on bearings or excessive tensioning of retaining bolts could accelerate wear. Testing too frequently or using test procedures that are not in accordance with the design and/or the manufacturer’s recommendations could have detrimental effects on SSCs. The use of trained staff is important. Maintenance and testing records need to be appropriately generated and retained.

2.8. AGEING ISSUES FOR RESEARCH REACTORS

Research reactors have some specific issues related to ageing that are distinct from those encountered at nuclear power plants. Operating organizations of research reactors have been dealing with such issues for many years, initially as a response to actual issues in specific reactors and more recently within systematic AMPs.

The following list identifies the main items specific to AMPs for research reactors:

(a) Degradation of the aluminium reactor tank and other aluminium components [20];
(b) Effects of neutron and gamma radiation in graphite and beryllium (reflector and moderator materials);
(c) Obsolescence of electronic equipment, particularly for old research reactors;
(d) Ageing of experimental and irradiation facilities.

The first item (a) on the ageing effects in aluminium components is unique to research reactors, and more information is available in the RRMPDB.

In addition, AMPs for research reactors include some aspects that are similar to those encountered at nuclear power plants, such as the following:

— Corrosion of cooling and other system components;
— Deterioration of heat exchanger tubes;
— Degradation of cooling towers;
— Degradation of concrete structures;
— New safety requirements and/or regulations.

The rate of degradation for many mechanisms in research reactors might not be as high as in nuclear power plants, but in the light of the specificities of research reactors, such as a much higher frequency of shutdowns and power variations and the age of a specific research reactor, appropriate measures need to be in place to counter the effects of ageing.

3. DEVELOPING AN AGEING MANAGEMENT PROGRAMME

3.1. INTRODUCTION

An AMP has to be developed and applied during all stages of the lifetime of a research reactor, including the design stage (see SSR-3 [1] and SSG-10 (Rev. 1) [2]). An AMP for research reactors needs to include the following elements:

(a) Administration and organization;
(b) Screening and selection of SSCs;
(c) Identification and understanding of applicable degradation mechanisms;
(d) Detection, monitoring and trending of ageing effects;
(e) Collection of relevant data and evaluation;
(f) Minimization and mitigation of ageing effects;
(g) Acceptance criteria;
(h) Assessment and prediction of residual life, including time-limited ageing analysis;
(i) Corrective actions;
(j) Review, including experience feedback and modifications;
(k) Documentation and records.

3.2. ADMINISTRATION AND ORGANIZATION

The operating organization of a research reactor holds the primary responsibility for the safe and reliable operation of the reactor at every stage of its life cycle. Effective AMP implementation requires the use of a systematic and proactive approach that provides a framework and organizational structure for administering and managing the programme and for coordinating with all other programmes, processes and activities. An AMP has to be part of the integrated management system of the operating organization (see IAEA Safety Standards Series No. GSR Part 2, Leadership and Management for Safety [21] and Ref. [22]). The operating organization needs to establish a competent body for managing the AMP, with responsibility for the development, implementation, review and continuous improvement of the AMP, including the following:

(a) A clear strategy to be adopted by senior management;
(b) A programme commitment, policy and expectations;
(c) Appropriate organizations and technical and administrative processes;
(d) Availability of proper tools and resources.

The allocation of decision making authority, governance, ownership, and administrative duties related to the AMP has to be assigned to specific individuals within the owner/operating organization. These individuals will have distinct roles and responsibilities for decision making, as well as for governing, implementing, maintaining and enhancing the AMP across various levels. The structure of the competent body needs to include at least a decision making authority, a programme manager, a coordinator, a reviewer, an auditor and a reporting authority.

3.2.1. Planning

Planning is one of the key elements of an effective AMP. The planning includes the needs and scope of the tasks, resources and a time schedule. The task management process has to provide the tasks and allow for their execution in an efficient and timely manner and include the necessary competences, skills, methods, tools, information exchange, hold, review and check points and verifications, as well as overall coordination of simultaneous activities to optimize schedule and resource utilization.

3.2.2. Communication

The communication and exchange of information on activities plays an important role in the success of the AMP. Therefore, timely, clear and consistent communication by the senior management is a key aspect of an effective programme.

3.2.3. Training and qualification

A structured training system is required to ensure awareness, understanding and interpretation of the AMP in the planning and performance of tasks, as well as in the preparation and implementation of procedures for those tasks. Guidelines on this subject can be found in IAEA Safety Standards Series No. SSG-84, The Operating Organization and the Recruitment, Training and Qualification of Personnel for Research Reactors [23]). The training programme will ensure that the plant and/or project personnel and contractors who are preparing, performing and monitoring tasks, including those who are administering and maintaining the programme, have the necessary skills, knowledge and competences to carry out the tasks to the required level and extent. Qualification and/or certification is an integrated management system process that grants permission to individuals to assume certain roles and responsibilities and perform certain roles or tasks based on the skill, knowledge and competence level that is necessary for correct performance.

The training programme and qualification and/or certification processes need to include the following aspects:

(a) Training and qualification objectives with audiovisual examples from operating experience and lessons identified;
(b) Training needs and qualification requirements for individuals and organizations according to their roles and responsibilities;
(c) Objectives, policies and procedures for the AMP;
(d) Training methods, for example classroom lectures, reading material, walkthroughs and direct observations, knowledge transfer by mentors, mock-ups, computer based training;
(e) Periodic evaluation of training adequacy and effectiveness, undertaken where possible by persons other than those directly responsible for the training.

3.3. SCREENING AND SELECTION OF STRUCTURES, SYSTEMS AND COMPONENTS

Different screening methodologies may be accepted by the regulatory body if they are carried out in accordance with the established safety requirements and recommendations (see SSR-3 [1] and SSG-10 (Rev. 1) [2]). In any case, the specific screening methodology used has to be justified and documented. A systematic screening process during all stages of the life cycle is to be used to assess how ageing or obsolescence of SSCs may have an impact on the safe operation of a research reactor. The maintenance programme of any research reactor includes many SSCs, and not all of them may be included in an AMP. Screening of the SSCs for an AMP needs to be performed in a manner that ensures the safety and reliability of the research reactor on a long term basis. Therefore, it is recommended that two factors are used to determine the applicability of the AMP to SSCs: (i) impact on safety and (ii) impact on the ability to achieve the mission outcomes for the research reactor.

As an input to the screening process, a complete list of SSCs at the facility, including experimental and other associated facilities, is to be compiled. For research reactors, this list is typically developed during the design stage and compiled in the safety analysis report and other design documents. For old reactors, the list of SSCs might be a later regulatory obligation for renewal of the licence. In any case, the list of SSCs has to be reviewed periodically for completeness. The effectiveness of the SSC screening process will be contingent upon the knowledge and experience of those personnel who are establishing and implementing an AMP.

3.3.1. The first stage of the screening process

SSG-10 (Rev. 1) [2] provides guidance on the screening process for SSCs for research reactor AMPs. The screening process is based on the safety significance of SSCs. In order to also ensure high availability of the research reactors, the impact of non-availability of SSCs on research reactor operation also has to be taken into account.

As an example, the first stage in preparing a screening process model is to evaluate the list of SSCs against the categories of two parameters: safety impact and mission impact. Three categories of safety impact can be used — high, medium and low — based on the safety significance of the SSC, with a low safety rating having little or no safety impact. The safety impact is based on a determination of whether a failure could lead directly or indirectly to the loss or impairment of a safety function required during normal operations, anticipated operational occurrences and accident conditions. Failure of an SSC, or unavailability due to component obsolescence, could also lead to the inability to meet the mission outcome for the research reactor, for example by forcing an outage that prevents the conduct of important experiments or that interrupts the radioisotope production process.

Although it is recognized that safe operation is inherently a mission objective for research reactors, the mission impact has to be evaluated independently of the safety significance. Two categories of mission impact can be used — high and low. The thresholds for defining the categories for safety impact or mission impact are to be determined by the operating organization, so that the SSC screening process will be meaningful and relevant.

A suggested applicability matrix for ageing management is shown in Fig. 1. The SSCs of high safety significance, independently of mission impact, will be screened for ageing management. Additionally, the SSCs with high mission impact and medium safety impact are to be subjected to further ageing management evaluation. The proposed model recommends that a case by case graded screening approach be applied to the remaining SSCs when considering the accuracy and number of the measurements, the monitoring systems and data processing models and tools. The management has to define and bear the responsibility for the graded application, recognizing that a graded approach is intended to apply limited resources to the most important activities for an effective AMP in accordance with IAEA Safety Standards Series No. SSG-22 (Rev. 1), Use of a Graded Approach in the Application of Safety Requirements for Research Reactors [24].

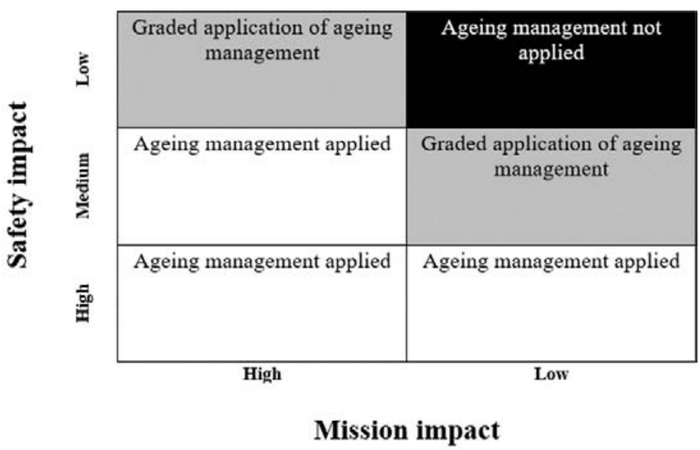

FIG. 1. Applicability matrix for an ageing management programme based on safety impact and mission impact.

SSG-10 (Rev. 1) [2] also provides information on the screening of SSCs based on the criteria of ease of replacement and cost; see annex II of SSG-10 (Rev. 1) [2] for several examples of the screening of SSCs using such criteria. This method is very useful for applying a graded approach. As an example, ageing management for easily replaceable and not very costly SSCs could be limited to periodic replacement and less effort could be invested in in-service inspection (ISI) and/or maintenance. The SSCs in category A (very difficult to replace), such as core components, and category B (technically difficult or costly to replace) will need more rigorous and detailed inspection and/or analysis for ageing management. The SSCs in category C (normal to replace) can be subjected to normal inspection and maintenance, and ageing management for the SSCs in category D (readily replaceable) could be limited to ensuring the availability of spares and replacement frequency. Category D SSCs do not need any ISI for ageing management. This method can also be used in conjunction with other screening methods for prioritizing the SSCs for ageing management.

3.3.2. The second stage of the screening process

The second stage of screening applies to SSCs requiring further ageing management review (AMR). For these SSCs, the specific structural elements or components that are important for safety or mission impact need to be listed, and a review needs to be performed to determine which components are susceptible to ageing effects resulting in a failure that would affect safety or mission outcomes. It might be efficient to consider grouping similar components (e.g. valves, pumps, small diameter piping) that operate in comparable service conditions (e.g. pressure, temperature, water chemistry).

A flow chart of the two stages of the SSC screening process following the guidance in SSG-10 (Rev. 1) [2] is presented in Fig. 2. For good practice, the specific screening methodology used is to be justified and documented.

3.3.3. Alternative screening methodologies

Alternative screening methodologies (e.g. approaches based on probabilistic safety assessment) are acceptable if they do not contradict the safety requirements for research reactors established in SSR-3 [1]. An example is the use of probabilistic methods, such as the incremental conditional core damage probability, to calculate the probability of failure of SSCs to quantitatively prioritize the SSCs for ageing management. This method can also be used in refurbishing and modernization projects.

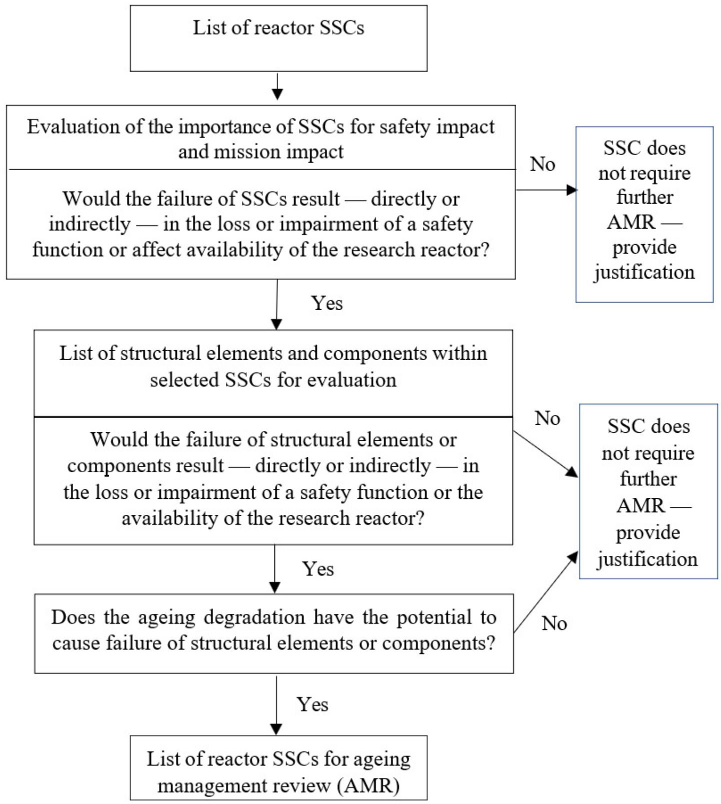

FIG. 2. A flow chart of the overall proposed screening process (adapted from SSG-10 (Rev. 1) [2]).

Some of the alternative models of SSC screening are more detailed than the method presented in Sections 3.2.1 and 3.2.2 and may be suitable for larger multipurpose research reactors. To initiate an SSC screening process for a new AMP or when reviewing the existing AMP for an operating research reactor, it is recommended that the facility engage a multidisciplinary team, including members with knowledge of the detailed facility system and equipment configuration and condition, safety case knowledge, and operations and maintenance experience, in addition to knowledge of applicable material degradation or ageing processes. For large facilities, an expert review team may be appropriate to conduct the screening review.

3.4. AGEING MANAGEMENT REVIEW OF SCREENED STRUCTURES, SYSTEMS AND COMPONENTS

A successful AMP requires effective detection, management or mitigation of the ageing effects or the potential for them. Therefore, it is recommended that the next step in the development of an AMP, following the SSC screening process, is to perform an AMR (see IAEA Safety Standards Series No. SSG-48, Ageing Management and Development of a Programme for Long Term Operation of Nuclear Power Plants [25]). The AMR is a process in which ageing effects are systematically assessed with respect to the applicable anticipated or experienced degradation mechanisms. The assessment includes all SSCs that are screened and an evaluation of the impact of the ageing effects on their capability to perform their intended function, taking into account their current condition. Many times, ageing effects may be obvious and managed through typical preventive maintenance activities performed at the research reactor facility. However, a systematic approach to the conduct of the AMR will result in an in depth review of SSCs at the facility that may not be covered by normal preventive maintenance activities (e.g. in inaccessible regions of the facility, at interfaces such as a steel support plate with the concrete floor or wall).

The assessment of materials and service conditions may often be performed using analytical or empirical models that predict future ageing degradation. The level of rigour in the assessment depends on the complexity of the component. For example, ageing studies for cables in a specific environment or fatigue analysis of reactor vessel core supports may be necessary.

Facilities with limited resources may be able to accomplish a more rigorous AMR by also taking into account the experiences of other research reactors published in the RRADB.

3.4.1. Procedure to prepare an ageing management review

The procedure to prepare the AMR may be summarized as follows:

(a) Assemble the appropriate information regarding the SSC:
   - (i) Design information, including intended function, design basis, safety analysis, applicable codes and standards and regulatory requirements;
   - (ii) Material specifications, including fabrication history;
   - (iii) Performance specifications;
   - (iv) Design margins.

(b) Group components according to similar materials and operating environments (to apply a similar ageing management approach).

(c) Identify the potential ageing effects and key environmental stressors (degradation mechanisms) that the SSC is subjected to (see Sections 2 and 3 for additional guidance).
(d) Review the material properties to determine if current or future analysis can be used to justify the ability of the SSC to perform its intended function with no additional ageing management actions. Factors to consider include corrosion allowance, fatigue cycles, loading conditions, chemical exposure, radiation exposure and environmental exposure.
(e) Review the operating and maintenance history of the SSC, including the information collected by the operating experience programme, noting those instances where the degraded condition affected the ability to perform the intended function.
(f) Review the periodic testing and inspection history of the SSC, including trend analysis to ascertain the suitability of the SSC to continue in service and to determine the frequency and details of such testing and inspection to reveal ageing effects.
(g) Determine whether it is possible for the ageing effects to result in the loss of the SSC's intended functions and conclude whether there is reasonable confidence that the functional capability can be maintained, in accordance with the facility's design basis, through the current operating period.
(h) Perform destructive tests on coupons if the facility has installed them to determine ageing effects on some materials, such as core component materials for irradiation and/or corrosion, as they could reveal degradation in material properties.

In some instances, there may not be enough information on the operating history or operating conditions of the SSC to confirm the existence of a degradation mechanism or the potential for ageing effects. For facilities that have been in existence for several years (e.g. more than 30 years), the conduct of a one time inspection for SSCs may confirm, or reject, the presence of ageing effects and allow for the exclusion of such SSCs from the AMP or assist in defining a longer period before additional inspections are conducted. For some SSCs, inspection may not be enough to ascertain the degradation (e.g. from irradiation effects) of material properties. It may therefore be necessary to perform studies and analyses to determine the ageing effects.

The most complete information resources are available from the nuclear power industry, which has performed several ageing management studies and compiled ageing information for hundreds of combinations of components, materials and operating environments. Valuable resources for this information are the RRADB, the RRMPDB and Refs [26–28].

For the examples provided below, these publications are used as the primary source of reference. However, other resources that provide information on reliability or ageing management can also be used, in accordance with the good practices of the specific organization. In cases where information is not available, engineering judgement might be an appropriate option.

3.5. IDENTIFICATION AND UNDERSTANDING OF DEGRADATION MECHANISMS

For all screened SSCs, the applicable degradation mechanisms need to be identified on the basis of the material properties and service conditions of the SSC. As discussed in Section 2.3, multiple degradation mechanisms may be present for some SSCs. As an example, the in-core components may be subjected to both radiation embrittlement and corrosion.

An AMP needs to consider various physical and non-physical degradation mechanisms on the basis of service conditions. Table 5 provides an example of a document that can be used to record the results of the AMR, considering physical mechanisms. This documentation is referred to as the 'AMR worksheet' and is only an example; the reader may choose to document the review process in a different manner. The column headings used in Table 5 are defined as follows:

(a) Grouping of structures or components. The review does not need to be performed on specific reactor equipment or items (unless the item is unique within the facility). Therefore, grouping components made of similar materials and operating in a similar environment may be useful. The grouping of components is completed by the user to best fit the preferences of the facility or programme.

(b) Materials. List the material types for the SSCs in a specific worksheet. Multiple materials may be present in the list, representing subcomponent materials operating in the same environment. When a system group is evaluated, multiple components with multiple materials may be listed.

(c) Operating environment:

   (i) Various operating environments to which the SSCs are exposed are to be listed. When considering process piping systems, the system or component may have an internal environment as well as an external environment, both of which may contribute to ageing degradation. Therefore, the worksheet includes one column for each environment.

   (ii) Typical environments for many of the components in the reactor facility include, for example, radiation, demineralized water at >60°C or <60°C, raw water, treated water, wastewater, lubricating oil, fuel oil, dry air, wet air, gases (i.e. helium, argon, CO_2, N_2), and buried pipelines with or without weathering protection.

(iii) It has to be noted that unique environmental conditions may be present for some of the SSCs in the reactor facility.

(iv) If more than one operating environment exists for a component, or more than one material exists, it is suggested that an individual row be used to ensure that the appropriate degradation mechanism is identified for a given material and operating environment separately. This ensures that the appropriate ageing detection is applied.

(d) Ageing effects:

(i) Typical ageing effects include, but are not limited to, radiation embrittlement, cracking due to stress corrosion, blockage due to fouling, loss of material due to general corrosion, pitting and/or selective leaching, shrinkage due to elastomer degradation, loss of preload due to thermal effects or self-loosening, hardening or loss of strength due to polymeric degradation, loss of insulation resistance of electrical cables, loss of material due to delamination, peeling and/ or wear, and blistering due to exposure to ultraviolet light, ozone, radiation and/or chemical attack.

(ii) The RRADB, the RRMPDB and Refs [26, 27] contain several practical examples of ageing effects on SSCs in research reactors or similar SSCs in other nuclear facilities that provide information on component types, their various material compositions and operating environments experienced in the nuclear industry. When a combination of material and operating environment applicable to the research reactor facility is found, the corresponding potential ageing effects can then be applied.

(iii) It has to be noted that there may be more than one ageing effect listed for a given combination of material and operating environment.

(iv) Once the potential degradation mechanism is identified, the facility programmes (e.g. maintenance, periodic testing, inspection) have to be reviewed to confirm that they are able to detect the presence or absence of the ageing effect or otherwise as currently comprised.

TABLE 5. EXAMPLE OF AN AGEING MANAGEMENT REVIEW WORKSHEET

Structure and/or component[a]	Material[b]	Environment[c]	Ageing effect[d]	Currently managed? List the activity performed[e]
Primary coolant pipe	Stainless steel	Demineralized water >60°C	Loss of thickness due to corrosion	Yes — chemistry control of primary loop Need to add periodic thickness measurement
Primary coolant pipe welds	Stainless steel	Demineralized water >60°C	Cracks due to stress corrosion cracking	Yes — chemistry control of primary coolant Need to add non-destructive examination of welds
Primary heat exchanger tubes (secondary side)	Stainless steel	Raw water	LOM[f] due to pitting, erosion; blockage due to fouling	Yes — in-service inspection of tubes Need to improve chemistry control of cooling water
Core structure	Aluminium	Radiation	Loss of ductility due to embrittlement	No — need to add evaluation of material properties through sample testing or from the database
Core structure	Aluminium	Demineralized water >60°C	LOM due to corrosion	Yes — visual examination using high resolution camera for any cracks and corrosion
Intake fan (housing)	Carbon steel	Air — condensation	LOM due to pitting or crevice corrosion	No — add inspection for corrosion

TABLE 5. EXAMPLE OF AN AGEING MANAGEMENT REVIEW WORKSHEET (cont.)

Structure and/or component[a]	Material[b]	Environment[c]	Ageing effect[d]	Currently managed? List the activity performed[e]
Exhaust ductwork	Aluminium	Air — indoor controlled	Not applicable	Not applicable
Piping vent valve	Stainless steel	Process fluid	LOM due to pitting or crevice corrosion	Yes — valve is replaced periodically
Power cables	Insulation and conductor	Air — temperature	Reduction in insulation resistance due to moisture ingress, degradation of jacket material	No — need to include measurement of insulation resistance, inspection to detect any cracks in the jacket material
Relays	Various metals	Air — indoor	Contact point damage	Yes — preventive maintenance and periodic replacement

[a] SSC subject to review.
[b] If more than one material, use separate rows for each.
[c] Identify the operating environment. Use separate rows for internal and external.
[d] Describe the ageing effect to which the item is subjected.
[e] Do the current facility programme or preventive maintenance tasks manage the identified ageing effect?
[f] LOM: loss of material.

3.6. DETECTION, MONITORING AND TRENDING OF AGEING EFFECTS

For all screened individual SSCs, the identification of actions to effectively detect, monitor and trend the ageing effects has to be included in the AMP. These actions could be component inspections (visual or non-destructive examinations); preventive, predictive or corrective maintenance activities that reveal ageing effects; calculations or analysis; performance monitoring or tests; walkdowns; or control or monitoring actions. These actions need to be converted into inspection tasks, maintenance tasks or operations tasks, and executed with the appropriate frequency. Results have to be monitored and feedback evaluated to determine whether inspections or other actions are effective in managing the related ageing effects. The recommended approach for monitoring and trending ageing related information is to implement a systematic AMP, typically led by the engineering organization of the facility.

The reactor facility may already have a preventive or predictive maintenance or inspection activity in place and with the potential to monitor and identify the ageing effects (see SSG-81 [7]). In this case, the effectiveness of that process is determined to be adequate to detect the ageing effect and the AMR worksheet notes this conclusion (i.e. 'managed') (see Section 4 for an additional perspective on the types of detection that are effective in detecting ageing effects). When the maintenance activity is determined to be ineffective or absent, then the worksheet identifies this as a gap that can be addressed through the appropriate action in the AMP.

The AMR is commonly focused on SSCs that are important for safety and reliability and their subcomponents. However, in some cases, portions of a component include material that is purposely designed to be replaceable. Examples include packing, gaskets, component seals, O-rings and structural sealants. From the perspective of equipment reliability, many of these may already be considered within a facility's preventive maintenance programme and are therefore subject to routine inspections or replacements. However, when an ageing effect is found not to be managed, the impact on these additional items is also evaluated to determine whether a replacement item and/or a revised replacement schedule is needed.

When evaluating the ageing management task, existing methods for inspection, testing, surveillance, monitoring and assessment are considered with account taken of relevant operating experience and research results. This helps in determining whether the activity is effective for the timely detection of ageing effects before the failure of the structure or component occurs.

When it is identified that the reactor facility does not perform an activity for detecting the ageing effect on all SSCs (e.g. bolting inspection), for completeness the AMP needs to include additional tasks on top of the existing facility programmes.

3.6.1. Inspection methods

Using the results of the AMR, an assessment of various examination methods is performed to select those that are appropriate for detecting the effects of the identified degrading mechanisms (see SSG-10 (Rev. 1) [2] and SSG-81 [7]). Ageing surveillance activities are part of the long term AMP, are planned as early as possible and continue throughout the operating life of the research reactor. On the basis of design, manufacturer specifications, operating experience and judgement, the ageing surveillance activities are to be planned to be consistent with the equipment selection, categorization process and equipment qualification previously discussed. Surveillance activities have to take advantage of the existing ISI, maintenance and periodic testing programme. These surveillance activities may consist of the following activities [3].

3.6.1.1. Inspection and visual examination

Evidence of ageing effects can appear progressively or suddenly. A rigorous inspection and visual examination plan based on a periodic ISI programme or on a schedule for all selected components and systems needs to be established. It may also be part of the maintenance programme. Scheduled inspections and visual examinations have to be consistent with the SSC category. Operators and maintenance staff are to be trained to report evidence of changes in the state or appearance of a component or material. Examples of symptoms of ageing related problems are distortion of dimensions, deterioration of surfaces or materials, leaks, cracks and even discoloration. These reports, along with those from the scheduled inspections, are crucial for timely intervention to minimize or mitigate ageing effects. A culture among staff of ‘always being alert to report on trouble’ is the best way to cope with potential problems.

Long maintenance and shutdown periods could be utilized for inspection activities, especially those that take a long time or require preparation. They could include internal inspections of SSCs such as verification of tolerances based on manufacturers’ recommendations, visual and other examinations of core support structures or pool liners, and corrosion checks.

3.6.1.2. Testing, including non-destructive tests

Many ageing effects cannot be measured directly. Properly scheduled activities are to be prepared to facilitate timely performance of comprehensive tests as needed. Testing may be used to look for signs of deterioration. Regularly scheduled tests provide comprehensive information to assess ageing effects (e.g. resistance of cable insulation, leakage tests for confinement or containment structures, hardness changes in a material due to irradiation). Non-destructive examination techniques may be useful to identify ageing related degradation. Such techniques include ultrasonic thickness measurements to monitor the corrosion or erosion of pipe walls; measurement of physical distortions such as fuel element length or bow; dye penetrant measurements or ultrasonic examination for welded joints in a pool liner; vibration measurements for degradation of rotating equipment or interconnected SSCs; and radiography measurements for internal component conditions. In some cases, a destructive test may be necessary, for example to measure the stored energy in a piece of graphite; to test coupons irradiated in the research reactor to determine changes in the mechanical properties of material as a result of irradiation; and to conduct tests on polymer materials to determine changes in mechanical properties, including elasticity. Examples of various non-destructive testing methods and their capabilities, together with the associated techniques, are given in table 1 of SSG-10 (Rev. 1) [2]. Further information on non-destructive testing methods and techniques that can be used for detecting ageing of SSCs in research reactors can be found in Ref. [29].

3.6.1.3. Performance tests

Ageing effects can be detected by checking the performance of an SSC. For example, the drifting of set points or the deterioration of electronic or mechanical components of valves and valve actuators or control rod drive mechanisms may cause changes in the performance of a control system. Similarly, the performance of the primary and secondary cooling systems could reveal ageing effects. For this reason, the SSC performance results, which are dependent on the specific design and operation of the facility, have to be examined for evidence of trends that may indicate ageing effects. Specific performance tests (e.g. control rod drop time checks) could be implemented as part of the AMP.

3.7. COLLECTION OF RELEVANT DATA AND EVALUATION

Paragraphs 5.15–5.17 of SSG-10 (Rev. 1) [2] state:

> "5.15. The results of the examinations should be evaluated using baseline data collected in previous examinations, or acceptance criteria, to assess the condition[6] of the SSCs and whether they are acceptable for continued

safe operation or whether remedial measures or corrective actions need to be taken. The examination results should be added to the baseline data for use in subsequent examinations, and records should be kept of any remedial measures or corrective actions.

"5.16. The capability and feasibility of detection methods should be periodically evaluated to check their adequacy (including whether they are sufficiently sensitive, reliable and accurate).

"5.17. The frequency of examination of an SSC for ageing management should be in accordance with the recommendations of the designer, manufacturer and/or supplier. The frequency may be adjusted on the basis of the likelihood of failure of the SSC and on the basis of experience, including experience from similar facilities. Any proposed changes to the frequency of examinations should be justified.

"[6] Condition assessment of an SSC is an assessment to determine the SSC's current performance and condition (including assessment of any ageing related failures or indications of significant material degradation) and to predict its expected future performance, future ageing effects and residual service life."

Paragraph 5.19 of SSG-10 (Rev. 1) [2] states:

"5.19. Ageing effects may be detected by a change in measurable operating parameters (e.g. control rod drop time, water chemistry parameters, temperature, flow rate, pressure). Parameters that can be used to predict ageing effects should be routinely monitored (either on-line or periodically). Readings should be assessed, and trends identified, in order to predict the onset of ageing effects in a timely manner."

Baseline data could also be the pre-service inspection data, or the first data collected. Such baseline data have to be reviewed against the design and technical requirements and margins established for continued service of the SSCs. If the research reactor has an on-line data acquisition system for parameters that could reveal the ageing effects, then such data need to be reviewed for monitoring and identifying trends in ageing effects.

3.8. MINIMIZATION AND MITIGATION OF AGEING EFFECTS

Minimization and mitigation actions are implemented to reduce the impact of ageing effects on SSCs.

3.8.1. Minimization

Although ageing of a component cannot be prevented, the effect of ageing can be minimized through suitable facility programmes such as preventive maintenance (see Ref. [4] and SSG-81 [7]). The intention of a preventive maintenance activity is to prevent the condition that can lead to the failure of SSCs. These actions contribute to the minimization of present or potential ageing effects.

Ideally, the minimization of ageing effects begins with the reactor facility design, which will take into consideration the end of life of equipment associated with the fabrication material and the operating environment into which the equipment will be placed. In addition to the design of the equipment, the configuration and physical facility layout consider access for performance of maintenance and testing or inspections of the equipment to be able to detect ageing effects. Advances in design have resulted in the ability to continuously acquire important data (e.g. through the installation of a data acquisition system that collects and analyses the data and identifies trends), which precludes the need for repetitive equipment surveillance. Furthermore, self-diagnostic features, typically in control systems, reduce the need for testing and reveal faults or failures.

The minimization of ageing effects is often accomplished as part of a refurbishment or replacement task, and in many cases a modernization or upgrade of the system or specific equipment occurs.

Refurbishment or replacement of a near like for like component or subcomponent is an ageing management technique that ‘resets’ ageing effects on equipment or portions of equipment. When an exact replacement component is not available, an engineering process within the integrated management system is to be used to verify that a near like for like component will be acceptable and will not compromise the capability of the research reactor to operate safely and reliably. However, the non-physical factors associated with ageing management described in Section 2.7 may necessitate the modernization or upgrade of equipment.

Therefore, alternatives to replace equipment or portions of a facility are likely to need consideration. Modernization allows the reactor facility to reduce to the extent practical the effects of ageing in a similar way to that previously described for a new reactor facility design.

3.8.2. Mitigation

Mitigation is applied when a condition is identified as being present and action can be taken to limit the impact, or effect, of the ageing. These are the operation, maintenance, repair or replacement actions taken to mitigate the detected ageing effects. This can also be corrective in nature, for example where a process parameter value is brought back into acceptable limits or altered within the operating range (e.g. downgrading the safe working load of a crane) to slow the ageing effects. While minimization and mitigation actions are conceptually different, some minimization activities are also mitigatory in nature.

An example of a mitigatory action to counter the ageing effects could be as follows: a pipe that is buried and in direct contact with soil (or encased in concrete) may be coated to preclude the onset of corrosion. Any failure of that coating will probably result in an external corrosion of the pipe and loss of material of the pressure boundary, and could eventually result in pipe failure. The application of an AMP prompts the facility to recognize the potential for the onset of an ageing effect on that buried piping because the operating life may already be beyond that originally intended and there is potential for failure of that coating (and the potential for a loss of pressure boundary function). In this case, the mitigatory action will be to inspect the coating and replace it before the onset of corrosion of the pipe.

Research reactor facilities that have been operating for several decades, and especially those operating for more than 40 years, have an increased likelihood of replacing or modernizing facility equipment. A refurbishment or modernization project may become necessary to mitigate ageing effects on several SSCs and this project may include the repair or replacement of them. However, when mitigation is the most cost effective means to manage the effects of ageing, the facility will need to ensure that ageing is detected or predicted in a timely manner so that it can then be mitigated.

3.9. ACCEPTANCE CRITERIA

An acceptance criterion is to be established to keep an SSC in service where an ageing effect is determined as a result of inspection and monitoring (e.g. loss of material, loss of strength, loss of cable insulation). Such acceptance criteria are based on the design basis or technical requirements and the relevant codes and standards and regulatory requirements. Care has to be taken to maintain sufficient margins while establishing the acceptance criteria.

3.10. ASSESSMENT OF RESIDUAL LIFE, INCLUDING TIME LIMITED AGEING ANALYSIS

Using the data collected for detection of and identifying trends in ageing effects, design margins, and minimization and mitigatory actions, an assessment of the residual life of the SSCs has to be made. Caution is to be applied not to extrapolate the ageing effects linearly. Often the combined effects of various degradation mechanisms may not be the same as when a single ageing mechanism is present. An example of this is the effect of radiation or stress on corrosion. Further attention needs to be paid to possible 'cliff edge' effects (i.e. the occurrence of a sudden failure after slow degradation).

An example of residual life assessment is fatigue, which results in life limitations that are based on cyclical loading. Fatigue of components is managed through the monitoring of various parameters that provide an understanding of the growth and impact of the ageing effect, primarily that associated with crack growth.

The following are examples of cycle based fatigue analyses:

— Fatigue flaw growth analyses (based on cyclical loading assumptions);
— Fracture mechanics analyses (based on cyclical analyses);
— Fatigue analysis calculation (associated with environmentally assisted fatigue).

In research reactors, for some of the SSCs a time limited ageing analysis (TLAA) may be available, for example with respect to the number of total drops in the lifetime of safety rods or control rods; the number of pressurized thermal shocks in the lifetime of high pressure, high temperature irradiation loops; and the total fluence that can be reached in the core components before their properties are degraded to a point that they cannot be in service. Such analysis is performed as part of the design process. In such cases, it is sufficient to check whether the TLAA is still valid for continued operation. If the TLAA becomes invalid, other methods of detection and trending are to be performed for the continued operation of the SSC (e.g. more ISI, including destructive testing of samples and associated analysis) or the SSC has to be replaced.

It is important to note that assessment of life and minimization and mitigation of ageing effects may be iterative. The results of assessment could redefine the minimization or mitigatory actions, such as frequency of replacement or inspection.

3.11. CORRECTIVE ACTIONS

A corrective action is needed when ageing effects are detected on SSCs and the SSCs cannot be accepted for continued operation. These corrective actions could be replacement, repair or refurbishment of the SSCs. The feedback from such corrective actions has to be incorporated into the regular facility programmes, such as maintenance, inspection and periodic testing.

3.12. DOCUMENTATION AND RECORD KEEPING

Ideally, the most effective approach to ageing management includes the development of a living AMP starting from baseline data that are updated periodically to include the results of actions taken to minimize or mitigate identified conditions leading to ageing effects, or from the consideration of operating experience from other research reactors or similar facilities.

The ongoing implementation of an AMP includes the periodic evaluation of data and the documenting of the decision making process that led to either taking an action to minimize the deterioration process or replacing a component. An alternative to the specific programme documentation may include a simple summary report produced periodically (e.g. one, two or five years) that maintains the available data concerning the specific problems addressed or ageing management tasks performed since the previous report. This can include summaries of historical records, evaluation and assessment reports, and the material supporting evaluations for continued operation.

Records of maintenance and replacement of, and modifications to, reactor components can be included in the programme documentation or the summary report. In many cases, this information is maintained, or controlled, as part of the facility records control system (configuration management). Regardless of the means of maintaining these records, it is important to ensure that they are readily available, for the lifetime of the facility, for use in future ageing management assessments. Section 5 provides additional guidance on considerations during replacement or modification.

To assist with the determination of the types of information that a reactor facility may want to retain and make readily available, the following items are suggested in para. 5.31 of SSG-10 (Rev. 1) [2] (this list may not be all inclusive for some facilities):

“(a) Identification and evaluation of degradation, failures and malfunctions of SSCs caused by ageing effects;

(b) Prediction of the future performance of SSCs, which is necessary for continued safe and reliable operation of the research reactor;
(c) Decisions on the type and timing of preventive maintenance actions, including calibration, repair, modification, refurbishment and replacement, and decisions on revisions to the ageing management programme;
(d) Optimization of service conditions and practices that reduce degradation of SSCs;
(e) Identification of emerging ageing effects before they jeopardize the safety, reliability and service life of SSCs or the operating lifetime of the research reactor."

3.13. IMPLEMENTING AN AGEING MANAGEMENT PROGRAMME

Once a framework for ageing management is developed that includes all necessary elements, an AMP is to be developed and implemented. An AMP needs to include all items listed in Section 3.1. An AMP has to state which facility programme is used for managing ageing for each screened SSC. These programmes could be one or more of the following:

— Maintenance activities, including preventive and predictive;
— Periodic testing;
— ISI, including non-destructive examinations;
— Equipment qualification;
— Operational activities;
— Control of service conditions;
— Performance monitoring;
— Sample and/or coupon testing;
— Analysis;
— Time limited ageing analysis;
— Walkdowns.

For each SSC, the specific actions that are needed to detect, monitor, minimize and mitigate the ageing effects are to be specified. Compliance with national regulations, codes and standards and with the integrated management system of the facility needs to be ensured. The acceptance criteria in the AMP are to be reviewed to ensure that the actions specified to manage the ageing of SSCs and their frequency are sufficient to detect the ageing effects well before failure, while they need to be based on the design margins and technical requirements for the SSCs. Where it is found that the existing facility programme is not sufficient to fully manage the ageing of SSCs, actions such as additional inspections or analyses or revision of their frequency are to be specified in the AMP. These additional or different actions have to be included in the relevant facility programme. Depending on the facility's size and complexity, a graded approach could be used. Reference [30] provides information on ageing management for specific SSCs in research reactors and nuclear power plants.

Information collected from the AMP has to provide the current actual condition of the SSCs and this needs to be reviewed to determine the effectiveness of the AMP. If possible, performance indicators are to be developed that represent the effectiveness of the AMP. Paragraph 5.56 of SSG-48 [25] provides examples of such performance indicators.

3.14. REVIEW AND CONTINUOUS IMPROVEMENT OF THE AGEING MANAGEMENT PROGRAMME

The AMP has to be reviewed periodically (i.e. once every five or ten years) to determine its effectiveness in managing the ageing of SSCs. If necessary, the activities in the programme need to be adjusted to ensure its effectiveness.

A mechanism has to be in place to exchange information on ageing management with similar facilities within the country or outside the country to take advantage of their experience. Where applicable, experience and knowledge from other nuclear facilities or non-nuclear facilities could be used. Emerging knowledge regarding the ageing of SSCs, such as new degradation mechanisms and the results of research and development in ageing management, also have to be considered to improve the facility's AMP.

If the life of an SSC is defined and needs to be increased, an in depth safety demonstration has to be performed and additional measures, such as increasing the inspection frequency or more detailed inspection, have to be implemented in the AMP.

The AMP is to be reviewed independently by a knowledgeable person or persons to ensure its completeness and effectiveness. Where such independent expertise is not available within the country, this peer review could be outsourced, including through available bilateral, regional or international arrangements. However, the operating organization remains responsible for implementing the AMP.

4. AGEING MANAGEMENT OF STRUCTURES, SYSTEMS AND COMPONENTS

4.1. INTRODUCTION

This section provides examples of practices for the evaluation of SSCs in the framework of ageing management. These practices are in use in several research reactors and can support other facilities in improving their AMPs. Examples of various activities performed with respect to SSCs in specific research reactors are given below. It may be noted that some might not be applicable to all research reactors and that some research reactors may need additional activities, such as tests or inspections. In practice, ageing in research reactors is managed by a combination of several facility programmes, including inspection, maintenance, surveillance and testing. In a few cases in the examples given below, inspection and maintenance intervals are suggested. This suggestion is not to be interpreted as a requirement. The frequency of inspection and maintenance tasks depends on the specific requirements of the facility. However, it is important to define the frequency in the AMP and the required interventions are executed in accordance with this.

4.2. CIVIL STRUCTURES

The type, composition, grade and properties of structural concrete have to be known. In some older installations, this information might not be available. However, it needs to be possible to determine these properties by taking core samples (e.g. through core drilling) and performing measurements in laboratories. Reference [15] provides more information on concrete ageing. The RRMPDB contains data on concrete properties and ageing related issues and this information could be useful for an AMP for similar facilities. The general degradation mechanisms applicable to concrete structures mainly include weathering, loss of moisture content, carbonation, disbonding and corrosion of reinforcement bars.

Visual inspection is commonly performed for a preliminary assessment of the health of the concrete structure. This has to be done by a specialist in the proper manner. Special attention is to be paid to the presence, for example, of cracks, spalling, mould, fungus and foreign matter.

In the case that cracks are detected, these need to be evaluated by a qualified expert to determine whether the crack is superficial or deep enough to pose a threat to the stability of the structure, or if the crack is stable or growing; the length and depth of the crack are to be checked periodically. If a crack represents a threat to stability or is found to be growing, a repair strategy needs to be formulated and implemented.

Beside cracks, attention is also to be paid to differential settlement between buildings, and the stability of the buildings needs to be checked.

Another threat is carbonation of the concrete. This is the reaction of the concrete with carbon dioxide from the environment. Carbonation can be a serious threat to the reinforcement, and the depth of the carbonation has to be measured, using a quite simple standard test.

In addition, several other inspections and tests (e.g. for chloride and sulphate depths) are conducted to assess the condition of the concrete. Tests that can be carried out include ultrasonic pulse velocity testing by surface probing at selected locations to assess the homogeneity of surface concrete, measurement of corrosion potential at selected locations, and rebound hammer testing to assess the integrity of cover concrete.

Containment or confinement leak tests are routinely carried out in most research reactors. The results of such tests are also useful for assessing any new or growing cracks in the building.

If reinforcement is found to be exposed to the environment, urgent repair will be necessary. The corrosion of reinforcement bars can lead to stability problems and the cracking of concrete.

Specialists who are qualified to assess concrete structures will generally not be present in organizations that operate research reactors. However, the inspections and follow-up for concrete structures can easily be outsourced.

Attention is also to be paid to steel structural components. These can be liners or support structures. The condition of the corrosion protection paint needs to be checked.

Contact areas between concrete and other materials are a special case. Differential thermal expansion can cause cracks in the concrete, while the concrete can be chemically aggressive to some materials (e.g. aluminium).

Many of the civil structures in research reactors are seismically qualified. However, this qualification would have been done during the design and construction stage to the standards prevailing at that time. Usually, the equipment qualification programme of the facility covers these aspects. An AMP has to include verification of the seismic qualification of SSCs with respect to the current seismicity of the location of the research reactor and the approaches to safety evaluation [31].

Pool liners are of special interest in research reactors. Generally, the liners are made of either aluminium or stainless steel. Many pool liners in research reactors have leak detection arrangements, typically on weld joints. However, many of the old research reactors do not have any arrangement for pool liner leak detection. A pool liner may be susceptible to corrosion on its outer surface if moisture and air are present because water and air will form nitric acid in the presence of gamma radiation. Ultrasonic testing or eddy current testing could be used to detect such corrosion, depending on the design of the reactor pool. Radiation resistant underwater cameras can be used to inspect the pool liners visually, with special emphasis on weld joints. Remote ultrasonic testing is another technique that can be employed. The monitoring of unaccounted water loss from the pool can also indicate leakage.

Leaks in pool liners affect the concrete structure and the reinforcement bars in particular. These reinforcement bars, generally made of carbon steel, corrode in the presence of water and tend to swell, causing either cracks in the concrete or spalling. One of the measures adopted in current practice is to use coated reinforcement bars to minimize corrosion resulting from water leaks.

4.3. ELECTRICAL COMPONENTS

This section provides examples of common electrical items used in research reactors and the associated maintenance, inspection or testing that is performed, which is useful for their ageing management. In most cases, these programmes are established on the basis of applicable codes or manufacturers' recommendations and adjusted according to operating experience. The list is by no means comprehensive and a similar programme has to be developed and implemented for all electrical items in the scope of an AMP. Reference [32] provides more information on the qualification of electrical equipment for ageing management.

4.3.1. Battery banks

Batteries are sensitive to ageing and care needs to be taken to keep them in good condition such that they can deliver the required power to equipment on demand. Standard battery bank capacity tests or load testing (discharge tests) are two effective methods to assess the condition of the battery bank. Thermography is an efficient method to detect faults such as bad contacts.

Regular preventive maintenance, such as rundown and equalization charging, checks on the reference cell (e.g. voltage, electrolyte make-up, temperature), terminal tightness and greasing, and visual inspection help in minimizing and mitigating ageing effects.

Batteries have a limited service life and need to be replaced. The replacement interval is normally specified as part of the maintenance programme. The results of battery bank capacity tests are to be used to assess whether the battery's performance is degrading faster than expected. If so, the replacement schedule has to be adjusted to ensure that the battery is always capable of supplying power to meet the full demand of the most onerous design basis accident.

4.3.2. Battery chargers and converters

Battery chargers and converters (AC–DC) contain several components that are sensitive to ageing. Environmental conditions such as temperature and humidity accelerate ageing and need to be controlled. Preventive maintenance, including cleaning and tightening of joints, functional tests, and thermography or visual checks for overheating, are helpful in assuring uninterrupted service.

4.3.3. Inverters

Inverters (DC–AC) contain a number of components that are susceptible to ageing. Environmental conditions such as temperature and humidity accelerate ageing and need to be controlled. Preventive maintenance checks, monitoring of the vibration and noise of cooling fans, checking of the coolant condition functional tests, and thermography or visual inspection for overheating have to be conducted.

4.3.4. Equipment specific DC power supplies

Owing to the limited lifespan of typical internal components, replacement has to be performed periodically.

4.3.5. Circuit breakers and switchgears

Periodic cleaning is essential for good function. Functional tests need to be conducted with a predefined periodicity. Thermography is a useful test to reveal hot spots.

4.3.6. Relays

Periodic cleaning is essential for good function. Functional tests need to be conducted with a predefined periodicity. It is recommended that relays that are important for safety (especially those that are continuously energized or with high frequency switching) be replaced with a predefined periodicity.

4.3.7. Variable frequency drives

Film type capacitors need to be replaced after predefined periods of use. Cabinets and fans are usually cleaned annually. Fans need to be replaced after predefined periods of use.

4.3.8. Transformers

Transformers have to be inspected at predefined inspection intervals, usually specified by the manufacturers or by State regulations.

4.3.9. Electrical motors

Electrical motors have to be inspected at predefined inspection intervals. The tests performed include the following:

— A visual examination;
— Brush and commutator inspection to detect sparking or damaged surfaces;
— Vibration and noise measurements to detect any incipient failure;
— Motor winding test at a predetermined frequency to determine any damage;
— Thermography to detect excessive heating inside the motor;
— Current signature analysis.

4.3.10. Lightning protection and earthing or grounding

Periodic testing of lightning protection (visual and resistance measurement) is necessary if lightning protection is a requirement. Continuity checks for earthing or grounding strips are necessary to ensure the integrity of the ground path.

4.3.11. Power cables

Visual examination of power cables is useful to detect any cracks in the insulation on the outside. Continuity and resistance measurements can be used to identify trends in cable integrity, if performed on a regular basis. Samples of cables can be exposed to radiation and subsequently tested to assess the impact of irradiation.

4.4. MECHANICAL COMPONENTS

This section provides examples of common mechanical items used in research reactors and the associated maintenance, inspection or testing that is performed, which is useful for their ageing management. In most cases, the programmes are established on the basis of manufacturers' recommendations and adjusted according to operating experience. The list is by no means comprehensive, and a similar programme is to be developed and implemented for all mechanical items in the scope of an AMP. References [13] and [33] provide additional information.

4.4.1. Reactor vessel or tank

The reactor tank is generally made of aluminium, stainless steel or zircaloy and is difficult to approach, replace and/or repair. Radiation induced damage and/or corrosion usually determine the service life of the tank. It is easy to predict the effect of individual degradation mechanisms, but assessing or predicting the combined effect of two or more degradation mechanisms is difficult. It is good practice to install a number of coupons at strategic locations at the commissioning stage to obtain practical information on the degradation occurring with progressive service of the tank. In the absence of coupons, a replaceable core component that has seen similar conditions may be used for this purpose. Non-destructive examination techniques such as visual inspection, eddy current testing, ultrasonic testing and radiation mapping can also be deployed.

For tank type reactors, inspection of the tank is an important part of the AMP. Reactor designers have to include provisions for inspection equipment to access both the inside and outside walls of the reactor tank. Operating organizations may have to schedule special shutdowns, including removal of fuel assemblies and core components, to facilitate inspections for ageing effects that could prevent the tank from meeting its design requirements.

If the reactor is pressurized, a non-destructive examination (e.g. ultrasonic testing, eddy current testing, visual inspection) has to be performed on a regular basis (typically every ten years), with attention paid to material property changes resulting from neutron irradiation. Pressurized reactor vessels are also subjected to fatigue load and, accordingly, a suitable theoretical analysis has to be performed.

For pool type reactors, the mechanical integrity of the core structure is important. In this case, a visual inspection (e.g. to check for deformation, loose components, broken components, corrosion, erosion) could be sufficient. Special attention needs to be paid to neutron irradiated parts or parts subjected to fatigue. Usually, radiation resistant high resolution cameras are deployed for visual inspections. In addition, dimension measurement of some components may be incorporated.

4.4.2. Connections and penetrations

Pipe penetrations of research reactor tanks are usually welded and, owing to residual stresses, are more prone to accelerated corrosion. These penetrations can be inspected together with tank internals. It is preferable that replacements be planned to coincide with long outages for refurbishment or upgrades. Reactor vessel expansion joints require special care, as they are sensitive to thermal fatigue and can be difficult to inspect.

4.4.3. Core components and support structures

In many cases, research reactors have beryllium or graphite parts in the core, typically as reflector elements. Beryllium swells as a result of neutron irradiation. This will cause cracks owing to the brittleness of beryllium. If possible, the beryllium elements can be shuffled to even out the fluence on all sides. Graphite parts also undergo changes in physical properties, such as specific heat, thermal conductivity and dimensions, as a result of irradiation. Additionally, graphite accumulates stored energy (Wigner energy) with progressive irradiation depending on irradiation temperature. The release of Wigner energy under power transients or loss of cooling may lead to safety concerns. Stored energy needs to be estimated to ensure that it remains within safe limits or a process for annealing to release the stored energy has to be established.

Other core structures are usually made of aluminium or stainless steel. Regular visual inspections (using underwater cameras or videoscopes) are to be performed. Inspection has to include checks for corrosion, deformation, cracks, foreign materials and loose parts, or any other abnormality.

4.4.4. Heat exchangers

Heat exchangers are inspected at regular intervals based on service conditions, using non-destructive examination techniques (e.g. visual inspections, ultrasonic testing, eddy current testing, radiography) on shells and tubes. If possible, eddy current testing of tubes in large heat exchangers is to be performed periodically. Cleaning (mechanical, chemical) of tubes and/or plates where feasible needs to be performed. Large heat exchangers can be cleaned by rubber sponge balls. The condition of heat exchangers can be assessed by the frequency of maintenance, ISI and performance evaluation (fouling factor) data. This can help in assessing residual life.

4.4.5. Major pumps

Generally, pumps are easily replaceable except in the case of large pumps in high radiation areas. The pumps need to be inspected in accordance with manufacturers' recommendations or the construction or inspection code and on the basis of experience feedback.

For pumps that have condition based maintenance, feedback from oil analysis, vibrations and bearing temperatures needs to be collected. Trend analysis has to be performed on these data. Visual inspection to assess the condition of supports and foundations needs to be performed. Residual life assessment requires surveillance, performance and maintenance data and modelling.

4.4.6. Control and safety rods

Control rods need to be tested frequently (especially the scram function and drop time). The results are to be kept for trend analysis. The status of the absorber parts needs to be checked periodically, especially if the absorber is burnable (e.g. cadmium). Preventive maintenance has to be performed on the drive mechanism to detect any incipient deterioration. Where an auxiliary or supplementary control room is available, tests to ensure the operability of the scram function also need to be included. The control rods can be easily replaced, and it is prudent to have several spares available to make the maintenance independent of the operation cycles of the reactor.

4.4.7. Piping

Piping has to be inspected in accordance with its construction or inspection code. Visual inspection could reveal external corrosion.

For internal corrosion, non-destructive examination techniques such as ultrasonic thickness measurement are useful; reference points are to be established on the piping for such measurements and it is useful to include vulnerable points, such as pipe bends, high velocity and/or temperature zones, crevices or dead zones, and the parts of the piping affected by pressure surge or flow induced vibrations.

Weld joints require special attention and non-destructive examination methods such as liquid penetrant tests and ultrasonic flaw detections are useful. Pipe supports need to be inspected for any deterioration, in particular where the pipe and support materials are different.

For painted pipes, a frequency for repainting needs to be established. Corrosion is normally the degradation mechanism that governs service life. Modelling of corrosion behaviour is a better technique than linear extrapolation.

For pipes in pressurized reactors, the possibility of low cycle fatigue needs to be considered.

4.4.8. Valves

Valves are subject to potential ageing effects as a consequence, for example, of temperature, corrosion, radiation and cycling (fatigue). Water hammering can become a life limiting factor. Major valves are to be inspected in accordance with their construction or inspection codes. Where the valve has an important isolation function, a leak test has to be performed. Non-return valves have to undergo regular functional testing. Non-destructive examination techniques such as radiography and acoustic emission testing help in the discovery of incipient defects such as hinge pin wear.

4.5. INSTRUMENTATION AND CONTROL SYSTEMS

In general, the instrumentation and control (I&C) systems of a research reactor undergo modernization at some point in the lifetime of the research reactor because of obsolescence, the unavailability of spares or physical ageing. In particular, the electronics and software systems are modernized because of obsolescence. This section provides examples of common I&C items used in research reactors and the associated maintenance, inspection or testing that is performed, which is useful for their ageing management. In most cases, these programmes are established based on manufacturers' recommendations and adjusted on the basis of operating experience. The list is by no means comprehensive and a similar programme has to be developed and implemented for all I&C items in the scope of an AMP. SSG-37 (Rev. 1) [19] provides recommendations and guidance, and Refs [34–36] provide more information on the ageing management of I&C systems.

Analysis of surveillance (e.g. monitoring, instrument checks, functional tests) and periodic calibration data for instrumentation is a good way of detecting any ageing effects. Response time checks can be performed for the sensors or the entire channel to detect any deterioration. In modern instrumentation, self-diagnostic features are usually provided. This generally provides sufficient information for trend analysis to detect potential degradation.

4.5.1. Nuclear measurements (neutron, alpha, beta and gamma radiation)

Apart from surveillance, performance and maintenance data, detectors need to undergo periodic testing for residual life assessment (e.g. sensitivity and saturation levels). Modern computer based digital systems may have self-diagnostic and calibration features.

4.5.2. Process instrumentation (temperature, pressure, flow)

The process instrumentation has to be calibrated periodically, including set point checking. The typical periodicity is one year. Data have to be recorded and trend analysis needs to be performed. This may provide sufficient information to detect potential degradation. Noise analysis is another technique used for diagnosis of transmitters. Impulse lines may become blocked by the deposition of corrosion products or may suffer loss in thickness because of corrosion. Replacement during a long outage is a good option.

4.5.3. Relays

The life span of relays depends on their service conditions, for example whether they are continuously energized and the number of times they are actuated. Although tests such as contact resistance measurement and current signature analysis can reveal deterioration, in most cases replacement based on their expected life span is a better solution.

4.5.4. Computer based systems

Computer based systems are finding increasing use in protection, regulation and operator information systems such as data acquisition systems. The modular concept and software with diagnostic features make surveillance user-friendly. On-line monitoring and ease of maintenance are added advantages. Generally, these systems have built-in programmes to detect malfunctions and the designers or suppliers provide the frequency at which these programmes are to be run. In many cases, they run automatically at the given frequency and generate a report. An important concern in such systems is to ensure that the latest compatible versions of software are used and that hardware is replaced at periodic intervals. Care needs to be taken to avoid any malware that can jeopardize the operation of the software. Technological advances make such systems more amenable to periodic replacement than to measures for mitigation of ageing related issues. Many research reactors still have old analogue systems and intend to replace them with computer based digital systems. SSG-37 [19] and Ref. [36] provide the necessary guidance.

4.5.5. Radiation monitoring

Radiation monitoring instrumentation is to be calibrated and set points are to be checked periodically. The frequency of testing will vary in accordance with manufacturers' recommendations and the importance of the instrumentation for safety. A functional test with a radioactive source provides a good test that can be performed frequently. Data are to be preserved and trend analysis has to be performed to provide sufficient information to detect any potential degradation.

4.5.6. Signal cables

Results of continuity checks, conductor impedance, insulation resistance measurements and visual checks provide good input for assessing the health of signal cables. Specific checks (e.g. for tensile properties, hardness, polymer disbonding) could be employed to detect deterioration.

4.6. EXPERIMENTAL DEVICES

An AMP for experimental devices is to be developed when experiments are running for long periods or are permanently connected to the reactor (e.g. experimental loops, rabbit systems, cold neutron sources, dedicated irradiation positions). The AMP for experimental devices also needs to include those devices in temporary storage for future deployment.

Many research reactors are equipped with beam tubes. These are quite independent from the reactor, but failure can lead to loss of pool water and airborne radioactivity in the vicinity. Remedial action could be time consuming (resulting in a loss of service to users/stakeholders) and replacement during a long outage appears to be the better option. Periodic visual examination and non-destructive examination of the beam tubes is recommended.

4.7. AUXILIARY SYSTEMS

4.7.1. Ventilation system (containment/confinement functions)

The condition of the ventilation system can be monitored using performance tests such as air flow measurement and measurement of pressure drop across filter banks. Trend analysis will indicate signs of degradation. Components with containment or confinement functions have to be tested in accordance with predefined test planning. The efficiency of high efficiency particulate absorbing

(HEPA) and charcoal filters has to be tested on a regular basis to ensure that particles and contaminants are properly removed and that the integrity of the filter housing is maintained.

Regular leak testing of containment or confinement systems has to be performed to assess any degradation in integrity. Vibration and noise testing are useful in detecting ageing effects for rotating equipment such as fans and blowers. Acoustic emission tests can detect leaks from ventilation ducts effectively, while walkdowns along the ducts are also useful in detecting corrosion or deposition of dust inside inlet/outlet plenums and ducts.

Stacks or chimneys have to be inspected periodically to detect any degradation.

4.7.2. Diesel generators (emergency power)

The system for emergency power has to be tested frequently for its response on demand. Usually, no-load tests are performed to test the response, and load tests are performed to check the full functionality. During these tests, several important parameters have to be monitored: response time, delivered current, delivered power and frequency. Trend analysis will indicate signs of degradation.

The inspection and maintenance scheme for the diesel engines will generally be defined by the original equipment manufacturer and adjusted on the basis of experience. Inspection and maintenance of the electrical generators for any ageing effects have to be performed periodically.

Assessment of the condition of the fuel storage and supply for the engines has to be performed periodically. For research reactors where the emergency diesel generators are operated infrequently, testing them for short periods and ensuring the integrity of the fuel supply is important. Periodic draining, cleaning, inspection and refilling of the fuel tanks could be necessary.

4.7.3. Compressors (including air drums and receivers)

The performance of compressors is to be monitored periodically using several tests. The main compressors are to be inspected in accordance with the construction or inspection schedule. Testing is recommended to verify that the air is dry and free from contaminants. When moisture causes corrosion inside compressed air systems, the AMP could lead to the timely replacement of large sections of piping.

For compressors that have condition based maintenance, feedback from oil analysis, vibrations and bearing temperatures needs to be collected. Trend analysis could reveal any ageing effects. Visual inspections to assess the condition of supports and foundations need to be performed. Air drums are to be checked periodically. Pressure relief valves are to be tested in accordance with a predefined periodicity. In many cases, this periodicity is a legal requirement.

4.7.4. Waste handling (liquid, gas, solid)

Drain tanks and sumps are susceptible to a buildup of sediments over time. The design of such components needs to include provision for periodic cleaning or for redundant sumps to facilitate replacement. Sumps that receive chemical waste need to be monitored more frequently.

Visual inspections and hold tests that include leak measurement from the tanks are helpful in detecting the degradation of tank integrity. Containers that store solid waste on-site are to be monitored for corrosion from weathering conditions. It is advisable to store them in enclosed areas.

4.7.5. Spent fuel storage

Visual inspection of storage racks is to be performed periodically. Leaks from the pools can be detected by performing hold tests that consider loss of water by evaporation. Usually, trends in the make-up rates for pools can reveal any degradation of the integrity of the pools.

The water chemistry of the storage pool has to be controlled to avoid corrosion of spent fuel cladding. The pool liner is to be inspected by visual examination to detect corrosion signs. Inspection of stored fuel elements and other assemblies by visual examination with radiation resistant underwater cameras will help determine their status.

4.7.6. Water purification

The efficiency of the water purification systems can be monitored by measuring the pressure drop across the resin beds during the service period and by checking the quality of the water product delivered by the system (i.e. by measuring pH and conductivity).

Non-destructive examination of tanks to detect any ageing effects can be performed when they are empty. Monitoring of differential pressure across filters and their periodic replacement are to be included in the surveillance and maintenance programme. Periodic cleaning of mechanical strainers is to be included in the maintenance programme.

4.7.7. Cranes and material handling devices

Cranes and other material handling devices for the manipulation of loads that can damage reactor components need to be checked carefully. A checklist of minimum requirements has to be in place and completed before any manipulation. An integral inspection and maintenance needs to be performed on a regular basis. Data records of results have to be kept, as they can reveal ageing issues (e.g. the same faults are found during multiple inspections).

In most countries, load handling devices are to be tested periodically (typically annually) by an accredited agency. Such tests include the thorough inspection of components, and brake testing and deflection measurements on test loads. These tests can reveal any ageing effects.

4.7.8. Fire protection systems

Maintenance (corrective, preventive or predictive) of fire protection systems (detection and extinction) is a specialized discipline. In many cases, it needs to be performed by the supplier or a specialized agency.

Fire water feeds can be tested by the internal or external fire department responsible for the site. Sometimes the tests are part of their periodic training exercises. Fire water pipes usually have stagnant water and hence are more prone to corrosion. The piping is to be inspected periodically, including using non-destructive examination techniques.

Flushing of fire systems demonstrates adequate flow and unobstructed flow paths, and assists in removing debris from the system. Fire detectors and alarm systems have to be tested at regular intervals to reveal any ageing issues.

4.7.9. Tanks and vessels

Tanks and vessels require periodic visual inspection from inside and outside (if accessible) to check for corrosion, damage or leaks. Integrity checks (i.e. hydro tests or air hold tests) need to be performed on tanks, with special emphasis on leaks from weld joints. Supports and foundations need to be inspected for any deterioration. Non-destructive examination techniques such as ultrasonic thickness measurement or flaw detection are very useful for tank and vessel inspections.

4.7.10. Cooling towers

Periodic cleaning of cooling tower basins is recommended. Visual examination of components for corrosion, deposition and algae growth is to be performed. Chemistry control to minimize corrosion, including the addition of algaecides, helps to extend a cooling tower's life. Performance checks on cooling towers reveal any signs of degradation. The presence of *Legionella* bacteria has to be detected for the protection of workers and the general public.

4.7.11. Hot cell facilities

Hot cell windows require follow-up as they degrade owing to irradiation. In order to limit damage, high activity sources have to be kept away from the windows as far as possible. Periodic cleaning and checks to verify the quality of the oil and gas charge in the windows are also recommended. Ventilation and air cleaning by filters (HEPA, charcoal) are to be monitored frequently. Measurements (purge flow) are to be taken and trend analysis is to be performed to detect degradation in a timely manner. Light efficiency tests with a monochromatic source are an effective way to monitor deterioration in the glass.

4.7.12. Fuel handling equipment

Equipment for the handling of research reactor fuel comprises fresh and spent fuel handling equipment in the reactor and fuel storage areas. The fuel handling may be manual or automated using a fuel handling machine. Maintenance and inspection of fuel handling and fuel transfer equipment are to be performed periodically to detect any signs of ageing. Most research reactors qualify the equipment through dummy runs before using it with real fuel.

5. MANAGEMENT OF MODIFICATION, MODERNIZATION AND REFURBISHMENT PROJECTS

5.1. INTRODUCTION

As part of the AMP, there could be a need to perform modifications and mitigatory actions that cannot be undertaken as part of normal facility programmes such as maintenance, inspection or periodic testing programmes; this is the case for work on SSCs that cannot be undertaken without fuel unloading or systems that cannot be shut down (e.g. passive core cooling system). Quite often, this situation results in a modernization or refurbishment project. The project could be a small to medium size modernization (e.g. of days or a few weeks of effort) or refurbishment activities. Less often, the situation will result in a large

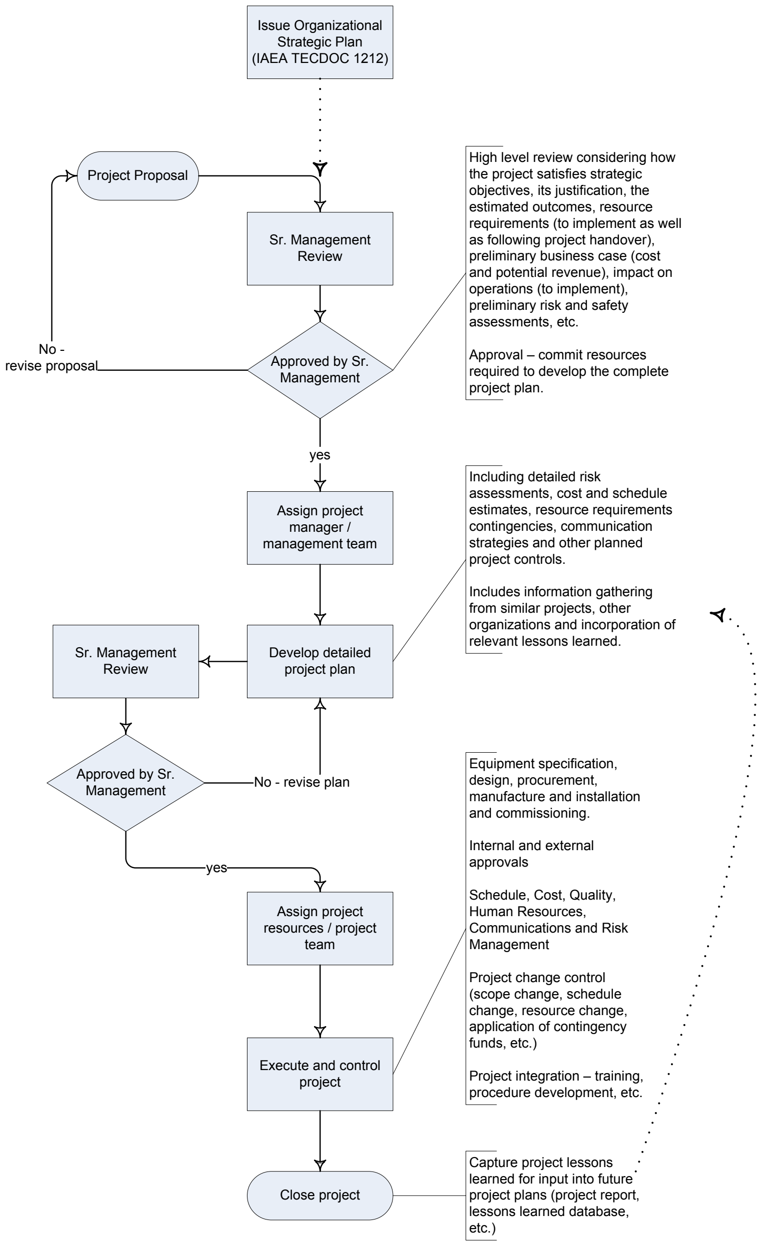

FIG. 3. Project flow chart (reproduced from Ref. [5]).

modernization or refurbishment effort over a period of many weeks or months. Small modernization or refurbishment activities can be completed within the integrated management system of the facility by the operation and maintenance personnel at the facility. It is common to think of the larger effort as a ‘project’ but less common to consider the smaller activities as such. If the effort requires significant resources or coordination between several groups, then there is value in treating the effort as a separate project and scaling the use of the project management phases and principles described below to the needs of the specific effort — large or small. SSG-24 (Rev. 1) [8] provides guidance regarding the safety aspects of modifications or modernization projects. References [5] and [6] provide several examples of modernization and refurbishment projects at research reactors. This section provides an overview of how to manage a modification, modernization and refurbishment project.

A Guide to the Project Management Body of Knowledge (PMBOK Guide) [37] contains generic information and recommended practices for any organization embarking on engineering projects, whether associated with equipment modernization or refurbishment. The present publication will not go into the level of detail presented in the PMBOK Guide. However, it will utilize the project management process outlined there as a guide for the use of project management principles in research reactor organizations for modernization and refurbishment efforts. For many small to medium size projects, the guidance here will be adequate. For very large ageing related projects, a more detailed review of the project management principles covered in the PMBOK Guide is recommended. Figure 3, along with the subsections below, will provide basic guidelines for the implementation of this process as it relates to modernization and refurbishment projects of all sizes. In this context, Ref. [38] provides more information on strategic planning and a methodology for the development of a strategic plan, and provides a model that may be followed.

5.2. INITIATING THE MODIFICATION, MODERNIZATION OR REFURBISHMENT PROJECT

The first step in the initiating phase of the modification, modernization or refurbishment project is to develop a project charter. The charter is a document that identifies the project manager and formally allocates the resources necessary to complete the detailed project planning. It will include a discussion about the project and the way in which it meets the operating organization’s goals or objectives. This includes a more general description of the rationale for launching the modernization or refurbishment project at a research reactor, and it has to address why the proposed project is required.

5.2.1. Justification of the project

The reactor management may identify the need for a modification, modernization or refurbishment project related to ageing management owing to a variety of circumstances, such as a recommendation from the AMP as a result of inspection; a new requirement from the regulatory body; operating experience or trends from the operating organization; or operating experience reported by other installations or equipment suppliers. It might also arise from obsolescence, such as changes in technology, changes in safety requirements, the discovery of inadequacies in design, or improper maintenance and testing. The modification may also become necessary to upgrade the products or services, for example new irradiations such as silicon doping, or to meet the requirements of other users. The modification may involve changes to safety related systems. In such cases, the reason for a modification and the general concept are to be discussed by the reactor management and the regulatory body during this initiating phase. In the case that an additional licence or an amendment to the licence is necessary, the procedure has to be discussed with the regulatory body. It may also be appropriate to include in the discussion other groups, such as the safety committees, experimentalists, equipment suppliers and independent consultants [5].

The format of the complete project charter may vary, but it is intended to be a document that contains the key elements discussed above and it provides a foundation for the project over its course. During this phase, it is important to identify all project stakeholders. These might include regulators, experimentalists, customers and technical experts. It is important to identify each stakeholder and to understand their expectations and ability to affect project outcomes. Early involvement with the stakeholders can help to determine the approach that will be taken, whether that is refurbishment, replacement using identical components or replacement using an alternative. That decision will depend on several factors and has to include input from the entire stakeholder group. It may also involve use of an alternative analysis that considers the safety, cost, schedule and impacts of the various options, and then decides on the best path forward.

The reactor manager is responsible for the decision to proceed with any modernization or refurbishment project, and for ensuring that the project does not affect the ability of the facility to operate safely and reliably.

5.2.2. Objective

During initial planning for an ageing related modernization or refurbishment project, a scope statement that clearly defines the project objectives and outcomes has to be included in the planning. Further details are provided in Section 5.3.1.

5.2.3. Safety assessment, analysis and review

When the scope of the project is being refined, a detailed safety analysis for any modification has to be carried out to the extent necessary to identify potential hazards (see SSG-24 (Rev. 1) [8]). The analyses have to be capable of demonstrating that the proposed modification is safe and, in particular, confirming the following:

(a) Any new SSC complies with all relevant safety requirements and will function safely for all operational states and accident conditions, as applicable.
(b) New systems will not adversely affect the safety characteristics of other items that are important for safety under any operational states and accident conditions, as applicable, or the safety relevant characteristics of the reactor.
(c) The modification can be carried out without adversely affecting the safety of reactor operation.
(d) Any new hazards introduced by the modification can be safely managed at any stage of the project.
(e) The modification enhances overall safety, for example including safety upgrades that are practicable and reasonable.
(f) The modification enhances reliability and availability, including efficiencies in operation and maintenance.

The technical and operational relationship of the systems proposed to be modified needs to be evaluated for each of the accident sequences considered in the safety analysis report for the reactor. The implications of the modification for the management of potential accidents and for their consequences have to be analysed. Care is to be taken that up to date safety documents and data are used in these analyses.

The modification, modernization or refurbishment is to be carried out by minimizing the radiation dose to staff and members of the public. An effort also needs to be made to address the reduction of the future dose to staff and members of the public in the project.

Each of the above considerations is to be addressed in this initiating phase so that the final scope of the modification can be determined and agreed to by all stakeholders. This increases the awareness of all involved, ensures that safety is not compromised and sets the stage for both the technical and financial resources that will be required to complete the modernization or refurbishment project.

5.3. PLANNING THE MODIFICATION, MODERNIZATION OR REFURBISHMENT PROJECT

Proper planning of the modification, modernization or refurbishment ensures that time and resources will be saved during the project. Several aspects need to be considered in the plan to achieve the required goals.

5.3.1. Scope statement

During initial planning for an ageing related modification, modernization or refurbishment project, many considerations need to be understood in order to effectively achieve the desired project outcomes, including the timeline. At a high level, there is a need for a clear statement of the project objectives. These are the items that, when accomplished, will determine the success of the project. This clear statement is often referred to as the 'scope statement'. The scope statement details the project deliverables and describes the major assumptions, requirements and objectives. The objectives need to include measurable success criteria for the project. This statement provides a simple summary for all stakeholders regarding the purpose of the effort, what is to be accomplished and how. The scope statement does not need to be too complex or lengthy, but should be long enough to communicate these important facts.

5.3.2. Work breakdown structure and schedule

An important early input to the planning phase is an order of magnitude cost estimate (budget) for the modification. A cost–benefit analysis has to be discussed in the early phase of the project with the reactor management and other stakeholders, so that they all understand the financial burden and benefits. For projects that involve high budgets, a review is to be made of extending the life of an existing reactor versus constructing a new reactor and the costs involved. As often only a rough estimate is available initially, this will then need to be refined further during this planning phase. To further refine this budget and begin to understand the project schedule, a detailed breakdown of the project work activities is needed. This list of activities, commonly known as a work breakdown structure (WBS), includes a list of the various steps involved in the modernization or refurbishment project and helps the project team to understand the full range of activities necessary to accomplish the project. The list will also include the tasks performed by subcontractors and suppliers, and all internal resources. Moreover, it also has to include the design activities that ensure the observability or testability of the modification, along with the time requested for testing and commissioning of the new equipment after installation. Furthermore, if all the technical expertise needed does not exist within the organization, the WBS will need to include activities related to the required contractor or outsourcing involvement.

The steps in the completed WBS are either sequenced or linked in the order that they are to be performed and the WBS becomes the foundation for the project schedule. Each activity is numbered, given an estimated duration (e.g. days, hours) and arranged in an appropriate order to develop the project schedule. The schedule will include the start date of the planned effort as well as hold points (milestones or intermediate markers during the project effort). For a limited refurbishment or small modernization effort, the sequencing of activities might be all that is necessary as a project plan; for larger projects this will require different project management tools, such as critical path methods or programme evaluation and review techniques, with possible parallel paths in the schedule. Several options may have to be considered to optimize the schedule to meet cost, time and quality constraints. Some typical questions that need to be answered (to reduce risk and save time and funds) before submitting the WBS for approval include the following:

— Is there a possibility of testing the new or refurbished equipment prior to installation in the research reactor?
— Are there hold points (or key milestones) that need to be included in the project schedule, especially before irreversible steps?
— Can more of the workload be completed prior to a reactor outage in order to minimize its impact on reactor operation?

These are a few examples of the many questions that can be considered to reduce risk and minimize project duration and cost. Often much of the work on modernization or refurbishment will need to be completed during one reactor outage. This is likely to affect the reactor operation, so some iteration and adjustment of the timing may be necessary. If the planned schedule does not support the desired reactor operation, it may be necessary to consider additional resources (e.g. hiring subcontractors) to complete the desired modification in an appropriate time frame. As these discussions proceed and decisions are made, the schedule will be refined. Ultimately, this arrangement and linking of project tasks and refining will produce an acceptable project schedule.

5.3.3. Budget content

The project schedule and the budget are dependent on one another. Changes in the project schedule (e.g. additional resources to speed up the schedule) will affect costs; hence, costs and schedule will be reviewed constantly. In the end, the project budget will account for the following financial resources that will be needed to complete the project successfully:

(a) Staff costs for the various scheduled activities (e.g. planning, design, installation);
(b) Work costs to complete the necessary procurements and subcontracts;
(c) Other costs associated with project specific activities.

A contingency for unexpected changes in scope or unmitigated project risks should also be included. The total cost, rolled together with other associated costs, will determine the planned budget for the project.

5.3.4. Risk management

Early in the project, it is important to consider the risks. These are the things that could come along unexpectedly and affect the ability to achieve project outcomes. For small refurbishment projects, these may be few in number and for larger projects they may be numerous and complex. It is important to identify these risks so that the team can then consider how to mitigate the likelihood or impact of each risk occurrence.

The list presented below is from Ref. [5] and includes items relevant to research reactor modernization and refurbishment projects that have the potential to add significant risk (e.g. schedule delay, scope, cost overrun). Each of the items needs to be considered and addressed in the planning phase, as appropriate for the project:

(a) All similar work performed previously, within the organization or externally.
(b) Lessons identified that can be applied to reduce project risk.
(c) Evaluation of expertise and resources available for large ageing related projects in the organization, as well as in accessible external project management and technical support organizations.
(d) Optimization of project implementation, including equipment installation and minimization of the impact on reactor availability.
(e) Optimization of the modification design for reactor availability, maintainability, testability and reliability.
(f) Consideration of plans and procedures to minimize radiation exposure of personnel at each stage of the project.
(g) Optimization of project related communications (e.g. internal — project meetings, management meetings, project reports; external — regulatory, customer, supplier interface).

(h) Specific project integration requirements (e.g. additional or reduced staff, customer interface changes, work procedures, adequate spare parts inventories, decommissioning and disposal of old equipment and radioactive waste, staff training, internal or external safety/regulatory approvals).
(i) Identification of work that involves any unique evolutions or abnormal requirements (e.g. additional or special shielding, confined spaces, mechanical handling equipment, plant configurations).
(j) Assessment of the impact of proposed changes on the project scope, schedule and budget, and approvals needed to modify the project.

5.3.5. Complete project baseline

The outcome of the planning phase is a complete project baseline for the ageing related modernization or refurbishment. This baseline includes, at a minimum, the scope statement, stakeholder list, WBS, schedule and budget, and a risk assessment for the project. This baseline is then to be presented and approved by the appropriate project stakeholders. In this sense, project approval means that the project has been reviewed and authorized by the appropriate authority in accordance with the policies of the operating organization.

5.4. EXECUTING AND MONITORING THE MODIFICATION, MODERNIZATION OR REFURBISHMENT PROJECT

The execution phase of a modification, modernization or refurbishment project will include multiple elements, or phases, such as design, procurement, installation, testing and commissioning. These phases can be sequential or parallel activities, depending on the size and complexity of the project, and have to address issues such as interdependencies of the activities, resource availability, constraints and hold points. Throughout the execution phase, the project manager has to work in accordance with the integrated management system of the organization to monitor and control the project — comparing the ongoing activities with the planned activities and resolving issues that might have an impact, for example, on the planned schedule, cost, scope and qualities. Generally, it is expected that the execution of the project will follow the WBS and schedule with periodic reviews and course corrections as needed.

5.4.1. Design phase

Depending on the scope of the project, items that need to be designed are to be identified. Regardless of whether an item is to be newly designed or is simply to be replaced using the original design, it has to meet the current regulations, codes and standards.

SSR-3 [1] provides the safety requirements for the design of SSCs for research reactors. The modernization or refurbishment project needs to meet the applicable requirements.

The design phase might involve analyses, assessments and evaluations, definition of technical specifications and the preparation of drawings that provide a technical foundation for the intended modernization or refurbishment. The design is to be carried out by qualified specialists in their area of expertise. In some cases, coordination and interaction between different designers will be necessary. The following aspects, among others, need to be considered during the design phase for the successful execution of the project:

(a) Management system criteria have to be established and implemented for the modification project, covering all aspects of the design, including construction and inspection and testing methods.
(b) Measures are to be provided for verification of the design. This verification has to be performed by qualified individuals other than those who developed the original design.
(c) Items that are important for safety and those required to ensure the reliability and availability of the research reactor are preferably to be of a proven design and, if not, need to be items of high quality that can be qualified and tested.
(d) Design of items is to be carried out using applicable national and international codes and standards. The quality of the items has to be commensurate with the safety function that they are required to perform or their importance for the reliability and availability of the research reactor.
(e) Within the design effort, consideration is to be given to the future testability of the modernized or refurbished equipment or system.
(f) Checks are to be made as to whether an additional licence or a licence modification is necessary.

5.4.2. Procurement phase

The procurement phases of project execution will involve interfacing with potential contractors or suppliers and will include the need for procurement and contract specifications. These specifications are the principal tool used to communicate the needs of the project to the contractors and suppliers. Simple yet thorough procurement documents are therefore required. Procurement documents for each item need to specify to the contractor(s) the requirement for a comprehensive final report on the phases in which they were involved (i.e. design, manufacturing, testing, supply, installation and/or commissioning) and need to contain the following information:

(a) A certificate of compliance with technical specifications and requirements;
(b) Testing and inspection results;
(c) A report on non-conformances and their disposition;
(d) Procurement records;
(e) User manuals, including instructions for storage, installation, testing, operation and maintenance;
(f) Operational limits and conditions;
(g) As built drawings, a bill of materials and a list of raw materials, components and parts;
(h) Personnel training requirements.

In the case that commercial grade components or products are procured for use in any item that is important for safety, the suitability of such components or products needs to be verified and their use justified. Experience feedback for such products from similar applications would be useful.

5.4.3. Installation phase

During the installation phase, the on-site work to modernize or refurbish the equipment begins. This is where the impact on facility operations begins as well; schedule adherence and regular updates to stakeholders regarding the schedule will be important. This is part of the ongoing monitoring and control effort.

During this phase, the principal installation activities of the project will include, at a minimum, the following:

(a) Monitoring and control of activities and personnel (internal as well as contracted) related to the manufacture and assembly of SSCs and the resolution of significant on-site and off-site safety issues.
(b) Establishment of the construction organization, allocation of the space and areas to contractors, and ensuring that the necessary site services, information and instructions regarding applicable nuclear safety and industrial safety requirements are provided and monitored.
(c) Identification of construction activities and development of standardized instructions, procedures and good practices and their monitoring, review and updating.
(d) Installation procedures that adequately address the safety measures applicable to all the personnel (internal as well as external), including nuclear and radiation, industrial and environmental safety.

(e) Verification of the safety arrangements of the construction organization and contractors on the construction site and their compliance with the applicable requirements.
(f) Monitoring of the policies and activities related to nuclear and industrial safety and their compliance with statutory and regulatory requirements with regard to safety and quality.
(g) Planning and monitoring of the progression of work to meet the schedule and project objectives, and coordination of the activities of the contractors involved in the construction of SSCs that interface with other installations on the site.
(h) Monitoring of the work carried out by the construction organization itself or by its contractors and ensuring its accordance with procedures, specifications and drawings.
(i) Ensuring that safety and quality requirements are specified and implemented, including inspections and tests conducted at suppliers' sites, and that these are appropriate and in accordance with plans for inspection, testing and associated surveillance schedules.
(j) Ensuring that the proper maintenance of installed equipment is carried out and dormant equipment is preserved to avoid any deterioration during construction.
(k) Control of operator workarounds and temporary modifications through procedures, administrative controls or management processes and their evaluation by competent personnel to ensure that regulatory requirements and design provisions are not violated. For example, the installation of temporary scaffolding or shielding for carrying out any modernization or refurbishment activity has to be analysed prior to installation as its presence may result in the facility being placed outside its design envelope. The seismic spatial interactions between temporary scaffolding and shielding and safety related SSCs have to be analysed and any shortcomings or issues need to be addressed. Temporary modifications (including the installation of jumpers, disconnection of interlocks, lifted leads and electrical disconnections) may result in unexpected system behaviour and performance. A record of temporary modifications to SSCs has to be maintained in the control room and in relevant documents. Such SSCs have to be restored to their normal configuration as early as possible. The workarounds and jumpers have to be utilized to the minimum possible extent and time frame and only after careful consideration of alternatives. They need to be controlled carefully and evaluated periodically to justify their continuation in use [39].
(l) Pre-service inspections of SSCs and generation of baseline data for interpretation of ISI results.
(m) Transfer of work and records from one group to another.

(n) Installation of coupons or material samples for assessment and/or analysis of corrosion or material behaviour under service conditions including irradiation, as a part of the AMP.
(o) Generation and maintenance of necessary documentation as evidence of due diligence, as built drawings, photographs and videos, quality assurance, technical audit, non-conformance reports and their resolution (corrective actions), and compliance with regulatory requirements — see IAEA Safety Standards Series No. SSG-38, Construction for Nuclear Installations [40].

This phase could also be well utilized for detailed data collection, such as radiation mapping, detailed inspection of other SSCs and any upgrades that the facility may consider suitable.

5.4.4. Performance verification (commissioning/operability testing) phase

In order to confirm the operability of the SSCs in the scope of the modernization or refurbishment project, the project team needs to plan for proper testing that will ensure that the newly installed components will perform their desired functions effectively. This is a key activity within the overall project execution for successful ageing related modernization or refurbishment. Such testing has to be considered early in the planning and executing phases because decisions made at this point can affect how effective and thorough this operability testing might be. It is recommended that operating personnel be involved in the development of the test plan. The test plan has to use a graded approach: tests might be simple for a non-safety related component but might require thorough review and approvals for safety related components.

Time, resources and any expertise necessary to execute the test plan have to be considered. The commissioning or verification plans need to include approval prior to the start of testing and acceptance based on the results at completion of the testing. Successful completion of the commissioning tests has to be an input to the project closure phase to ensure that the design intent has been met for the modernized or refurbished components, and for assurance that the project has been successful and will not adversely affect facility operation.

Acceptance criteria for specific SSCs based on performance and testing requirements specified as part of the modification process have to be included in the plan and procedures for acceptance testing. The plan has to be reviewed and approved by the reactor management, and the regulatory body, if required. Final approval of the modification before resumption of regular operation has to be based on successful completion of the commissioning stage, including functional tests to verify that the design intent has been met. A commissioning report has to be prepared that includes the performance data during commissioning, the results of tests performed and the acceptance criteria. The report has to be approved by stakeholders as appropriate, as a basis for permitting the normal operation of the modified facility — see IAEA Safety Standards Series No. SSG-80, Commissioning of Research Reactors [41].

5.5. CLOSE OUT OF THE MODIFICATION, MODERNIZATION OR REFURBISHMENT PROJECT

Close out of the modification, modernization or refurbishment project is also an important stage, with assessment of the progress through the duration of the project and its phases and tracking of the work done, with clear realization of the current status and planning for the next steps. Proper close out of the project requires the consideration of factors such as project reports, updating of records, temporary arrangements and lessons identified.

5.5.1. Project report

A project report has to be prepared, and this needs to include the objectives and scope of the originally planned modification, modernization or refurbishment project; the activities carried out; unexpected situations; how unexpected situations were managed; deviations from the originally conceived project and their impact on the overall budget and time schedule; and final outcomes, including the impact of the project on the safety and reliability of the SSCs that were in its scope as well as on the entire facility. The report also has to identify the facility documents and the programmes and procedures that need to be updated as a result of the project. The report also has to include any future actions that are needed. All the relevant updating is to be incorporated into the facility processes and programmes within the integrated management system of the facility. The report can have several annexes that contain relevant information — such as technical specifications, drawings, quality checks (e.g. radiographs) — or reference is to be made to such information if these records are maintained elsewhere.

5.5.2. Updating of records

Accurate information is dependent on maintaining good configuration management for the facility. When it comes to modification, modernization and refurbishment, it is crucial that the final procurement, quality, design, implementation and commissioning information is incorporated into the facility configuration management files. This way, all stakeholders are aware of the changes made and the verifications completed to ensure operability. This is to be considered in the planning phase so that the necessary resources are included in the initial project plan. This will ensure that the information is correct and the project is successfully closed.

Design documentation, analyses, drawings and operating and maintenance procedures are to be updated and reviewed and approved periodically, to properly reflect changes in the equipment. This includes any equipment that has been decommissioned and abandoned in situ as part of the modification, modernization or refurbishment. All abandoned equipment (disconnected from the system and removed from service) at the site has to be reviewed for impact on other SSCs that remain in service. Such abandoned equipment has to be clearly tagged, and facility drawings, operating procedures and records have to be updated to avoid any misunderstanding regarding the availability of SSCs.

5.5.3. Temporary arrangements

It has to be ensured that all temporary modifications such as scaffolding that were necessary for completion of the modernization or refurbishment works and are not needed for regular operation of the facility are removed and records are maintained. If, during the course of the modernization or refurbishment activities, some SSCs were disturbed from their original position, they have to be restored to their original position. Facility records need to be verified to ensure that after modernization or refurbishment activities, the SSCs have been restored to their design basis, including disconnection of interlocks and installation of jumpers. A detailed walkdown by the operating personnel is necessary to successfully close out the project. Finally, thorough housekeeping has to be conducted before the start of the operation of the facility.

5.5.4. Lessons identified

Configuration management is only one part of the close out phase of a project. In addition, lessons identified during the course of the project need to be recorded so that future modernization or refurbishment projects can benefit from them. Proper and complete project close out with all facility documentation updated and lessons recorded will result in optimal benefit being derived from the ageing related modernization or refurbishment. Proper close out defines the end of the successful ageing related modernization or refurbishment.

Appendix

AGEING MANAGEMENT OF STRUCTURES, SYSTEMS AND COMPONENTS

This appendix complements Section 4 and provides additional, more detailed information on maintenance, testing and inspection of several electrical and mechanical components commonly used in research reactors. The examples originate from practices in several research reactors and give an idea of possibilities. Frequency and scope can be adjusted to suit the specific needs of the research reactor. The methods outlined in this appendix are often utilized in a maintenance programme and assist in the detection and mitigation of ageing effects.

A.1. ELECTRICAL COMPONENTS

A.1.1. Battery systems

A.1.1.1. Flooded lead acid batteries

Perform the following for flooded lead acid batteries:

(a) Run down and equalize charge annually.
(b) Perform thermography of connections every two years.
(c) Complete visual inspection every six months.
(d) Check specific gravity on pilot cells every three months.
(e) Replace batteries at the end of their lives.

A.1.1.2. Battery chargers and inverters

Perform the following for battery chargers and inverters:

(a) Perform thermography every two years, including the following:
    (i) Power fuses, including the fuse holders, clips and terminations for fuse clips;
    (ii) Electrolytic capacitors, including their termination connections;
    (iii) Filter chokes;
    (iv) Float and equalize timers, potentiometers and switches (if applicable);
    (v) Silicon controlled rectifiers and power diodes;

    - (vi) Printed circuit boards;
    - (vii) Transformers;
    - (viii) Continuously energized DC relays;
    - (ix) Bus connections;
    - (x) Power cable terminations;
    - (xi) Input/output circuit breakers.
- (b) Inspect, clean and adjust chargers and inverters every two years.
- (c) Perform charger and inverter overhaul or replacement every six years.

A.1.2. Relays, power and control

A.1.2.1. Five year calibration for control relays

Calibrate the control relays and perform cleaning and inspection, including the following:

- (a) Control the relay setting and perform a calibration check if needed (timing relays only).
- (b) Measure and trend inrush current, as required.
- (c) Inspect electrolytic capacitor, if applicable.
- (d) Inspect solid state relays for tin whiskers.
- (e) Record as left relay settings.
- (f) Perform restoration.
- (g) Measure pick-up and drop out voltage.
- (h) Measure contact resistance.

A.1.2.2. Ten year replacement

Relay replacement should include the following:

- (a) Bench test the new relay.
- (b) Remove the old relay.
- (c) Install the new relay.
- (d) Calibrate the relay as required.
- (e) Restore the relay.
- (f) Ensure that the removed relay is sent to an engineer for evaluation.

A.1.3. Oil filled transformers

A.1.3.1. Cooler (radiator) maintenance

Perform cooler (radiator) maintenance every four years as follows:

(a) Inspect for damage, cracks or chipping of the porcelain insulators/bushings, grounding resistors and lightning arrestors.
(b) Check for correct oil levels.
(c) Check for signs of oil leakage — tank penetrations, gaskets and flanges.
(d) Check that all required equipment is operating (e.g. fans).
(e) Verify that the temperatures and pressures are within specifications.
(f) Check for loose, missing or damaged hardware and fittings, and for any degraded or discoloured cables or connectors.
(g) Verify the status of alarms.
(h) Check the condition of the grounding straps.
(i) Listen for unusual noises and smells.
(j) Check the cooler fans for debris and general cleanliness.
(k) Verify that the desiccant has the appropriate colour.
(l) Check for proper tap setting — record and trend the load tap changer cycles.
(m) Calibrate and test relays.
(n) Clean the cooler/balance fans.
(o) Check ground–resistor connection continuity and insulation.
(p) Check for leaks/damage/contamination.
(q) Check fasteners, links, fittings, gaskets, hardware and foundations.

A.1.3.2. Dissolved gas analysis

Perform dissolved gas analysis annually.

A.1.3.3. Calibration and testing

Perform calibration and testing, including the following:

(a) Indicators.
(b) Relays.
(c) Functional tests:
  (i) Verify that the appropriate groups and/or banks of cooler pumps and fans operate at appropriate set points.
  (ii) Verify that all alarms operate at appropriate set points.
  (iii) Verify that remote locations receive alarms, if applicable.

A.1.3.4. Hand switches

Hand switches are to be replaced at ten year intervals to maintain reliability.

A.1.4. Large motors

A.1.4.1. Refurbishment interval

There is a 25 year refurbishment interval for large motors.

A.1.4.2. Electrical testing

Electrical testing at three year intervals provides trending information for degradation rates, including the following:

(a) Winding impedance/resistance;
(b) Insulation resistance;
(c) Polarization indexing;
(d) Motor circuit evaluation;
(e) DC step voltage.

A.1.4.3. Vibration monitoring

Vibration monitoring should be performed at six to nine month intervals, including the following:

(a) Motor bearings;
(b) Motor housing;
(c) Shafts;
(d) Coupling.

A.1.4.4. Thermography

Thermography should be performed for connections every three years.

A.1.5. Small motors

A.1.5.1. Electrical testing

Electrical testing at three year intervals provides trending information for degradation rates, including the following:

(a) Winding impedance/resistance;
(b) Insulation resistance;
(c) Polarization indexing;
(d) Motor circuit evaluation.

A.1.5.2. Vibration monitoring

Vibration monitoring should be performed at six to nine month intervals, including motor bearings.

A.1.5.3. Thermography

Thermography should be performed for connections every three years.

A.1.6. Cables

The following should be performed for cables:

(a) Visual inspection for general condition;
(b) Insulation resistance checks.

A.2. MECHANICAL SYSTEMS

A.2.1. Air compressors, dryers and vacuum pumps

The following should be performed for air compressors, dryers and vacuum pumps:

(a) Test or replace the relief valve as required by the code at the time of vessel inspection.
(b) Change the compressor or vacuum pump oil at the interval recommended by the manufacturer.
(c) Replace the oil filters as recommended during oil replacement.

(d) Change the air filters at the recommended interval, typically in conjunction with the oil changes.
(e) Check the performance of and clean intercoolers and air dryers.
(f) Measure vibration and noise for trend analysis.
(g) Monitor oil consumption.
(h) Visually inspect internals during overhaul.

A.2.2. Filters, strainers and ion exchange vessels

A.2.2.1. Filters/strainers

Cleaning is incorporated into maintenance for filters and/or strainers that can be cleaned cost effectively versus replacement.

A.2.2.2. Ion exchange vessels

Ion exchange vessels are inspected at ten year intervals, including the following:

(a) Clean and inspect the tank internals as follows:
    (i) Clean all interior surfaces.
    (ii) Clean the tank sight glass or level indications, as required.
    (iii) Inspect the tank internally for general condition and signs of corrosion, erosion or deterioration.
    (iv) Inspect the tank internal liner, distributors, grids, supports, braces and baffles for degradation.
(b) Drain or pump out the tank contents for video inspection.
(c) Inspect the man-ways and man-way covers and seals for degradation, binding and leakage.
(d) Check the tank seals and gaskets for degradation and replace as necessary.
(e) Remove all loose paint and repaint the tank surfaces as required.
(f) Conduct ultrasonic testing or non-destructive examinations of the tank wall thickness as required.
(g) Monitor for leakage.

A.2.3. Tanks and pressure vessels

Pressure vessels, reactor tanks and reactor pools are normally inspected to assure integrity and confinement of the primary circuit. Inspections are conducted at the intervals required by national regulations; typically these are set at five to ten years and the frequency can be increased if discontinuity or ageing effects are detected.

A.2.4. Heat exchangers

The following should be performed for heat exchangers:

— Perform non-destructive examination (ultrasound, radiography, visual inspections) of shells and tubes on the basis of service conditions.
— Clean tubes and plates where feasible.
— Perform an eddy current inspection of tubes in large heat exchangers.
— Evaluate and analyse trend performance (fouling factor).

A.2.5. Large pumps, fans and blowers

A.2.5.1. Monitoring

For large pumps and fans or blowers, non-destructive examination is typically performed at ten year intervals.

A.2.5.2. Maintenance

Maintenance is condition based, using feedback from oil analysis, vibrations and bearing temperatures. It can include the following steps:

(a) Disassemble the pump in accordance with equipment repair specifications.
(b) Document as found conditions, including clearances, fits, condition of welds, and evidence of damage, wear and degradation of impellers, volutes, nozzles and hardware.
(c) Inspect all gaskets, O-rings and elastomers for damage, wear or deterioration, and replace.
(d) Clean, inspect and test cooling coils, if applicable.
(e) Inspect bearings and seals for wear and replace as necessary.
(f) Inspect casing, volutes, diffusers and barrel assemblies for thinning, cracking and corrosion/erosion.
(g) Inspect shafts for damage, defects, run out and radial position.
(h) Inspect impellers and wear rings for wear and damage.
(i) Inspect couplings and belts.
(j) Evaluate performance, including efficiency checks.

A.2.6. Air operated valves

A.2.6.1. Calibration

Calibrate the control valve and accessories every three years as follows:

(a) Take as found data.
(b) Clean, inspect and lubricate positioners, replacing worn parts.
(c) Calibrate the positioners.
(d) Check the condition of the positioner linkage.
(e) Inspect the air filters in regulators and replace as required.
(f) Adjust the valve stroke as required.
(g) Adjust the valve actuator spring force as required.
(h) Adjust the valve packing as required.
(i) If installed, adjust the valve position limit switches as required.
(j) Monitor the valve stroke to ensure smooth operation.
(k) Take as left data.
(l) Hydrotest and check for leaktightness.

A.2.6.2. Diagnostic testing

Conduct diagnostic tests every three to five years, including the following:

(a) Stroke time;
(b) Dynamic valve travel;
(c) Total friction;
(d) Air pressure;
(e) Spring rate;
(f) Seat load;
(g) Pressure drop test;
(h) Inspect regulators, hoses, fittings and tubing, and replace or repair as required;
(i) Inspect other accessories, including linkage arms;
(j) Adjust valves as necessary based on as found conditions;
(k) Perform a final diagnostic test.

A.2.7. Check valves

A.2.7.1. Small valves

For small valves, replace check valves. Observe the condition of the valve being removed or visually inspect the valve internals as follows:

(a) Check for debris and damage to seats, hinge arms and discs.
(b) Inspect for loose, damaged or missing parts.
(c) Inspect that the check arms and disc assemblies move freely and easily.
(d) Inspect for damage, unusual wear and cracked or missing disc pins or posts.
(e) Inspect disc arm post holes and disc hinge pinholes for unusual wear.
(f) Check for erosion and corrosion of the valve bodies, discs, disc arms and hinge pins.
(g) Check for proper alignment of the discs or plug assemblies and the seats.
(h) Inspect for cracked, chipped or distorted seats.
(i) Inspect for crud buildup.
(j) Clean and lubricate all parts as required.
(k) Check for evidence of leakage around or near the valve body cover gaskets, hinge pin covers, valve position indicators, fasteners, pipe flanges and connections.
(l) Refurbish the valves as required.

A.2.7.2. Check valves in raw water systems

Perform the following for check valves in raw water systems:

(a) Inspect the valve internals for evidence of microbiologically induced corrosion.
(b) Record if silt deposits are present.
(c) Record if microbiologically induced corrosion is present.

A.2.7.3. Non-isolatable or safety related valves

Non-destructive examination techniques (radiography, acoustic emission techniques) should be applied to non-isolatable or safety related valves.

A.2.8. Manual valves

A.2.8.1. Maintenance

Maintenance is condition based, using information gathered from operator rounds and engineering walkdowns, as follows:

(a) Clean and inspect the exterior of the valve.
(b) Inspect the packing and packing glands for degradation.
(c) Check the integrity of the valve support, and that bolting is in place and tight.
(d) Inspect the valves for leaks and leaktightness.
(e) Visually inspect and lubricate valve actuators.
(f) For rising stem valves, inspect, clean and lubricate the stems as required.
(g) Partially stroke the valves to verify smooth operation.
(h) Perform hydrotest and check for leaktightness.

A.2.9. Motor operated valves

A.2.9.1. Maintenance

Conduct electrical inspection of and lubricate motor operated valves as follows:

(a) Match-mark and then remove the limit switch cover.
(b) Inspect the actuator interior for moisture and corrosion.
(c) Remove any excess oil and grease.
(d) Inspect and clean the T-drain.
(e) Inspect the torque switch and record settings.
(f) Verify that the torque switch max stop plate is installed.
(g) Inspect contacts and clean as necessary.
(h) Remove and inspect the limit switch finger bases.
(i) Inspect the rotors for cracks, particularly around roll pinholes, and clean the rotor contacts and fingers.
(j) Visually inspect all internal control wiring for damage such as cracking, swelling, pinched insulation.
(k) Inspect and, if necessary, replace the lubricant in the limit.
(l) Verify the limit switch adjustment.
(m) Verify that the terminal connections are properly tightened.
(n) Clean the surfaces of the gasket on the limit switch compartment and cabinet cover.

(o) Check the gaskets and seals for any damage.
(p) Check the armature brushes for proper contact and wear when the DC motors are employed.
(q) Hydrotest and check for leaktightness.

A.2.10. Safety relief valves

A.2.10.1. Maintenance

Replace the relief valve or inspect and perform test as follows:

(a) Perform visual inspection.
(b) Remove the valve from the system.
(c) Perform an as found test of the valve.
(d) Repair, replace or set the pressure relief value, as required.

A.2.11. Solenoid valves

A.2.11.1. Maintenance

Refurbish or replace the solenoid valves as follows:

(a) Disassemble or remove the solenoid valves from the system.
(b) Inspect the gasket surfaces and exposed valve parts.
(c) Perform a visual inspection to the extent practical to determine any corrosion, deformation or abnormality that might adversely affect the performance of the valves.
(d) Refurbish the solenoid valves, replacing elastomeric parts or the entire valves.

A.2.12. Expansion joints (elastomeric and metallic)

A.2.12.1. Inspections

Perform inspections every four years for all expansion joints to detect the following:

(a) Leaks;
(b) Ruptures;
(c) Unanticipated vibrations;
(d) Axial misalignments;

(e) Lateral misalignments;
(f) Torsional misalignments (twists);
(g) That the face to face dimensions are correct (overelongation or overcompression);
(h) Wear, loose fasteners and improper assembly of hinges, limit rods or tie rods, where installed;
(i) Weld cracks;
(j) Damage to flanges;
(k) Internal erosion (when accessible);
(l) Cracks, missing bolts and loose nuts in covers and fasteners, when accessible;
(m) Deformations in bellows (rubber/fabric expansion joints);
(n) Blistering, deformation and ply separation of rubber or fabric bellows;
(o) Exposed or torn fabric or metal reinforcement of the expansion joint core;
(p) Scale, flakes, cracks, cuts and tears on the outer surface;
(q) Deterioration (looking for soft spots and gummy texture) of the rubber (cover and joint) and arch;
(r) Soft spots in arches that may indicate cover separation or separation between core layers (depressing arches to identify these);
(s) Indications that fasteners or other hardware are coming into contact with the expansion joint;
(t) Evidence of paint or other coatings that could cause damage to the expansion joint;
(u) Excessive bulging at the flange connection, indicating that bolts are overtightened.

A.2.12.2. Additional inspections

Perform additional inspections of metallic expansion joints every four years to detect the following:

(a) Signs of rubbing;
(b) Evidence of impingement;
(c) Evidence of overheating (discoloration);
(d) Corrosion (both external and internal when available);
(e) Abnormal noise indicating loose internal parts (internal liner damage);
(f) Proper clearance between covers and bellows where installed;
(g) Proper gap between convolutes;
(h) Cracking around circumference of bellows.

A.3. AUXILIARY SYSTEMS

A.3.1. Air handling units

For air handling units, perform the following:

(a) Monthly vibration and noise checks;
(b) Annual greasing;
(c) Quarterly filter replacement;
(d) Internal inspections every two years;
(e) Motor testing as applicable.

A.3.2. Dampers and damper actuators

A.3.2.1. Testing

Test dampers and actuators in accordance with safety requirements (i.e. safety analysis report or another basis document).

A.3.2.2. Inspection and cleaning

Inspect and clean the dampers and actuators every eight years, including the following:

(a) Inspect the dampers and actuators and verify free movement of the dampers and linkages.
(b) Exercise/cycle the dampers and ensure proper operation and indications.
(c) Inspect the dampers and linkages for evidence of racking or binding.
(d) Inspect the flexible connectors and replace if necessary.
(e) Inspect the duct frames for flexible boots.
(f) Inspect for evidence of damage, loose or missing parts, and fasteners.
(g) Lubricate the damper linkages and limit switch lever arms, bushings and bearings.
(h) Perform general cleaning and wipe down.
(i) Inspect the damper actuators.
(j) Inspect the ducting and frames for buildup of dirt and debris.
(k) Replace the damper drive shaft collars/brackets and shaft packing.
(l) Inspect for wear, excessive movement and general condition of damper linkages, dampers, actuator switch positions and all seals, bearings, blades and control shaft connections.
(m) Ensure that the insulation is intact and in the correct position.

(n) Ensure that the damper locking screws are tight.
(o) Verify that the damper position set points are within specified ranges.

A.3.3. Diesel generators

A.3.3.1. Fluid sampling

Sample diesel generator fluids at the following frequencies:

(a) Lube oil at six month intervals;
(b) Coolant at one year intervals;
(c) Fuel oil at three month intervals.

A.3.3.2. Minor inspections

Perform minor inspections for diesel generators annually, including the following:

(a) Change the lube oil (if oil sample results indicate that this is necessary).
(b) Replace the fuel filters and clean the fuel lift pump strainers.
(c) Replace the coolant filters.
(d) Check the air intake systems.
(e) Check the air filters and clean or replace as necessary.
(f) Inspect the heat exchanger plugs.
(g) Inspect the engine hoses.
(h) Clean and inspect the raw water strainers.
(i) Inspect the torque of the engine turbo charger mounting nuts.
(j) Ensure the engine mounting nuts are wrench tight.
(k) Inspect the drive belts.
(l) Clean and inspect the cooling systems.
(m) Inspect the fuel lines.
(n) Check the crank-case vent systems.
(o) Lubricate the tachometer drive adapters.
(p) Clean and inspect the electrical controls.
(q) Check the heater operation (Megger test).
(r) Check the engine fluids are at a proper level.
(s) Visually inspect the drive shaft U-joints (couplings).
(t) Check the mounting isolators.
(u) Monitor the oil pressure and coolant temperature.
(v) Take run meter readings.
(w) Verify that there is no external leakage from lube oil, cooling or fuel systems.

(x) Perform full load testing.
(y) Measure noise and vibration.
(z) Assess startup time trend.

A.3.3.3. Major inspections

Perform major engine inspections every six years, including the following:

(a) Remove the fuel pumps, calibrate the fuel pumps and reinstall.
(b) Remove, clean and calibrate the fuel injectors and reinstall.
(c) Adjust the injectors and set valves, valve lash.
(d) Install and adjust the valve crossheads.
(e) Verify the crosshead and valve spring retainer clearance.
(f) Install and adjust the rocker lever housing covers and gaskets.
(g) Remove the governors, calibrate and reinstall.
(h) Document the gasket material type used.
(i) Install the breather tubes.
(j) Visually inspect the turbo chargers and replace as required.
(k) Verify the clearance of turbine shafts.
(l) Check the clearance of compressor impellers.
(m) Check the clearance at turbine wheels.
(n) Perform an engine tune up.
(o) Check the engine fluids are at proper levels.
(p) Monitor the oil pressure and coolant temperature.
(q) Take run meter readings.
(r) Verify that there is no external leakage from lube oil, cooling or fuel systems.
(s) Inspect the generators.
(t) Inspect the governors and calibrate.

A.3.3.4. Two year inspection and replacement of worn items

Perform the following for diesel generators at two year intervals:

(a) Replace the air filters.
(b) Replace the belts (may be deferred with engineering concurrence if the belts are in good condition and periodic walkdowns include belt visual inspection).
(c) Replace the coolant hoses.
(d) Replace the coolants.
(e) Replace the thermostats.
(f) Inspect and tighten the high pressure fuel lines.

A.3.3.5. Trends in performance evaluation and load test/qualification test data

Monitor trends in performance evaluation and load test/qualification test data for diesel generators.

A.3.4. Cranes and hoists

A.3.4.1. Daily inspections

For cranes and hoists, perform daily inspections for the following:

(a) Operating mechanisms for proper operation, proper adjustment and unusual sounds;
(b) Upper limit device operation;
(c) Hooks and hook latches (if used) for distortion, wear, cracks, nicks, gouges, latch engagement/condition and hook attachment;
(d) Hoist ropes and end connections for gross damage, such as distortion (e.g. kinking, crushing, unstringing, bird caging, displacement of strand, protrusion of core), erosion or corrosion, broken or cut or damaged strands and number of visible broken wires (type and distribution);
(e) Rope for proper spooling onto the drums (this inspection is conducted by a qualified crane operator).

A.3.4.2. Monthly inspections

For cranes and hoists, perform monthly inspections for the following:

(a) Fasteners;
(b) Leakage in lines, valves and other parts;
(c) Hook latches for proper operation;
(d) Load and pull chain for obvious defects;
(e) External evidence of damage to supporting structures or trolleys;
(f) Warning labels in place;
(g) End connections of wire ropes or load chains;
(h) External evidence of worn, corroded, cracked or distorted parts;
(i) Hooks: visual inspection for cracks, missing parts or damage;
(j) Cables: inspect main hoist cables for broken/frayed wires, excessive wear, kinking, crushing, cutting, unstranding, heat damage and electrical arcing damage, and ensure rope diameters are within specification;
(k) Drums and reeving: verify that the cables are lying properly in the main and auxiliary hoist drum grooves;

(l) Generate records of inspections.

A.3.4.3. Annual inspections

For cranes and hoists, perform annual inspections for the following:

(a) Members: check for any deformations, cracks, erosion or corrosion.
(b) Fasteners such as nuts and bolts, pins or rivets: check for any missing and any looseness.
(c) Sheaves and drums: check for any cracks or wear and tear.
(d) Parts such as wheels, shafts, gears, bearings, rollers, pins, locking and clamping devices, bumpers and stops: check for any distortion, wear and tear.
(e) All parts of brakes: check for excessive wear.
(f) Controllers, master switches, contacts, limit switches and pushbutton stations: check for deterioration.
(g) Motion limit switches: check for proper operation.
(h) Rope reeving: check for compliance with manufacturer's recommendations.
(i) Function labels: check for legibility and replacement.
(j) Bridge wheel bearings, cable take-up reel, trolley wheels and drum bearings.
(k) Wheels and rails, tracks, track sweeps, steel, base plates and anchors (welded on trolley), rail splices and bolting, cable take-up reels and bumpers (trolley).
(l) Gearboxes (bridge drive gears, bridge drive spur gears, cable drum reduction gears, trolley drive spur gear speed reducers).
(m) Brakes (bridge drive brakes, hoist brakes, trolley drive brakes).
(n) Motor couplings (bridge, trolley, hoist motor couplings).
(o) Drums and cable reeving.
(p) Equalizer sheaves.
(q) Operational checks, run trolley and bridge.
(r) Smoothness and no unusual noise or vibrations.
(s) Hook and block: check for cracks, missing parts or damage, and measure twist and throat opening and ensure that they are within specifications.
(t) Cables: check for broken or frayed wires, excessive wear, kinking, crushing, cutting, unstringing, heat damage and electrical arcing damage, and that rope diameters are within specifications.
(u) Loose or spare parts, tools or trash left on crane: final visual checks.
(v) Load tests as required by national standards.

A.3.4.4. Annual crane electrical checks

For cranes, perform annual electrical checks as follows:

(a) Remove dirt, oil and grease from all electrical components.
(b) Inspect the electrical contacts for wear.
(c) Inspect the power cables, nuts and connection wires on panels and resistors, particularly those that are subject to vibration.
(d) Inspect the pendants and controls for proper operation of pushbuttons and switches.
(e) Check the enclosures for broken covers and loose fittings.
(f) Check the operation of the motor controls to verify that all accelerating contactors, timers, etc. are operating satisfactorily.
(g) Check the alignment of the collector arms with collector buses.
(h) Verify that the festoon cables travel freely and are held securely.
(i) Check the mainline and trolley conductors and collectors.
(j) Check the motor protection panel.
(k) Check the control panels, resistor panels and panel heaters.
(l) Check the motors (hoist, bridge, trolley).
(m) Check the brake linings, pins, pin keepers, solenoid plunger strokes and torques.
(n) Check the main and bridge master and limit switches and off/reset switches.
(o) Check the lights and warning signals.

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Annex I

AGEING MANAGEMENT PROGRAMME AND ITS IMPLEMENTATION FOR THE TRIGA MARK II RESEARCH REACTOR AT THE LABORATORY OF APPLIED NUCLEAR ENERGY (LENA), UNIVERSITY OF PAVIA, ITALY

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I–1. INTRODUCTION

Since 1965, the Laboratory of Applied Nuclear Energy (LENA) at the University of Pavia has operated a TRIGA Mark II type reactor built by General Atomics (Training, Research, Isotopes, General Atomics — TRIGA). This reactor operates at 250 kW in steady state and is used to support education and training programmes, neutron activation analysis activities, medical and industrial research, and applied nuclear science in general.

I–1.1. Licences

After the initial licence in 1965, the following new licences were obtained:

- 1990: new licence. Every five years the owner applies for a licence extension by sending the following to the regulator: information on safety matters for the previous five years of operation; a review of relevant structures, systems and components (SSCs) for nuclear safety and health protection; and any changes suggested by international operational experience.
- 2005: new operational limits and conditions for solid waste management.
- 2013: implementation of the IAEA Code of Conduct.
- 2019: design basis accident revision submitted to the regulatory body for approval.

I–1.2. Type of reactor

The pool type TRIGA Mark II nuclear research reactor offers different in-core and out-core neutron irradiation channels, each characterized by different neutron flux spectra. The light water in the pool serves as a coolant and moderator and also provides shielding. The fuel, with 8 wt% uranium content,

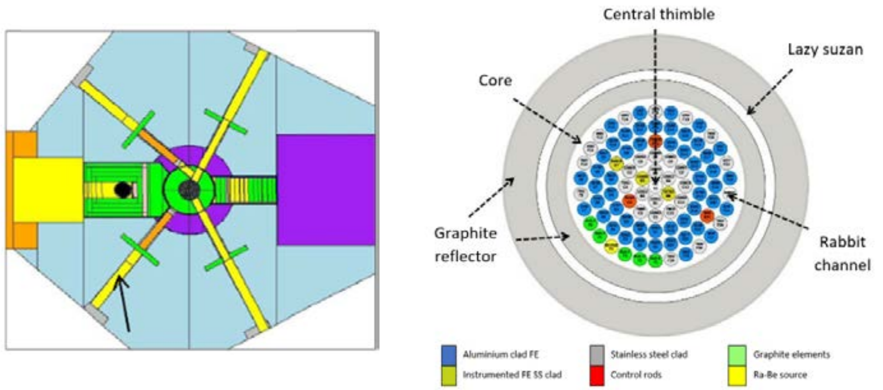

FIG. I–1. Left: cross-section of the LENA TRIGA reactor; right: core of the reactor.

enriched to 19.95 wt% in ^{235}U, and with zirconium hydride (91% zirconium and 1% hydrogen) as fuel moderator material, has a negative prompt temperature coefficient of reactivity. The reactor core (see Fig. I–1) has 90 positions, distributed over five concentric rings, which can contain either fuel elements or graphite (dummy) elements or control rods or in-core irradiation channels. The control rods, termed shim, regulating and transient, are used to control core reactivity. Shim and regulating rods contain boron carbide, while the other rod is filled with boron enriched graphite. The core is surrounded by a 30 cm thick radial graphite reflector, and two graphite cylinders located at the ends of each fuel element (inside the cladding) serve as axial reflectors.

I–2. AGEING ASSESSMENT AT THE FACILITY

To continuously improve the quality of reactor management and to accomplish stakeholder requirements (within both legal and commercial frameworks), LENA implemented an integrated management system (IMS) in 2010. This choice was the basis of the subsequent implementations, such as IAEA Safety Standards Series No. GS-R-3, The Management System for Facilities and Activities [I–1], and subsequently IAEA Safety Standards Series No. GSR Part 2, Leadership and Management for Safety [I–2]. Effective maintenance, ageing management and in-service inspection (ISI) are some of the most important activities to achieve safety and maintain the intent of the design objectives during the operation of the facility. As far as ageing is concerned, the introduction of an IMS led to the following main benefits, as presented in Ref. [I–3][1]:

(a) Better and more detailed in-service control plans have been defined to examine facility components and systems for possible deterioration in their integrity, in order to assess the safety margins and their acceptability for continued operation of the plant and to take corrective measures as necessary. The main systems and equipment that are important for the safety of the facility are identified in the maintenance and equipment control plan, which includes the requirements concerning frequency of inspections, methods for inspections and acceptance criteria.
(b) More accurate control of equipment has been achieved — all instruments are in a documented metrological confirmation plan.
(c) An enhanced surveillance programme has been implemented to verify and confirm that the provisions made in the design to ensure safety margins are maintained and the safety of the facility does not depend on untested or unmonitored SSCs.
(d) A performance review programme aiming to identify and rectify gradual degradation, chronic deficiencies and potential problem areas or causes has been implemented. This includes the review of safety related non-conformances and failures of SSCs at the facility, determination of their root causes, trends and patterns, and evaluation of their safety significance, lessons identified and corrective actions taken.
(e) The control of documents and records that is now in effect ensures that personnel only use up to date documentation, avoiding the accidental use of obsolete documents, work instructions or diagrams. Appropriate procedures have also been adopted for the management of obsolete documents. Well managed records ensure proper process traceability, as well as providing a database for the status of the individual components and systems.
(f) A quarterly audit has been implemented that considers the status of the different processes and previous findings, as part of the planned audit programme, which includes audit criteria, scope, frequency and methods, documentation and the inputs for the periodic management review.
(g) Periodic management review of the status of SSCs has been implemented; the review has a specific documented procedure and includes evaluations for improvement opportunities and for changes needed, quality objectives and quality policy. The review findings are documented, maintained and utilized as input for future action and review.

[1] Some of the content in this annex has been reproduced from Ref. [I–3] with permission.

(h) With regard to the supply chain, accurate control of purchased products and their suppliers has been implemented, ensuring compliance with requirements in terms of safety, quality and reliability. A key point is ensuring adequate availability of spare parts and the implementation of a purchase plan that can compensate for the obsolescence of components, ensuring that changes in technology are compatible with the installed components.

I–3. IMPLEMENTATION OF AN AGEING MANAGEMENT PROGRAMME

Based on the positive outcomes from the implementation of the above mentioned activities and for a better and more formal consideration of ageing concerns, in 2014 LENA implemented a formal ageing management programme (AMP) following IAEA Safety Standards Series No. SSG-10, Ageing Management for Research Reactors [I–4][2].

The AMP resulted in a set of organized policies, processes, procedures and activities for managing the ageing of SSCs, with the main purpose of ensuring the reliability and availability of the required safety functions throughout the extended life of the facility.

I–3.1. Method for screening and prioritizing SSCs

The categorization of SSCs susceptible to ageing was realized through a detailed analysis of systems, in accordance with the process depicted in Fig. I–2. Based on the screening results, SSCs were analysed in detail through a series of screenings aiming to identify the most relevant activity areas not already included in the IMS and in need of the implementation of new or revised procedures for ageing management.

Furthermore, to manage ageing, it was necessary to understand how ageing affects the components and materials that are used to achieve the overall safety of the reactor, or in other words, the ageing mechanisms. Based on a preliminary analysis, reviewed during the IMS activities, Table I–1 presents a list of the additional planned activities regarding the SSCs that LENA identified as important for safety that had not been previously included in the periodic maintenance programme or the test and inspection activities in the AMP.

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[2] SSG-10 has since been superseded by INTERNATIONAL ATOMIC ENERGY AGENCY, Ageing Management for Research Reactors, IAEA Safety Standards Series No. SSG-10 (Rev. 1), IAEA, Vienna (2023).

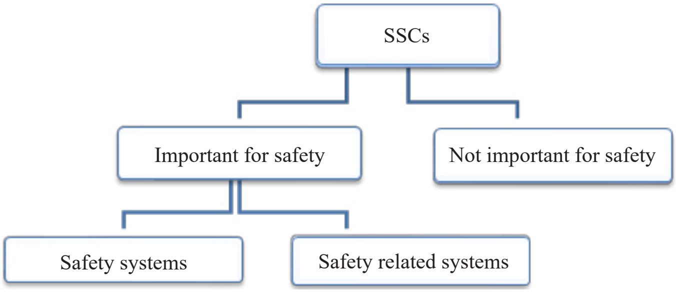


FIG. I–2. Categorization of SSCs.

TABLE I–1. ADDITIONAL PLANNED ACTIVITIES FOR THE STRUCTURES, SYSTEMS AND COMPONENTS INTRODUCED IN THE UPDATED AGEING MANAGEMENT PROGRAMME

Structure, system or component	Planned activity
Pool structure and vessel Core structure Reflector Shielding Beam tubes Liner Fuel assemblies and storage in reactor pool	Visual inspections with underwater cameras, development of procedures and definition of acceptance criteria. Assessment of results
Primary	Efficiency monitoring by on-line data acquisition and real time parameter evaluation. Trending of data to assess conditions. Periodic result evaluation
Biological shield	Efficiency of shielding of gamma and neutron dose to be tested every five years

TABLE I–1. ADDITIONAL PLANNED ACTIVITIES FOR THE STRUCTURES, SYSTEMS AND COMPONENTS INTRODUCED IN THE UPDATED AGEING MANAGEMENT PROGRAMME (cont.)

Structure, system or component	Planned activity
Ventilation: emergency	Improved maintenance and controls on the rotating equipment. Definition of procedures
Control console (LOG channel, scram loops)	New channel refurbishment. Updating of documentation and management of spare parts. New calibration procedure
Cabling (control console internals and interconnections)	Step by step cable replacement
Shielding	Visual inspections. Definition of test to be carried out periodically
Beam tube lines	

I–3.2. Content of the AMP

The AMP includes the following main elements:

(a) Screening of SSCs for reliability and safety;
(b) Detection, monitoring and trending of ageing degradation;
(c) Preventive actions to minimize expected ageing degradation;
(d) Continuous improvement of the AMP;
(e) Management of obsolescence.

The overall graded and systematic approach to reactor ageing management is based on the well known Deming cycle (plan–do–check–act, PDCA), as shown in Fig. I–3, and aims for the continuous improvement of safety and the efficiency and effectiveness of the AMP.

I–3.3. Ageing/modernization/refurbishment management programme

The complete and detailed AMP is summarized in Table I–2. Each activity for the SSCs included in the programme was assessed separately, considering replacement complexity (see Section I–3.3.1). For each SSC, the number code of the ageing mechanism is provided (following the recommendations

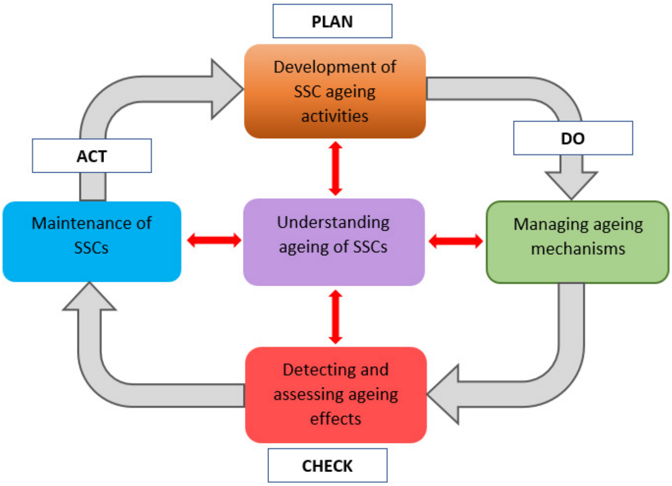


FIG. I–3. The plan–do–check–act cycle for ageing management.

in SSG-10 [I–4]), as well as information on periodic checks, minimizing and mitigating actions, frequencies and documentation used to record the information for each SSC.

I–3.3.1. Replacement complexity

Three categories of replacement complexity were considered in the AMP, as follows:

- *A: high.* The replacement is discussed, approved through the safety committee and approved by the regulatory body. Usually, the replacement implies shutdown of reactor operation. The commitment, in terms of working hours and staff qualifications, is very high; it usually implies external services. In some cases, the convenience is to be assessed by reviewing the facility strategies.
- *B: medium.* The replacement has to be scheduled, discussed and approved through the safety committee. Some of these activities have to be communicated to or approved by the regulatory body. Usually, the replacement implies shutdown of reactor operation. The commitment, in terms of working hours and staff qualifications, is high; it may imply external services.
- *C: low.* There are no special system requirements. In the reference documentation, systems are often described solely by functional properties,

TABLE I–2. SUMMARY OF THE COMPLETE AGEING MANAGEMENT PROGRAMME

SSC	Replacement complexity[a]	Ageing mechanism[b]	Periodic checks, minimizing and mitigating actions	Frequency
LINER AND INNER REACTOR STRUCTURES				
Tank structure, liner	A	1, 5	Video inspection, ordinary cleaning	Every 3 years
Core structure	A	1, 5	Video inspection, ordinary cleaning	Every 3 years
Reflector	A	1, 5	Video inspection, ordinary cleaning	Every 3 years
Control rods	A	1, 5	Video inspection, ordinary cleaning	Every 3 years
HANDLING OF CONTROL RODS				
Cabling	B	2, 4	Visual inspection, regular cleaning, screw clamping and connections	Every 6 months
Electrical components	B	2, 4	Visual inspections	Every 6 months
Mechanical components	B	2	Leak inspections, wear, tightening connections and joints	Every 6 months
Rod guide	B	2	Visual inspection, greasing, regular cleaning,	Monthly
Experimental channels (A, B, C, D, CT, thermal column)	A	1, 5, 7	Video inspection, ordinary cleaning	Every 3 years
Fuel	B	1, 3, 5	Visual inspection, and/or camcorder check for elongation and bending	Annual/1/3 of the fuel in core

TABLE I–2. SUMMARY OF THE COMPLETE AGEING MANAGEMENT PROGRAMME (cont.)

SSC	Replacement complexity[a]	Ageing mechanism[b]	Periodic checks, minimizing and mitigating actions	Frequency
Fuel storage systems in the tank	C	5	Video inspection, ordinary cleaning	Every 3 years
Measuring channels (inside the tank)	B	1, 5, 7	Video inspection, ordinary cleaning	Every 3 years
Core irradiation channels	B	1, 5, 7	Video inspection, ordinary cleaning	Every 3 years
Water quality (tank and pool)	n.a.[c]	n.a.	pH/conductivity measures	Monthly
PHYSICAL CONFINEMENT				
Structure of the reactor hall	A	n.a.	Internal visual inspection	Daily
			General cleaning	Biannual
			General visual inspection, including external base and cover (sheathing, waterproofing, plastering, bearing structures)	Annual
Concrete shield	A	n.a.	Internal visual inspection	Daily
			General cleaning, door inspections, channels	Annual
			Neutron map	Every 5 years
Ventilation	B	n.a.	System operation, depression check	Daily
			Check flow	Monthly

TABLE I–2. SUMMARY OF THE COMPLETE AGEING MANAGEMENT PROGRAMME (cont.)

SSC	Replacement complexity[a]	Ageing mechanism[b]	Periodic checks, minimizing and mitigating actions	Frequency
			Engine verification and transmission	On-line monitoring application
			Instrumental HEPA filtration efficiency check	Annual
Emergency ventilation	B	n.a.	System operation, start test	Monthly
			Check flow	Monthly
			Engine verification and transmission	On-line monitoring application
			Instrumental verification of active carbon filtration efficiency	Every 18 months
INSTRUMENTATION AND CONTROL				
Control console	A	4, 8, 9	Operability	Every utilization
			Instrumentation calibration	Every 2 years
Monitoring area	B	4, 8, 9	Operability	Daily
			Calibration on-site	Every 3 months
Radiation protection fixed instrumentation	B	8, 9	Operability	Daily
			Calibration on-site	Monthly

TABLE I–2. SUMMARY OF THE COMPLETE AGEING MANAGEMENT PROGRAMME (cont.)

SSC	Replacement complexity[a]	Ageing mechanism[b]	Periodic checks, minimizing and mitigating actions	Frequency
Environmental monitoring units, particulates	C	4, 8, 9	Operability	Daily
Particulate monitoring reactor hall	B	n.a.	Calibration on-site	
			Operability	Daily
Cooling system reactor	B	4, 5, 7, 8, 9	General visual inspection and sealing	Daily
			Pump operability	Monthly
			Conductivity verification	Every utilization
			Measurements and operating data acquisition	Every utilization
			Check filters	
Hydraulic auxiliary reactor systems (pool pump, demineralized water production, water tank)	B	4, 5, 7, 8, 9	General visual inspection and sealing	Daily
			Pump operability	Every utilization
Alarm and evacuation systems	B	8	Operability	Daily
Cables	B	2, 8	Visual inspection	Every 6 months
Remote monitoring	B	8	Operability	Daily

TABLE I–2. SUMMARY OF THE COMPLETE AGEING MANAGEMENT PROGRAMME (cont.)

SSC	Replacement complexity[a]	Ageing mechanism[b]	Periodic checks, minimizing and mitigating actions	Frequency
Pneumatic systems	B	4, 8	Operability, lubrication	Annual
AUXILIARY EQUIPMENT				
Electrical and mechanical systems	C	2, 8, 9	Ordinary maintenance for fire prevention, work safety regulations	Monthly/every 2 years/every 3 years
Diesel generator and uninterruptible power supply	C	2, 8, 9	Operability, battery test, levels	Every 2 weeks
Fire detection system	B	2, 8, 9	Scheduled maintenance according to local regulations	Biannual
Emergency communications (e.g. radio, telephone)	C	2, 8, 9	Operability, battery testing, communication testing	Every 2 weeks
Crane	A	8, 9	Visual inspection, operability, functional testing	Every 3 years[d]
Radioactive waste storage	B	5	Visual inspection, radiation protection inspection	Biannual
Fuel in well	A	5	Video inspection with camera, ordinary cleaning	Annual
Compressors	C	3, 4, 8, 9	Transmission inspection, pressure gauge, lubricating levels	Annual
Laboratory hoods	B	4, 8, 9	Check operability, depression, held	Each utilization

TABLE I–2. SUMMARY OF THE COMPLETE AGEING MANAGEMENT PROGRAMME (cont.)

SSC	Replacement complexity[a]	Ageing mechanism[b]	Periodic checks, minimizing and mitigating actions	Frequency
			Instrumental tests	Annual
DOCUMENTATION				
Documentation facility	B	9, 10	Document verification	Annual
Documentation QMS[e]	C	9, 10	Internal audit	Annual
Operating licence	A	9, 10		Every 5 years

[a] See para. I–3.3.1.
[b] See para. I–3.3.2.
[c] n.a.: not applicable.
[d] According to the National Institute for Insurance against Accidents at Work (INAIL).
[e] QMS: quality management system.

so, when needed, internal approval is sufficient. Usually, replacement does not imply shutdown of reactor operation. The commitment, in terms of working hours and staff qualifications, is low; it usually does not imply external services.

I–3.3.2. Ageing (degradation) mechanisms

The following ageing (degradation) mechanisms were considered, using coding in accordance with SSG-10 [I–4]:

(1) Change of properties (physical, chemical, mechanical) due to neutron irradiation;
(2) Change of properties (physical, chemical, mechanical) due to operating temperatures;
(3) Mechanical stresses or cracks due to temperature or operating pressure;
(4) Fatigue phenomena, material consumption due to thermal cycles, mechanical load, flow, induced vibrations;
(5) Corrosion;
(6) Chemical processes;
(7) Erosion;
(8) Technology changes;
(9) Changes of regulations, prescriptions, etc.;
(10) Documentation obsolescence.

I–3.4. Corrective activities and implementations

In recent years, many activities have been carried out to prevent, manage and mitigate ageing effects. The most relevant from safety, technical and economic perspectives have focused on the following:

(a) Biological shield efficiency test (1997). After approximately 35 years of utilization of the biological shield, a new neutron and gamma dose inspection was performed to verify the shielding efficiency. The 1997 campaign of measurements was performed with modern and calibrated instruments. Gamma dose and neutron dose were assessed separately on each wall of the biological shield, with a dedicated grid of measurement points. The tests showed that there were no changes compared with the original situation. Based on the results of the tests, changes were introduced and safety procedures were implemented in the field of radiation protection for some mechanical and electrical maintenance procedures.

(b) Electrical power distribution and emergency power supply replaced (2000). The electrical system was completely replaced owing to the obsolescence of components, changes in regulations and deterioration of cables. Even if this system is not strictly a safety system, its availability and reliability can ensure correct operation of the reactor. Furthermore, the installation of better performing components, together with more efficient surge suppressors, avoids and contains potential damage caused by external events such as spikes, transients or indirect lightning. Safety critical systems are operated as privileged loads, through an on-line uninterruptible power supply. The emergency power supply provided by a diesel generator was also replaced with a better performing one. The newly installed components lowered the overall fire related risk of the electrical power distribution, providing an overall safety improvement.

(c) Heating, ventilation and air filtration system renewed (2001). Owing to the ageing of components and repetitive unscheduled maintenance activities, and in order to avoid long unplanned periods of reactor shutdown, the new system was completely renewed with a new computerized air filtering and ventilation system. The inlet air is filtered by high efficiency (~95%) filters, while the air extracted from the reactor room is filtered by HEPA filters (total efficiency >99.95%) before release to the atmosphere. The air extraction is powered by an inverter driven motor that automatically keeps the reactor building pressure at 50 Pa less than atmospheric pressure, as required by technical prescriptions. The new system is now equipped with a modern computerized supervisory system capable of visualizing and analysing data, a feature that has been particularly useful for preventive maintenance purposes.

(d) Radiation monitoring system renewed (2006). The area radiation monitoring system was renewed after 30 years of operation. The new system — based on proportional counters, a microcomputer (programmable logic controller, PLC) and in-house software — completely replaced the former one based on analogue components and Geiger type counters. The system collects the data sampled by six β-γ dose rate proportional counters, a free air ionization chamber and a weather station through a serial data bus. Collected data are stored and displayed on a personal computer in the reactor control room as well as in the emergency control room. The software allows the operator to access the data, modify parameters and perform tests remotely.

(e) Cooling system refreshed (2007). A complete substitution of the tertiary heat exchanger and a partial substitution of the components of the secondary heat exchanger circuit was realized, owing to corrosion and degradation phenomena. In particular, the substitution involved the following components: secondary/tertiary circuit heat exchanger (plate type); tertiary circuit water flow control valve, valve drive motor and valve controller (proportional integral differential type); tertiary circuit water filters and magnetic filter for water macromolecules and carbonate removal. For predictive and improved maintenance purposes, a dedicated PLC based data acquisition system was implemented to collect data, thus obtain on-line parameters for evaluating the system behaviour (e.g. heat exchange efficiency, pump efficiency, pressure/temperature drops across the exchangers).

(f) Reactor console refurbishment (2008). Most instrumentation and control (I&C) systems had been in operation since their first installation in 1965. Over the years, several repairs had to be carried out, affecting system availability. Moreover, the original design was based on electromechanical components and vacuum tubes, and the availability of spare parts was becoming a critical issue. In order to provide safe and continuous reactor operation in the future, improving reliability and extending the system lifetime, most of the I&C components were refurbished with local resources using high quality commercial components. Channel by channel replacement of the complete I&C system was achieved without any change in the operating and safety logics. Owing to the new components, a dedicated acquisition system was implemented for data collection and analysis. The substituted systems were: power level channels, water radioactivity meter, water temperature meter, water conductivity gauges, peak neutron flow indicator circuit and integrated fuel temperature indicator circuit, automatic power adjustment circuit and high voltage supply.

(g) Off-gas radiation monitoring system replaced (2009). The off-gas radiation monitoring system was completely replaced with a new measurement system based on a NaI spectroscopy detector. The gamma ray spectrum of reactor gaseous effluents is collected on-line using commercial software, and data are remotely accessible (i.e. from the reactor control room or the reactor emergency control room). In addition, the monitoring system for environmental airborne particulates was completely upgraded and redesigned for better efficiency and reliability.

(h) Water purification system refurbished (2010). After approximately 20 years of utilization, the filling water demineralization system was completely replaced with a new mixed bed, laboratory grade demineralizer. In this type of demineralizer, cation and anion resin beds are mixed together. The new system allows safer and quicker resin replacement, avoiding personnel having to deal with resin regeneration and acid or alkali solution handling.

(i) Re-evaluation of accident scenarios and review of emergency plans (2010). A re-evaluation of the accident scenarios and their assumptions in the light of new guidelines, standards and legislation was performed, leading to a review of the emergency plans. Each year an emergency drill is organized in the presence of the regulatory body with the cooperation of the responsible institutions. Notes and recommendations are then discussed in a final briefing.

(j) Data acquisition system implementation (2012). Several efforts have been made recently to implement a comprehensive data acquisition system for the most important parameters (e.g. reactor console, radiation monitoring systems, ventilation, cooling systems). The system allows constant monitoring of parameters and early detection of anomalies or drifting instruments to prevent potential and unexpected failures. With this being an extensive predictive maintenance activity, it is also useful for ageing management; in fact, performance trends can be good indicators of system degradation, and the related data analysis can contribute positively to a more efficient understanding of ageing effects and countermeasures.

(k) Review of training programmes for operating personnel (2014). The proposed programmes provide general guidance to meet the training requirements and qualification of the operating personnel at the research reactor based on best practices.

(l) Video inspection campaign for the reactor pool internals and spent fuel dry storage (2014). A campaign of visual inspection (with miniature TVCC/endoscopes) of the reactor pool internals and spent fuel dry storage was carried out and future activities are scheduled. The results were reported to and evaluated by the safety committee during a meeting on 31 October 2014.

(m) Reassessment of external events (2016). Updated information on siting, demographics, seismicity, hydrology and meteorology was assessed.

(n) Bridge crane verification (2016). The crane was verified through operational testing.

(o) New particulate monitor (2016). An ambient monitor for beta measurements in the air was installed. The monitor has two cylindrical stainless steel ionization chambers and integrated electronic processing complete with a display and functional interface for the operator.

(p) New UNIT 300 control unit (2016). UNIT 300 was replaced for the following reasons: analysis of non-conformity recorded an increased number of scrams related to the control unit, decreasing reliability of analogue components, lack of spare parts, and cable ageing. The new UNIT 300 has the same logic and update components.

(q) New logarithmic channel (2017). Installing a new logarithmic channel was a preventive action prompted by the obsolescence of the components and the extreme difficulty of finding spare parts for the system in use. A new channel was selected, purchased and installed, including the preamplifier and the detection system (new fission chamber with the same characteristics as the one installed and connecting cables). The project involved a test phase with the new system operating in parallel with the old one (not connected to the safety circuits) and a solid database was obtained to determine the correct functioning of the system and the response of the measurements between the two channels. On the basis of the positive results obtained, the channel was replaced.

I–4. CONCLUSIONS

Having a management system already in place was particularly beneficial for the implementation of an AMP. Several aspects of the management system have been utilized for ageing management, for example the following:

— Control of documents and records. Well managed records ensure proper process traceability, as well as providing a database on the status of the individual components and systems.
— A periodic audit programme that considers the status of SSCs and the implementation grade of planned actions.
— Periodic management reviews and safety committee meetings on the status of SSCs.
— Control of supplies. Accurate control of purchased products and their suppliers ensures compliance with requirements in terms of safety, quality and reliability.

Periodic review and reassessment of ageing conditions is of paramount importance. Ageing is constantly monitored through the following mechanisms:

(a) Periodic management reviews;
(b) Safety committee meetings;
(c) Internal and external audits (quality assurance and ageing evaluations);
(d) Analysis of the data obtained through inspections and parameter checks, as foreseen in the AMP.

REFERENCES TO ANNEX I

[I–1] INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for Facilities and Activities, IAEA Safety Standards Series No. GS-R-3, IAEA, Vienna (2006).

[I–2] INTERNATIONAL ATOMIC ENERGY AGENCY, Leadership and Management for Safety, IAEA Safety Standards Series No. GSR Part 2, IAEA, Vienna (2016), https://doi.org/10.61092/iaea.cq1k-j5z3
[I–3] MAGROTTI, G., et. al, "Operational experience on ageing management at the TRIGA research reactor of LENA", Proc. IGORR 15, Daejeon, 2013.
[I–4] INTERNATIONAL ATOMIC ENERGY AGENCY, Ageing Management for Research Reactors, IAEA Safety Standards Series No. SSG-10, IAEA, Vienna (2010).

Annex II

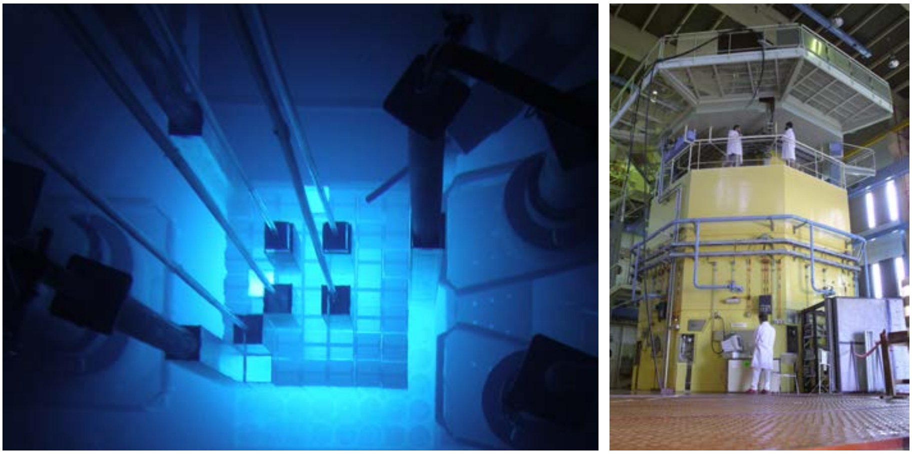
AGEING MANAGEMENT ACTIVITIES AT ARGENTINE RESEARCH REACTOR RA-6

F. Brollo, CNEA, Argentina

II–1. INTRODUCTION

The RA-6 (see Fig. II–1) is an open pool type materials testing reactor (1 MW thermal power, cooled and moderated by light water) that has been operated by the Argentinian National Atomic Energy Commission (CNEA) since 1982. It is mainly used for nuclear engineering teaching, neutron activation analysis, boron neutron capture therapy, nuclear operator training, and reactor physics and instrumentation research.

This annex is divided into two parts. In the first part, the methodology of the ageing management programme (AMP) is described. The second part is dedicated to the implementation of such a programme through a power upgrade of the research reactor.



(a) (b)

FIG. II–1. The RA-6 (a) reactor core and (b) concrete block.

II–2. AGEING MANAGEMENT PROGRAMME METHODOLOGY

II–2.1. Screening of SSCs for the ageing management programme

Research reactors have many structures, systems and components (SSCs). It is not practical or necessary to apply an AMP to all SSCs. The methodology was based on experience and engineering judgement (a case by case analysis of each SSC). Two aspects were considered to determine the applicability of the AMP to SSCs: safety and availability.

II–2.1.1. Factor A: safety

The safety classification process is a systematic approach to identify all items that are important for safety according to their functions and safety significance. Three safety categories (1, 2, 3) were considered on the basis of frequency of occurrence and severity of the consequences if the safety function is not performed.

II–2.1.2. Factor B: availability

Two availability categories (1, 2) were considered on the basis of the relative contribution of the different aspects to the availability and the lifetime extension of the facility. Factor B includes the following aspects:

(a) Availability. When failures of the element can provoke long shutdown of the facility.
(b) Obsolescence. When there are no longer suppliers or there are shortages or a lack of spare parts.
(c) Accessibility. When the elements are in locations not easily accessible for repair or replacement.
(d) Complexity. When the repair or replacement can involve an equipment requalification.
(e) Cost. When the costs of repair or replacement of the elements are high (several thousand dollars).

Categories of the previous factors were taken in pairs to obtain all the combinations, as shown in Fig II–2.

Grading can be applied in determining the appropriate frequency of inspections, in selecting detection methods and in establishing measures for the prevention and mitigation of ageing effects, and may also be applicable to the

(1, 1)	(1, 2)	(2, 1)	(2, 2)	(3, 1)	(3, 2)
Included in the ageing management programme			Included in the ageing management programme using a graded approach		Not included in the ageing management programme

FIG. II–2. Ageing management classification categories.

Categorization for RA6 ageing management programme			
SSC	Factor A	Factor B	To be included
Pool and reactor internals	1	1	Yes
Control rods and mechanisms	2	1	Yes
Fuel assemblies	1	2	Yes
Primary cooling system	2	1	Yes
Secondary cooling system	3	1	See note
Water purification system	3	2	No
Ventilation system	3	2	No
Reactor protection system	1	1	Yes
Compressed air system	3	2	No
Beam tube	1	2	Yes
Cranes	3	1	See note
Radiation monitoring	2	2	See note

Note: Graded approach has to be applied.

FIG. II–3. Summary of SSC categorization for the RA-6 ageing management programme.

resources necessary to implement the AMP. Figure II–3 provides examples of SSCs to which this categorization process was applied.

II–2.2. Detection, monitoring and trending of ageing degradation

On the basis of design, manufacturer specifications, operating experience and judgement, the ageing surveillance activities were planned in line with the categorization process described above. Surveillance activities also took advantage of the existing RA-6 preventive maintenance and periodic testing programmes.

In recent years, several specialized groups of experts from CNEA (e.g. on materials, vibrations, electrical and instrumentation systems, corrosion) were requested to begin with preliminary evaluations in order to detect incipient signs of degradation. The main degradation mechanisms are well known to the experts.

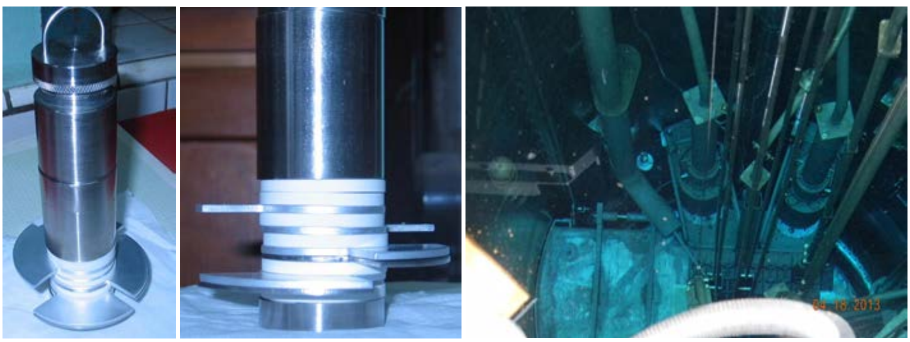
Ageing effects were also detected by looking for changes in measurable operating parameters (e.g. control rod drop time, water chemistry parameters, temperature, flow rate, pressure). They are examined periodically to detect evidence of trends.

The frequency of inspection activity was set on the basis of experience, including experience acquired from similar facilities.

II–2.2.1. Corrosion monitoring programme

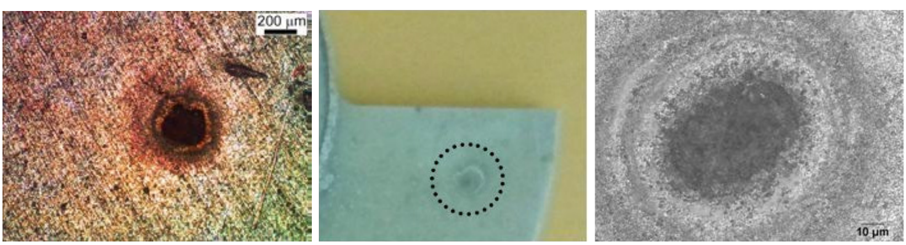
A particularly important material ageing concern is the corrosion of the aluminium cladding of the fuel elements. Racks containing aluminium coupons were placed in the reactor pool and periodic (annual) sampling of pool water was performed to conduct chemical analysis (see Fig. II–4).

In the past five years, aluminium coupons were extracted from the pool each year in order to look for signs of corrosion. As expected, the magnitude of corrosion is strongly dependent on the quality of the water (see Fig. II–5).



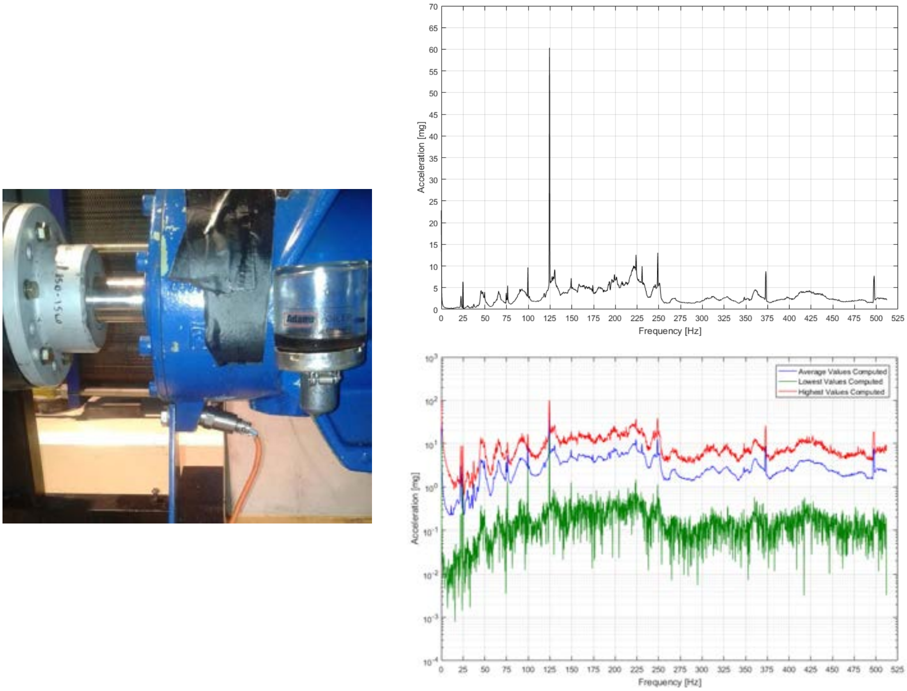
(a) (b) (c)

FIG. II–4. Racks containing aluminium coupons (a) and (b), and (c) racks at the core irradiation position.



(a) (b) (c)

FIG. II–5. Corrosion detected on various aluminium coupons extracted after five years in the reactor pool.



(a) (b)

FIG. II–6. (a) Accelerometer on pump bearing housing and (b) typical vibration analysis using appropriate signal processing.

II–2.2.2. On-line condition monitoring: pump vibrations

An on-line diagnosis tool for the principal rotating components of the primary cooling system was developed, based on vibration analysis using appropriate signal processing and pattern recognition techniques. These trend analyses are developed in order to detect misalignment, imbalance, bearing condition and other sources of vibration. Vibration trend analysis is performed at six month intervals. Figure II–6 shows the accelerometer on the pump bearing housing and typical vibration analysis using appropriate signal processing.

II–2.2.3. Underwater visual inspection

Scratches, wear, cracks, corrosion or erosion of surfaces are detected during underwater visual inspections (see Fig. II–7). During the inspections, lost tools and pieces of equipment at the pool bottom can also be found. Scheduled

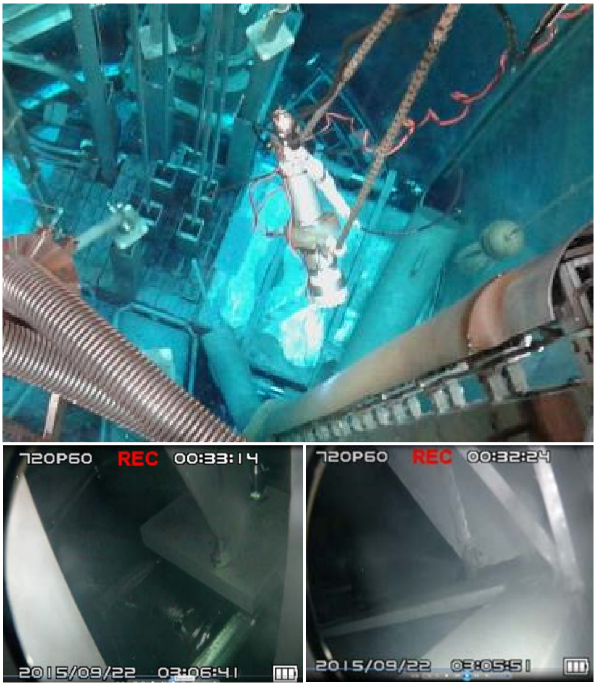


FIG. II–7. Underwater visual inspection.

inspections and visual examinations were established in line with the SSC category. Symptoms of ageing related problems are leaks, cracks, distortion (of dimensions, surfaces or materials), and even discoloration. Operators and maintenance staff are trained to report evidence of changes in the state or appearance of a component or material. Underwater visual inspections are performed every two years.

II–2.2.4. Neutron beam tube inspection

A large number of research reactors are equipped with beam tubes. They can cause a severe leak of pool water, and a periodic non-destructive examination is recommended. Integrity of the coolant boundary is ensured. Scratches, wear, cracks, corrosion or erosion of surfaces are detected through visual inspection every three years (see Fig. II–8).

FIG. II–8. Visual inspection of neutron beam tubes.

II–2.2.5. Flap valve inspection

The flapper (flap valve) in an open pool type research reactor has the safety function of core cooling by natural convection (see Fig. II–9). In the AMP, the following need to be checked periodically (every five years): movable parts, position detection sensor (reed switch and permanent magnet), evidence of corrosion distortion and any sign of malfunctioning.

FIG. II–9. Flapper (flap valve) inspection.

II–2.2.6. Inspection for seizing effects

When applying stainless steel or aluminium fasteners, 'cold welding' (also known as seizing) may occur during assembly. In this case, the threading sticks until no further movement is possible. Periodic visual inspection to detect this effect may prevent complex interventions later. The seizing effect may cause problems during disassembly (i.e. the fasteners do not loosen). Operation nuts, which are often used for reactor pool internals, may develop such problems. In this case, major interventions (e.g. pool water level lowering) are necessary to replace the parts.

An example of an intervention of this type was needed at RA-6 (see Figs II–10 and II–11).

II–2.3. Mitigation of ageing degradation

Once ageing degradation has been detected, mitigatory actions are to be taken. The technical and economic feasibility and viability of these actions need to be assessed on the basis of expert opinions, potential to cause component failure, duration of interventions, and budgetary constraints. Some activities are highly specialized and involve complex and sophisticated techniques. In general, such activities are often performed by contracted, external experts.

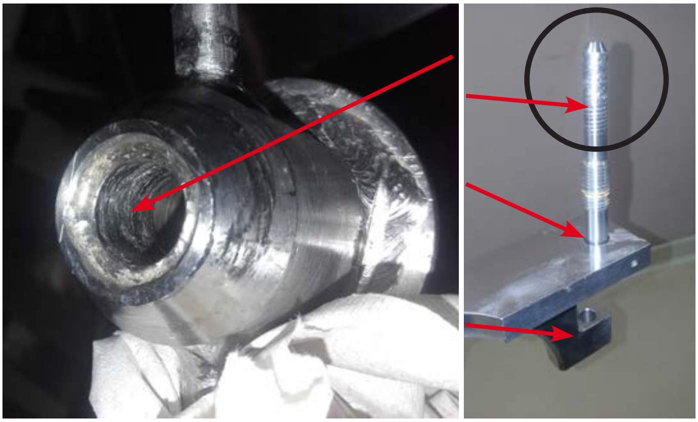


FIG. II–10. Seizing effect.

FIG. II–11. Intervention to solve a seizing effect problem.

II–2.4. Concluding remarks

(a) A methodology was developed for the screening of SSCs as candidates to be incorporated in the RA-6 AMP, taking into account both safety and availability. A graded approach to the programme is to be applied to some SSCs, considering parameters such as frequency of inspections and detection methods, recognizing that, in general, limited resources are available.

(b) To effectively detect or mitigate an ageing effect, the potential for degradation, and the types of degradation mechanisms, need to be understood. The main degradation mechanisms are well known to experts.

(c) The frequency of examination of the SSCs was adjusted on the basis of the likelihood of failure of the SSCs and on the basis of experience, including experience acquired from similar facilities. Once ageing degradation was detected, methods for the mitigation of ageing effects were implemented. Some examples of inspection, monitoring and mitigation activities at the reactor are described in this annex.

(d) Large modernization, refurbishment or modification projects at research reactors require a high degree of expertise in project management, and this can be a good opportunity to develop the skills of the reactor staff that could be useful in future implementation of an AMP. Moreover, these kind of modification projects facilitate some key inspections for early detection of ageing degradation effects, particularly for SSCs that are difficult to access during the operational life stage.

II–3. RA-6 POWER UPGRADE

In the framework of the Global Threat Reduction Initiative (GTRI), a cooperation agreement was signed in 2005 for the conversion of the RA-6 reactor from high to low enrichment. That initiative provided an opportunity to increase the reactor's power in order to optimize its applications, increasing the neutron flux in the core and its irradiation facilities.

From 2007 to 2009, an upgrade project was implemented to modify or replace some SSCs in order to improve safety and reliability and to increase the maximum thermal power of the RA-6 reactor from 0.5 MW to 1 MW. The main affected systems were the primary and secondary cooling systems (i.e. centrifugal pumps, heat exchanger, cooling towers, flap valves siphon breakers, decay tank and piping layout). Upgrades of the instrumentation and control systems, electrical systems and civil works were also performed.

II–4. LESSONS IDENTIFIED IN CONNECTION WITH A SUBSEQUENT AGEING MANAGEMENT PROGRAMME

Lessons identified during the project included the following:

(a) Large modification projects facilitate inspections to detect some ageing degradation effects on SSCs, particularly those SSCs that are difficult to inspect (e.g. decay tanks, flap valves, inner piping parts, core supports and pool internal structures).
(b) Particular attention has to be paid to SSCs with problems of obsolete technology (e.g. reactor protection system instrumentation, radiation monitoring systems).
(c) A configuration management procedure is to be implemented during the project. The systematic control and preservation of technical documentation, in order to support future traceability, is of vital importance.
(d) Modernization and power upgrades of research reactors require a high degree of expertise in the management of engineering projects. Reactor staff develop skills that can be useful in future modification or SSC replacement projects.

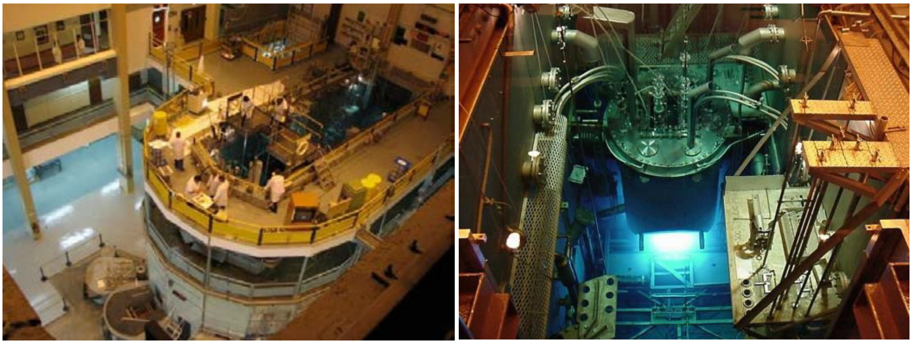
Annex III

AGEING MANAGEMENT PROGRAMME FOR THE SAFARI-1 RESEARCH REACTOR

S. Malaka, NECSA, South Africa

III–1. INTRODUCTION

The SAFARI-1 research reactor (see Fig. III–1) is a high flux materials testing reactor and has been operational in South Africa since March 1965. It is licensed to operate for a maximum power of 20 MW. It is operated 24 h a day, 7 days a week, and on average it runs 303 full power days per year at 20 MW. Throughout its operational history prior to establishing an ageing management programme (AMP), ageing of the facility was addressed by means of various reactive maintenance and upgrade initiatives to replace components that became unmaintainable because of various ageing effects. In 2009, an AMP was initiated in SAFARI-1 to systematically address ageing effects.



(a) (b)

FIG. III–1. The SAFARI-1 research reactor: (a) a general view of research reactor containment and (b) a view of the core.

III–2. AGEING MANAGEMENT PROGRAMME IN SAFARI-1

As presented in Ref. [III–1][1], three documents were developed in accordance with IAEA Safety Standards Series No. SSG-10, Ageing Management for Research Reactors [III–2][2]: (i) the ageing management philosophy/strategy, (ii) the ageing management plan, and (iii) the list of projects, to maintain an annual record of project progress and the status of modifications and upgrades and refurbishments as a result of the AMP.

The SAFARI-1 AMP is integrated with other key facility programmes and management systems to ensure continuous safe operation of the reactor. These programmes and management systems are the following:

(a) Maintenance programme and in-service inspection programme;
(b) Management of critical spares;
(c) Safety classification of structures, systems and components (SSCs);
(d) Reactor safety committee;
(e) The IAEA's integrated nuclear safety assessment for research reactors;
(f) Functional assessment of SSCs (facility health status);
(g) Safety reassessments;
(h) Safety self-assessments;
(i) Periodic safety review.

III–3. AGEING MANAGEMENT PLAN

The design basis for the facility contains no information relating to the design life of the facility, but a preliminary assessment of, for example, the effect of neutron fluence on the fixed core structure, based on current operation, confirms that the soundness of this structure is predictable up to a certain date, provisionally set at 2030. The result of a remedial action addressing this situation may change the prediction significantly (i.e. add a decade or so to the projection), but for the purpose of this annex, the above date remains a convenient threshold separating 'current lifetime' from 'lifetime extension'.

An ageing management plan was developed, which included the methodology for identifying, assessing, prioritizing and addressing ageing issues.

[1] Some of the content in this annex has been reproduced from Ref. [III–1] with permission.

[2] SSG-10 has since been superseded by INTERNATIONAL ATOMIC ENERGY AGENCY, Ageing Management for Research Reactors, IAEA Safety Standards Series No. SSG-10 (Rev. 1), IAEA, Vienna (2023).

III–4. METHODOLOGY FOR AGEING MANAGEMENT

One of the basic causes of ageing degradation of an SSC is the service conditions that support the activation of a particular degradation mechanism leading, unless properly managed, to a loss of SSC functionality — see SSG-10 [III–2]. These service conditions can be categorized as normal operation, anticipated operational occurrences, design basis accidents and environmental conditions, and include such effects as wear and tear, corrosion, erosion, chemical changes and physical damage due to operational incidents [III–3]. The effects of ageing (consequence/failure) for each condition under these four categories, with the associated degradation mechanisms, are summarized in Tables III–1 to III–4.

A further ageing mechanism identified for many SSCs at SAFARI-1 is technological obsolescence, in which either whole technologies (e.g. vacuum tubes) become obsolete, or suppliers and vendors of equipment simply no longer exist or have discontinued certain products to the point that support is discontinued and spares are not available.

TABLE III–1. EFFECT OF AGEING FOR NORMAL OPERATION

Condition	Degradation mechanism	Consequence/failure
Radiation	Change of properties	Chemical decomposition Strength change Ductility change Swelling Resistivity change Burnup
Temperature	Change of properties	Strength change Resistivity change Ductility change
Stress (pressure)	Creep	Changes of geometry (e.g. break, collapse) Stress corrosion cracking

TABLE III–1. EFFECT OF AGEING FOR NORMAL OPERATION (cont.)

Condition	Degradation mechanism	Consequence/failure
Cycling of temperature, flow and/or load; flow induced vibrations	Motion	Displacement Change of position or set point Loose connections
	Fatigue	Break, collapse Deformation
	Wear	Deterioration of surface Change of dimensions
Flow	Erosion	Strength change
Fluid chemistry	Corrosion/galvanic cells	Release of radioactivity Strength reduction Deposition of particles Short circuits Leakage
Technological	Obsolescence	Ineffective maintenance

TABLE III–2. EFFECT OF AGEING FOR ANTICIPATED OPERATIONAL OCCURRENCES

Condition	Degradation mechanism	Consequence/failure
Power excursion	Thermal and mechanical damage	Deterioration of systems Accelerated ageing
Unbalanced control rod positions	Thermal stresses	Reduction of strength Accelerated ageing
Power–flow mismatch (error in fuel loading)	Thermal stresses	Reduction of strength Accelerated ageing
Primary pump failure	Thermal and mechanical stresses	Accelerated ageing

TABLE III–2. EFFECT OF AGEING FOR ANTICIPATED OPERATIONAL OCCURRENCES (cont.)

Condition	Degradation mechanism	Consequence/failure
Erroneous maintenance or operation	Mechanical damage and adverse chemical conditions	Deterioration of systems Corrosion Accelerated ageing
Flooding	Deposition and chemical contamination	Corrosion Blockages Reduction of strength
Fire	Heat, smoke, reactive gases	Reduction of strength Loss of insulation, electrical/ instrumentation failures Corrosion

TABLE III–3. EFFECT OF AGEING FOR DESIGN BASIS ACCIDENTS

Condition	Degradation mechanism	Consequence/failure
Loss of coolant accident	Pipe break, break between the primary pumps (i.e. delivery side) and the reactor vessel inlet	Complete core uncover
Loss of flow accident	Indefinite 'insertion' of a certain amount of negative reactivity resulting from the temperature increase	Introduces negative reactivity to the core
Loss of primary coolant	Earthquake/severe seismic condition or extended design basis accident condition	Pool water inventory is completely lost Reactor primary inlet line in the pipe tunnel is broken
Cold water insertion	Earthquake/severe seismic condition or extended design basis accident condition	Possible limited core and fuel overheating and damage

TABLE III–3. EFFECT OF AGEING FOR DESIGN BASIS ACCIDENTS (cont.)

Condition	Degradation mechanism	Consequence/failure
Loss of heat sink	Earthquake/severe seismic condition or extended design basis accident condition	Time limited failure of the temperature surveillance or secondary coolant control valve, limited blockage of the heat exchangers

TABLE III–4. EFFECT OF AGEING FOR SEVERAL ENVIRONMENTAL CONDITIONS

Condition	Degradation mechanism	Consequence/failure
Humidity, salinity	Corrosion/galvanic cells	Leakage Release of radioactive material Strength reduction Deposition of particles Short circuits
Chemical agents	Chemical reactions	Undesirable chemical product Deterioration of structures
Wind, dust, sand	Erosion and deposition	Strength change Deterioration of surface Malfunction of components

III–5. CLARIFICATION OF DEGRADATION MECHANISMS

The SSCs were evaluated against the degradation mechanisms described in Table III–5, and ratings as well as allocation of risk factors were considered.

TABLE III–5. CLARIFICATION OF DEGRADATION MECHANISMS

Mechanism		Description
A	Radiation — change of properties	Neutron and other radiation damage. Generally well known and predictable phenomena, for which studies and data are widely available
B	Temperature — change of properties	Affects many synthetic materials, electronic circuits and sensors, cables and wiring, electric motors, transformers, etc., and concrete subjected to heat deposition. Also consider effects of historical fire events in the facility (see also J)
C	Creep due to stress/pressure	Typical examples are core components subject to the effects of A, for example Be reflectors, graphite components, and even fuel elements that are loaded or stored for very long periods in some reactors
D	Mechanical displacement/ fatigue/wear from vibration, cyclic loads	Routine loosening and fastening of bolts, periodic repair of breakages (e.g. retapping of threads, rewelding), changes due to operating modes, general wear and tear
E	Material deposition (e.g. crud)	Particularly in inaccessible places, such as regions below the reactor core, the decay tank, beam port front (core side) chambers, experiment penetrations and cavities in the pool structure (e.g. in the space below pool gates)
F	Flow induced erosion	Need not affect the normal flow paths of most research reactors, but look, for example, for erosion of flow measuring orifices (dulling of edges) that can affect accuracy. Erosion of concrete can occur in the biological shield and other concrete structures owing to pool leaks
G	Corrosion	This is by far the biggest contributor to the record of ageing in research reactors and is not limited to old facilities. Look particularly for corrosion on the concrete side of embedded pipes, components, reenforcing, etc. — especially if the pool has been leaking. Note that stainless steel is not immune to corrosion. There are many instances of, for example, incorrect welding procedures that have promoted rapid corrosion of stainless steel components. Look also at electronic and instrumentation components, where corrosion can lead to imperfect connections

TABLE III–5. CLARIFICATION OF DEGRADATION MECHANISMS (cont.)

Mechanism		Description
H	Damage due to power excursions, operational events	A single abnormal event or accident may cause permanent damage. Look also for historical handling errors and accidents causing mechanical damage. Has something heavy ever been dropped into the pool? Or into the reactor core? Or onto a concrete floor?
I	Flooding — deposition; chemical contamination	Both internal and external flooding. The latter can cause erosion around foundations, etc. (see also F). Chemical contamination can occur in demineralizer facilities and pool liners (e.g. Hg–Al reactions) and may lead to corrosion (see also G)
J	Fire — effects of heat, smoke, reactive gases	Both internal and external fires (induction of smoke and gases by the ventilation systems)
K	Obsolescence, technology change	This affects practically all aspects, especially of old facilities (e.g. design, mechanical, electrical, instrumentation, documentation, staff). However, even new facilities have reported rapid obsolescence and loss of support from vendors owing to discontinuation of products, etc. Also look at as built status of drawings
L	Changes in requirements or acceptable standards	This is typically applicable to regulatory requirements. Codes and standards (including IAEA Safety Standards Series publications for research reactors) also evolve with time and facilities' documentation and safety cases gradually become outdated. Furthermore, the operational focus of many research reactors today is far removed from their original design intent
M	Other (time dependent phenomena)	Typical aspects considered under this mechanism are incorrect or defective control over design or over installation — both during the original construction and during modifications or upgrades

III–6. AGEING MANAGEMENT EVALUATION (SCREENING) AND ASSESSMENT

Ageing management assessment specific to the SAFARI-1 facility was developed using a matrix to identify, evaluate and screen SSCs affected by ageing and propose remedial actions. This ageing management assessment matrix is presented in Table III–6 and is based on SSG-10 [III–2] and adjusted to fit the type of SSCs at the SAFARI-1 research reactor. The matrix presents the set of SSCs possibly affected by ageing in its vertical axis and ageing mechanisms in its horizontal axis.

The values displayed in Table III–6, indicated in the matrix, correspond to the remedial actions proposed to address the ageing effects on the SSC. For example, SSC No. 4 — instrumentation and controls — has certain ageing effects (e.g. 4a1, 4a2, 4b1–b4) and the corresponding remedial actions and the identified project titles to be undertaken by the AMP are shown in Table III–7.

The SSCs were grouped into the following numbered categories:

(1) Reactor block, fuel and internals;
(2) Cooling systems;
(3) Confinement and containment;
(4) Instrumentation and controls;
(5) Power supply;
(6) Auxiliaries (e.g. fire protection, crane, hot cells, radioactive waste handling);
(7) Experimental facilities.

TABLE III–6. AGEING MANAGEMENT ASSESSMENT MATRIX

SSCs relevant to safety and sustainability		Degradation mechanisms[a]												
		A	B	C	D	E	F	G	H	I	J	K	L	M
1. Reactor block, fuel and internals														
1.1	Fuel assemblies (incl. control rod followers)											1a; 1b	1a; 1b	
1.4	Reflector	1d			1d				1d					

TABLE III–6. AGEING MANAGEMENT ASSESSMENT MATRIX (cont.)

SSCs relevant to safety and sustainability	Degradation mechanisms[a]												
	A	B	C	D	E	F	G	H	I	J	K	L	M
2. Cooling systems													
2.1 Reactor primary cooling system		2a		2g	2c		2f; 2c				2a		
2.3 Emergency cooling system							2f						
3. Confinement/containment													
3.1 Structure				3a			3b		3b				
3.2 Biological shield													
3.3 Ventilation				3c			3c				3c; 3d		
4. Instrumentation and controls													
4.1 Reactor protection (incl. secondary shutdown)	4a	4a		4a		4h	4a; 4h; 4k				4a; 4h	4c	
4.4 Radiation monitoring							4k				4f; 4g	4f; 4g	
4.5 Control console		4e		4e			4e; 4k				4e	4e	
5. Power supply													
5.1 Main power supply		5a		5a			5a	5a	5a	5a	5a	5a	

TABLE III–6. AGEING MANAGEMENT ASSESSMENT MATRIX (cont.)

SSCs relevant to safety and sustainability	Degradation mechanisms[a]												
	A	B	C	D	E	F	G	H	I	J	K	L	M
5.2 Emergency power supply		5b		5b			5b		5b		5b	5c	
5.3 Power distribution, cabling/ routing		5a; 5b		5a; 5b			5a; 5b		5a; 5b		5a; 5b	5a; 5b	
6. Auxiliaries													
6.2 Lightning protection/ earthing							6a				6a	6a	
6.6 Crane				6d; 6e							6d; 6e	6d; 6e	
7. Experimental facilities													
7.1 Beam tube lines (ex-pool), shutters							7a						
7.3 Rabbit/ conveyer				7b								7b	

[a] See Table III–5 for an explanation of the degradation mechanisms.

TABLE III–7. REMEDIAL ACTIONS PROPOSED TO ADDRESS AGEING ISSUES FOR SSC No. 4

RA No.	Remedial action	Ageing issue(s) addressed on matrix	Project breakdown/title
4	Instrumentation and controls		

TABLE III–7. REMEDIAL ACTIONS PROPOSED TO ADDRESS AGEING ISSUES FOR SSC No. 4 (cont.)

RA No.	Remedial action	Ageing issue(s) addressed on matrix	Project breakdown/title
4a1	Upgrade safety critical nuclear safety and gamma safety nuclear detectors and instrumentation (incl. rationalization of detector locations)	4.1 (A, B, D, G, K) 4.9 (A)	Upgrade safety critical nuclear safety channels
4a2			Upgrade safety critical gamma safety channels
4b1	Upgrade control instrumentation (neutron control channel, primary temperature controllers, rod drop monitors)	4.3 (A, B, D, G, K, M) 4.9 (A)	Refurbish neutron control channel
4b2			Replace automatic flux controller
4b3			Replace temperature controller (reactor and pool primary)
4b4			Replace rod drop monitor

In addition, non-SSCs elements such as the safety analysis report, operational and technical specifications, documentation on design and project control, management systems and staff training, were also included in the ageing management assessment.

Ageing management evaluation workshops were held, during which the remedial actions to address ageing effects and implementation of the resulting projects related to ageing management aspects were identified and objectively prioritized. The remedial actions identified were originally divided into four groups: safety critical; mission critical; lifetime extension; and organizational. During the recent evaluation, the classification was changed to six groups, comprising those projects addressing additional ageing related issues as well as refurbishment and/or maintenance. Now, all the SAFARI-1 projects are classified into six distinct categories:

(1) Compliance. Projects or actions originating from processes and regulatory issues; safety compliance issues identified requiring the attention of the facility.
(2) Infrastructure. Safety, health, environment and quality issues requiring attention to maintain and improve the safety management and culture of the facility.
(3) Safety critical. Remedial actions without which the reactor will probably not be able to operate safely until the currently projected end of life (not considering the purpose of operating the reactor).
(4) Mission critical. Remedial actions without which the reactor will be safely operated until the end of life but reliability and/or availability may be compromised.
(5) Lifetime extension. Remedial actions required for lifetime extension of the facility.
(6) Maintenance. Projects or actions assisting with improvements to the general safety and maintenance of the facility.

III–7. PRIORITIZATION OF REMEDIAL ACTIONS

A mathematical model was developed to aid in the objective prioritization of remedial actions. The methodology allocates a score to each remedial action for each impact factor (I) on a scale of 1 to 10 (see Table III–8(a)). The impact factor is then multiplied by an urgency factor (U) on a scale of 1 to 10 (see Table III–8(b)). The priority (P) is the product of these two factors, ranging from 0 (lowest priority) to 100 (highest priority). Table III–9 provides a sample list of prioritized projects.

The resulting priority, $(P) = I \times U$, ranges from 0 to 100.

The identified projects are specified in the sample list of SAFARI-1 projects in Table III–9. The SAFARI-1 Project Management Office was established to facilitate the delivery of projects under the auspices of the AMP.

The personnel were encouraged to focus resources on high priority projects. An AMP resource plan was drawn up to identify the resources required to successfully implement the SAFARI-1 AMP projects.

TABLE III–8(a). PRIORITIZATION OF REMEDIAL ACTIONS: IMPACT FACTOR (*I*)

10	7	5	3	1
Probable that nuclear or radiological safety will be compromised; may lead to suspension of nuclear licence	Drastically impedes operational capability (availability, efficiency, commercial benefit) of the reactor system. Reactor availability <280 d/a	Conventional safety compromised OR increased personnel dose OR regulatory intervention	Somewhat decreased operational capability (availability, efficiency, commercial benefit) of the reactor system. 280<reactor availability <300 d/a	No safety impact; no influence on reactor availability

TABLE III–8(b). PRIORITIZATION OF REMEDIAL ACTIONS: URGENCY FACTOR (*U*)

	Burning 10	Pressing 7	Slight 4	Low 1
Time (*T*) when outcome is needed — time to complete project	T<3 months	3 months <T<6 months	6 months <T<12 months	T>12 months

TABLE III–9. SAMPLE LIST OF SAFARI-1 AGEING MANAGEMENT PROJECTS

No.	RA No.	Remedial action or project description	Priority	Status	Classification
1	1c1	Grid plate manufacture, including inserts	100	In progress	Mission
2	4l	Rehabilitate N-16 channels	40	Delayed	Maintenance
3	1e	Assessment of reactor vessel lifetime	100	In progress	Lifetime

TABLE III–9. SAMPLE LIST OF SAFARI-1 AGEING MANAGEMENT PROJECTS (cont.)

No.	RA No.	Remedial action or project description	Priority	Status	Classification
4	2g2	Manufacture and install new heat exchanger	70	In progress	Lifetime
5	4b2	Replace automatic flux controller	100	Complete	Mission
6	4b4	Replace rod drop monitor	90	In progress	Mission
7	6d	Install auxiliary cranage in reactor hall	20	Closed	Mission

III–8. REGULATORY REVIEW AND REQUIREMENTS

For any facility modifications that SAFARI-1 plans to implement or commission, the following nuclear regulatory requirements have to be met [III–4, III–5]:

(a) The proposed modification has to comply with regulatory approved processes and procedures relating to control of such modification to the design of existing facility, facility or system design, including modifications that may be of temporary nature.
(b) These approved processes have to provide for the classifications of modifications according to their safety significance.
(c) These modifications have to be organized into stages or phases, with clear and unambiguous regulatory approval required at each step. This ensures that no activities commence or proceed to the next phase of the modification until the regulator has granted the necessary approval.
(d) The process has to include a requirement for the provision of adequate documentation to justify the safety of the proposed modification.
(e) The facility is expected to implement processes for the periodic and systematic review and reassessment of safety cases.
(f) As far as the nuclear installation stipulates, the licensee has to, if so directed by the national nuclear regulator, carry out a review and reassessments of safety and submit a report of the said review and reassessment to the

regulator at such intervals, within such period and for such matters or operations as may be specified in the directive.

III–9. UPDATE ON AGEING MANAGEMENT MODERNIZATION, REFURBISHMENT AND UPGRADES

III–9.1. Maintenance upgrades for instrumentation and control systems

The instrumentation and control system at the SAFARI-1 research reactor, as schematically depicted in Fig. III–2, comprises, among others, the following major instrumentation subsystems:

(a) Reactor protection system:
  (i) Nuclear safety instrumentation:
    — Neutron safety channels for measuring neutron flux;
    — Gamma safety channels for monitoring gamma flux.
  (ii) Process safety instrumentation.
(b) Rod control system — rod drop monitor.
(c) Reactor automatic flux controller.
(d) Process instrumentation and controls.
(e) Radiation protection monitoring.

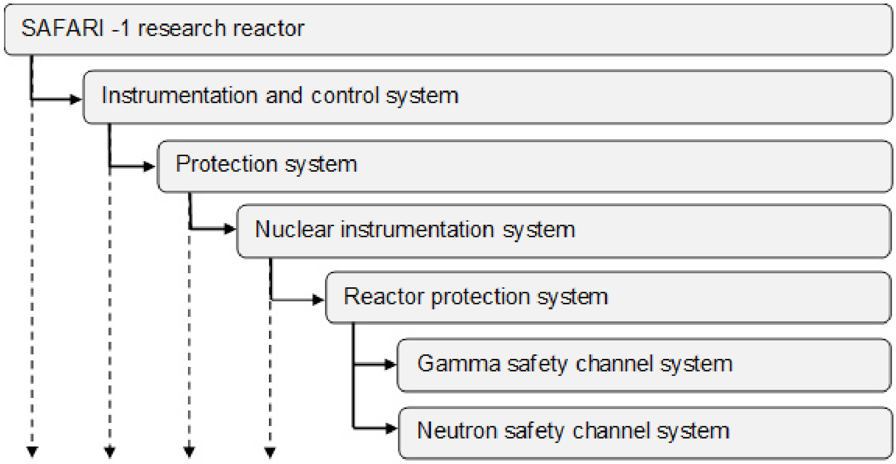


FIG. III–2. Section of the breakdown structure of the instrumentation and control system.

Most of the instrumentation projects undertaken under the auspices of the AMP are in the installation and commissioning phase. The instrumentation and maintenance projects were essential to ensure that the reactor can be operated safely until the end of its life. Reliability and/or availability might be compromised if issues are not addressed.

III–9.1.1. Gamma safety channel upgrade — installation in progress

The existing gamma safety channel was designed and manufactured in the early 1970s by the electronic engineering group of the Atomic Energy Board. The channels have reached the end of their serviceable life and are difficult to maintain owing to obsolescence of the manufacturing technology used in their construction. The need for an original equipment manufacturer to upgrade the design and manufacture and support a new gamma safety channel has been identified through the SAFARI-1 AMP. The gamma safety channel and the neutron safety channel systems thus fulfil the requirements for redundant, diverse and separate reactor overpower protection functions as part of the reactor protection system. The installation and commissioning will focus on the facility installation and verify the operation of the system and its interfaces with the relevant reactor instrumentation systems.

III–9.1.2. Neutron safety channel — installation in progress

The neutron safety channel is one of the ageing reactor nuclear instrumentation channels that forms part of the reactor protection system. The channel, originally supplied and installed in 1995, was returned to the original equipment manufacturer for realignment and changing of the front panel displays from linear liquid crystal display bar graphs to circular analogue meters. The upgrade requirements were updated and specified in the user requirements specification document and the supplier complied with the requirements.

The neutron safety channel provides an independent measurement of neutron flux for use as a redundant means of indicating reactor power, and as an input to the reactivity computer. As it is a multirange instrument, it is useful for neutron flux measurement from startup conditions to full power operation. The neutron safety channel consists of a single measurement channel. The major subsystems of the neutron safety channel are the fission chamber detector amplifier assembly and signal processor assembly.

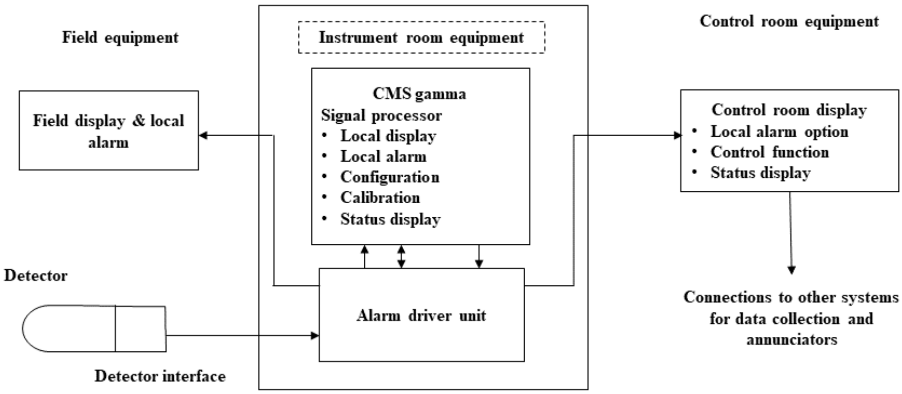


FIG. III–3. Configuration of the area monitoring system channels.

III–9.1.3. Area monitoring system upgrade — commissioning in progress

The area monitoring system is an important tool used to monitor the radiation levels in areas of the SAFARI-1 facility where knowledge of such radiation levels is essential for the well-being of personnel occupying, conducting tasks in or passing through them. The installed monitoring systems were ageing, intermittent failures were experienced and some of the replacement components became obsolete, hence the upgrade project. The design of the area monitoring system and its configuration (see Fig. III–3) are based on generic IAEA requirements for radiation monitoring as described in section 7 of IAEA Safety Standards Series No. NS-G-1.13, Radiation Protection Aspects of Design for Nuclear Power Plants [III–6].

Each channel of the area monitoring system consists of the following:

(a) A detector, with the appropriate detector interface;
(b) Field equipment, consisting of a display, an audible alarm and a beacon light system;
(c) Instrument room equipment, incorporating the signal processor (also referred to as the continuous monitoring system), gamma and alarm driver unit;
(d) Control room equipment, incorporating the control room display and alarm assemblies, the operator interface and other interfaces between the control room annunciators and the facility data log system.

FIG. III–4. The old and new rod drop monitors installed to run in parallel for commissioning.

III–9.1.4. Rod drop monitor upgrade — completed

The rod drop monitor, shown in Fig. III–4, consists of a single rack mounted signal processor installed in the control room that performs both the signal processing as well as the display of the measured control rod release and drop times. The monitor measures both the release and the drop times individually for each control rod, and the measurements are performed in increments of 1 ms. It also monitors the release and drop times of each control rod to verify if these times are within the limits as specified in the operational limits and conditions. This verification is performed before each startup of the reactor, and during actual reactor scram events. The rod drop monitor was upgraded because the old design was experiencing intermittent failures due to age and the old unstable printed circuit board technology was no longer supported.

III–9.2. Stack monitoring system upgrade — completed

The stack monitoring system provides on-line measurement requirements for radiation released through the SAFARI-1 stack and emits alarms at predetermined levels to warn of a significant release of radionuclides. The old stack monitoring systems could not be maintained owing to age and the effects of changing environmental conditions existing in the SAFARI-1 stack.

III–9.3. Reactor vessel assessment — completed

The SAFARI-1 reactor vessel and its support structures are made from aluminium alloy of ASTM 5052-O designation. This aluminium alloy is a non-heat treatable wrought aluminium–magnesium alloy for sheets and

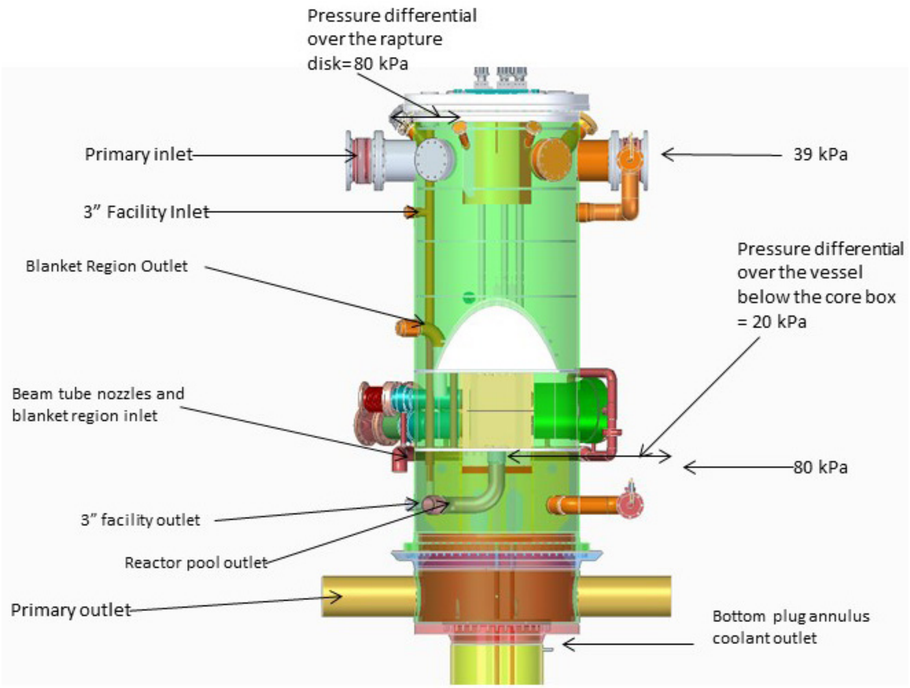


FIG. III–5. Reactor vessel showing the inlet and outlet together with the pressures.

plates with good formability and weldability and excellent corrosion resistant properties. The 'O' indicates that the aluminium plates were fully annealed after manufacture.

The reactor vessel was designed in accordance with Section VIII of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code [III–7] and has an internal pressure of 248 kPa and a temperature of 65.5ºC. It is made of a welded 5052 graded aluminium cylindrical shell with an internal diameter of 1.66 m and an average height of 4.52 m between flanges. The circulation of cooling water is driven by a pressure drop between the inlet and outlet reactor vessel pipes. The pipes and flanges are made of graded 6061-T6 aluminium (see Fig. III–5).

The SAFARI-1 reactor vessel has been bombarded with thermal neutrons for more than 50 years, which may have impacted negatively on the design life of each item. In addition, during its operation over the years, there have been multiple minor impacts that may have affected the reactor vessel in some way. Changes in the material properties of the reactor vessel are expected. These changes are generally characterized by the reactor vessel material losing its plasticity and becoming brittle, leading to susceptible crack propagation.

Owing to the absence of a surveillance programme allowing monitoring of the ageing of components, an analytical investigation through design verifications was required to determine the mechanical integrity of the SAFARI-1 reactor vessel.

The mechanical integrity of the SAFARI-1 reactor vessel was investigated through structural analysis based on ASME III [III–8] code requirements to determine the fitness for purpose period of the reactor. A computational fluid dynamics analysis was carried out to determine the pressure and temperature distribution in the reactor structure under operating conditions. The results of this investigation showed that the highest stress area was found to be at the bottom weld. A fatigue life of approximately 300 000 cycles was calculated based on a 1% probability of crack initiation, and using these calculations it was concluded that the stress intensity stays below the irradiated fracture toughness of the material and the shell will therefore not fracture (leak before break). The study recommends ultrasonic inspections of this area every ten years to detect and monitor any cracks.

III–9.4. Biological shield — completed

The main purpose of SAFARI-1's concrete biological shield structure is to provide radiation shielding for the reactor vessel, for active equipment in the pools and for active piping embedded in the concrete structure itself. As part of the AMP, an investigation of the biological shield was proposed, which aimed at assessing the structural soundness of the reinforced concrete members associated with the concrete biological shield (see Fig. III–6).

A structural analysis was performed to determine the presence of any high stress concentrations in the structure that might cause propagation of cracks or compromise the structural integrity of the shield in any way. From the detailed stress calculations, it was found that the stresses in the biological shield and its supports were within limits. No high stress concentrations were found at the openings or cavities in the shield.

III–9.5. Reactor in-service inspections

The SAFARI-1 in-service inspection plan provides the necessary information with respect to the inspection and testing of all relevant

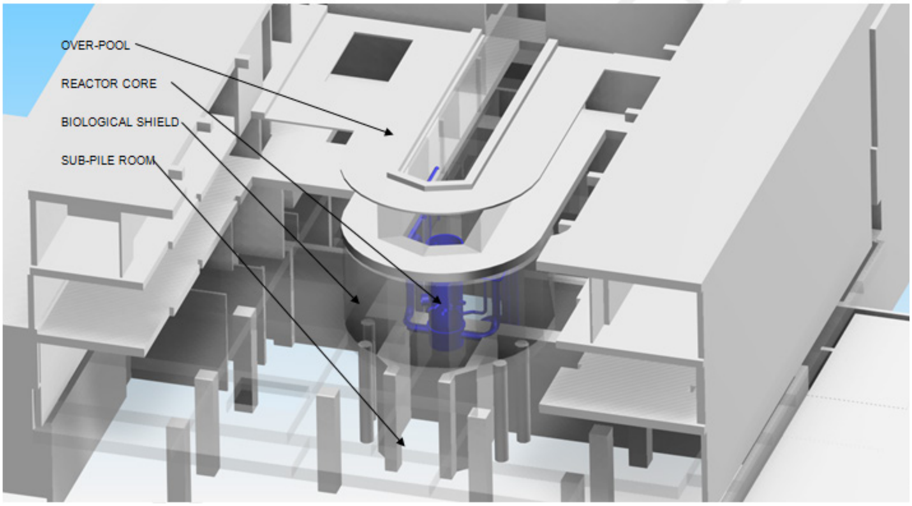


FIG. III–6. A 3-D solid edge figure showing the over pool and biological shield.

equipment or systems of the facility. Such equipment or systems may typically include the following:

— Vessels (reactor vessel and components) and containments (control areas);
— Pipe systems (e.g. pumps, valves, heat exchangers);
— Pool liners, structures and penetrations, gloveboxes;
— Fume cupboards and vacuum induction furnaces;
— Ventilation equipment, such as filter banks;
— Storage tanks, including their respective supports.

At SAFARI-1, an in-service inspection item is a component and/or an assembly of components of the highest priority that will be inspected for the safe operation of the reactor. These include items of, and items connected to, the reactor vessel and the reactor pool liners. The inspection results for these items need to be reported to the National Nuclear Regulator on an annual basis.

III–10. CONCLUSIONS

The main conclusions from this annex describing the AMP of the SAFARI-1 research reactor are the following:

(a) The currently projected end of life of the facility at the present rate of operation is provisionally set to at least the end of 2030. The design basis for the facility contains no information relating to the design life of the facility and as such an AMP was a necessary tool to ensure the safety and soundness of structures and components. The SAFARI-1 AMP is based on SSG-10 [III–2].
(b) The major critical tasks undertaken in the SAFARI-1 AMP include the upgrade of instrumentation and control equipment to ensure the safe and reliable operation of the reactor. The investigations of the reactor vessel and the biological shield were to determine the mechanical integrity of the SAFARI-1 reactor vessel and the structural soundness of the reinforced concrete members associated with the concrete biological shield, respectively.
(c) The outcomes of the above investigations have shown that the stress intensity of the reactor vessel stays below the irradiated fracture toughness of the material and the shell will therefore not fracture (leak before break). The stresses in the biological shield and its supports were also found to be within limits.
(d) The in-service inspection was performed on the SAFARI-1 reactor under the AMP, with the purpose of determining wall thickness. Measurements were conducted in parts of the reactor vessel assembly and pool liners to determine material loss due to corrosion and/or other operating constraints. The conclusion was that no reportable wall thickness reduction was observed during the inspection.
(e) The programme developed a methodology and an assessment to assist SAFARI-1 in identifying ageing mechanisms and to provide remedial actions to counter the anticipated age related effects. Application of the guidelines provided by the IAEA for the implementation of an AMP at SAFARI-1 research reactor has yielded positive results.

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[III–8] AMERICAN SOCIETY OF MECHANICAL ENGINEERS, Boiler and Pressure Vessel Code (BPVC), Section III — Rules for Construction of Nuclear Facility Components, ASME, New York (2023).

Annex IV

AGEING MANAGEMENT PROGRAMME FOR THE BR2 RESEARCH REACTOR

F. Joppen, SCK•CEN, Belgium

IV–1. BACKGROUND

Ageing management of class I nuclear installations became obligatory through the Royal Decree of 30 November 2011 on safety prescriptions for nuclear installations [IV–1]. Class I includes the following installations:

(a) Nuclear reactors;
(b) Installations with potential criticality risk;
(c) Nuclear waste treatment plants.

Article 10 of the Royal Decree deals with the physical and economic impact of ageing as well as with the ageing management programmes (AMPs). The AMP is to be reviewed at least once during each periodic safety review (i.e. every ten years), to update the following:

— Safety classification of structures, systems and components (SSCs) that are important for safety;
— Definitions of maintenance and programmes.

The periodic safety review of 2016 did not result in any fundamental modifications to the AMP. A number of procedures and working methods were further detailed. The next periodic safety review is to be completed by June 2026.

The AMP is based on codes and standards that were applicable during its main development, essentially between 2011 and 2015. During revision, more recent versions of these codes and standards are taken into account. However, priority is given to the continuity of the programme and new versions are only applied if they do not change the programme significantly.

The BR2 reactor is a heterogeneous thermal high flux engineering test reactor, designed in 1957 for SCK•CEN by the Nuclear Development Corporation of America (NDA, White Plains, NY). It was built on the site of the SCK•CEN laboratories in Mol, Belgium. First criticality of the reactor was obtained in June 1961 and routine operation started in January 1963.

The reactor has a compact core composed of hexagonal beryllium blocks with a central hole for loading fuel elements, control rods or experimental devices. The beryllium matrix is positioned inside a tank. Pressurized light water is used as coolant and moderator (together with the beryllium). To date, the reactor has been operated with high enriched uranium. A conversion to low enriched uranium is planned by 2026, on the condition that fuel plates with sufficient uranium density are qualified and available. The maximum thermal flux approaches 10^{15} n/cm^2/s. There have been a number of inspections, refurbishments and modifications during the lifetime of BR2. The major modification was the increase of the ultimate cooling capacity in 1971 from 50 MW to 125 MW. In the past few years, the reactor has operated at a power level of 50–70 MW. The beryllium matrix, which is damaged by neutron irradiation and builds up ^{3}He (a strong thermal neutron absorber), has been replaced three times.

The general layout of the reactor is shown in Fig. IV–1, which gives a cross-sectional view of the containment building and the machine hall. In the containment building, the reactor vessel is shown as being located in the reactor pool. The floors for experimental devices are located around the reactor pool. The room under the lower vessel head is accessible and allows the introduction of experimental loops. Figure IV–1 further shows a section of the hydraulic channel for spent fuel elements and a section of the hot cell. Both are located in the machine hall. A major part of the primary circuit, namely the primary heat exchangers, the pressurizer and the primary pumps, and the primary purification circuit are located outside the containment building. Automatic valves are foreseen in the primary circuit that can isolate the part of the circuit in the containment building from the outside in the case of an incident with potential radioactive release.

Main data for the BR2 are given below:

(a) Beginning of use: January 1963.
(b) Maximum heat flux:
    (i) Routine operation: 470 W/cm^2;
    (ii) Maximum admissible: 600 W/cm^2.
(c) Nominal power: 60–100 MW.
(d) Maximum neutron flux (for 600 W/cm^2):
    (i) Thermal: 1.2×10^{15} n/cm^2/s;
    (ii) Fast (E >0.1 MeV): 8.4×10^{14} n/cm^2/s.
(e) Irradiation positions: up to 100.
(f) Fissile charge at start of cycle: 10–13 kg ^{235}U.

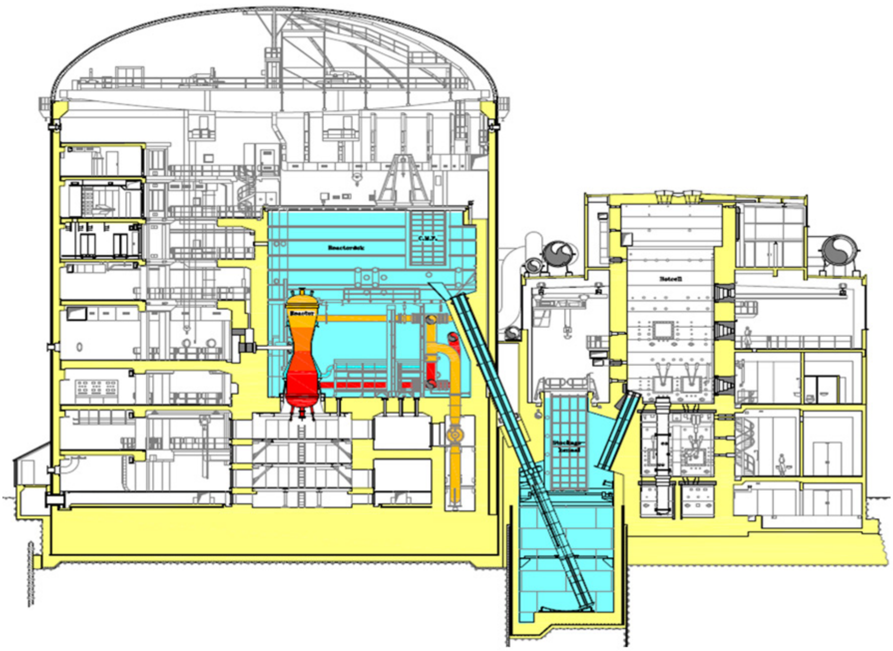

FIG. IV–1. Cross-sectional view of the containment building and machine hall of the BR2 research reactor (reproduced courtesy of SCK•CEN, Belgium).

(g) Operation cycle:
  (i) Minimum 7 days shutdown;
  (ii) Nominal 21 or 35 day operation;
  (iii) Possibility of short cycles.

(h) Days of full power operation per year: variable, currently up to 210 d/a.

BR2 is mainly used to perform the following activities:

— Production of ^{99}Mo by the irradiation of uranium targets, for which eight irradiation baskets are available;
— Production of isotopes for medical and industrial purposes by neutron irradiation;
— Irradiation of materials for nuclear power plants and for fusion projects;
— Irradiation of silicon crystals for semiconductor fabrication with two production devices: one tube loaded in the reflector for blocks up to 12.7 cm and another one in the pool near the vessel wall for 15.2 cm and 20.3 cm blocks;

— Testing of new fuel for research and test reactors in the framework of conversions to low enrichment;
— Testing of new power plant fuels, eventually in transient conditions.

IV–2. INTERNATIONAL STANDARDS

A number of IAEA Safety Standards Series and other publications were used by SCK•CEN for defining the overall AMP. These included IAEA Safety Standards Series Nos SSG-22, Use of a Graded Approach in the Application of the Safety Requirements for Research Reactors [IV–2], SSG-10, Ageing Management for Research Reactors [IV–3] and NS-G-4.2, Maintenance, Periodic Testing and Inspection of Research Reactors [IV–4],[1] as well as Refs [IV–5 to IV–7].

IV–3. DESCRIPTION OF THE OVERALL AGEING MANAGEMENT PROGRAMME

IV–3.1. Scope of the overall AMP

IV–3.1.1. Responsibilities

As presented in Ref. [IV–8][2], the overall AMP is conducted by a dedicated group — the plant asset management, or PAM group — under the final responsibility of the BR2 reactor manager. This group was launched in 2012–2013 in the framework of the preparation for BR2 long term operation, as well as the preparation for the last periodic safety review and the introduction of the reference levels of the Western European Nuclear Regulators Association (WENRA) into Belgian regulations. The PAM group started the AMP project by classifying all SSCs (known as asset configuration management, or ACM). This classification was performed in multidisciplinary meetings with persons

[1] These have been superseded by INTERNATIONAL ATOMIC ENERGY AGENCY, Use of a Graded Approach in the Application of the Safety Requirements for Research Reactors, IAEA Safety Standards Series No. SSG-22 (Rev. 1), IAEA, Vienna (2023); INTERNATIONAL ATOMIC ENERGY AGENCY, Ageing Management for Research Reactors, IAEA Safety Standards Series No. SSG-10 (Rev. 1), IAEA, Vienna (2023); and INTERNATIONAL ATOMIC ENERGY AGENCY, Maintenance, Periodic Testing and Inspection of Research Reactors, IAEA Safety Standards Series No. SSG-81, IAEA, Vienna (2023).

[2] Some of the content in this annex has been reproduced from Ref. [IV–8] with permission.

from operation, maintenance and safety groups. In the second phase (known as installation concept management, or ICM), a more detailed analysis is performed to define the inspection and maintenance strategy for all SSCs with safety importance. Support is provided by those groups responsible for maintenance (i.e. mechanical, electrical, nuclear instrumentation and non-nuclear instrumentation). In the final step (work order and management and skills, or WMS), maintenance and inspection procedures are developed by the groups responsible for the respective SSCs.

All information regarding the AMP is kept in databases maintained by the PAM group.

IV–3.1.2. Project scope

The project includes all SSCs that are of importance for the operation of the reactor. This includes not only the SSCs that are important for safety, but also SSCs related to reliability, such as the cooling towers. However, the classification is made such that a safety related item is always prioritized. The security system is not included in the BR2 AMP and the fire detection and firefighting equipment is only included in a limited way, since these assets are under the responsibility of the Department of Health Physics and Safety. Assets not directly related to the operation of the reactor, such as workshops and storage areas, are not included either.

IV–3.1.3. Methods used for identifying SSCs

The method for identifying SSCs is known as asset configuration management, or ACM. The process started with the choice of a general subject, such as the mechanical parts of the main primary loop. All SSCs were listed using the recently checked and updated flowsheets. With this information, meetings to classify all these assets were organized with personnel from maintenance and operations. During these meetings, the listed SSCs were given scores according to their impact on the research reactor's safety, operational availability and reliability, and replacement cost and replaceability:

(1) Safety score (SS)[3]:
- — Score 0: a safety critical asset. The asset could be the cause of an accident or of a significant release of radioactivity.

[3] It should be noted that the score is not always determined by the failure of the asset's own function. For example, a primary pump is not required for safe shutdown of the installation, but the pump is a part of the pressure retaining boundary.

- Score 1: an asset that is important for safety. Failure means the reduction of a defence in depth barrier.
- Score 2: an asset without safety importance.

(2) Operational score (OS):
- Score 1: an asset that would cause a long shutdown of the reactor (i.e. longer than one month).
- Score 2: an asset that would cause the loss of one operation cycle of the reactor (i.e. between five days and one month).
- Score 3: an asset that is straightforward to replace and would only cause a short shutdown (i.e. less than five days).

(3) Replacement score (ERS):
- Score 1: an asset that is not replaceable (or very difficult to replace).
- Score 2: an asset with a high replacement cost.
- Score 4: an asset with a medium replacement cost.
- Score 6: an asset with a low replacement cost.

In order to obtain the grouping of all SSCs, the SS, OS and ERS are multiplied. In doing so, a total impact (TI) figure ranging from 0 to 36 is obtained. This figure is used to classify all assets into four classes:

(1) Class A: $0 \leq TI \leq 4$;
(2) Class B: $5 \leq TI \leq 18$;
(3) Class C: $19 \leq TI \leq 24$;
(4) Class D: $25 \leq TI \leq 36$.

The following considerations also apply:

- Components that are important for safety will always be in class A or class B;
- Components with a very high importance for safety will always be in class A, even if their replacement cost is low and they can be replaced on the spot;
- Classes C and D are components that play a role in the reliability of the installation.

This classification is shown in Fig. IV–2.

The distribution of the different SSCs across these classes is visualized in Fig. IV–3.

Nearly half of the assets (47%) are in class D, which means that they have no safety importance, have a limited impact on reliability and are straightforward to replace. In this way, major attention can be paid to SSCs that are important for safety: classes A (9%) and B (29%).

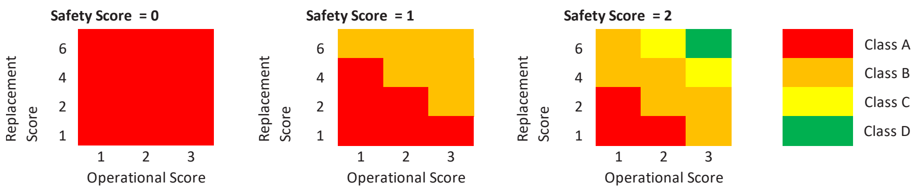

FIG. IV–2. The classification of components according to their score.

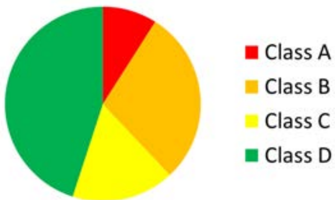

FIG. IV–3. The distribution of the classification of components.

The following list provides some examples of the classification of components:

- Class A: the valves in the primary loop that, in the case of a loss of coolant, isolate the part of the loop inside the reactor building from the part outside.
- Class B: instrumentation gauges that measure parameters important for safety (e.g. pressure, temperature, flow), but for which a redundancy exists.
- Class C: service building ventilators.
- Class D: cooling towers.

IV–3.1.4. Remark

During the IAEA Safety Review Mission on ageing management and continued operation of the BR2 reactor, conducted in November 2017, several recommendations and observations relevant to the overall AMP were provided. One of these observations was that the scoping of the asset configuration management allows non-safety related components to obtain class A or B ratings. This is against the general principle that safety has the highest priority. The classification will not be redone. However, the item will be taken up again in the next phase of the project (installation concept management), where the detailed maintenance concepts are defined. If the item has no safety classification, it will be declassified at this stage.

The IAEA mission report, Ref. [IV–9], is published on the web site of the Belgian Federal Agency for Nuclear Control.

IV–3.2. Ageing management required by the operating licence and other legal requirements

The actual operating licence of BR2, which dates from June 1986, has a number of requirements for ageing management of specific components:

(a) Periodic testing of the leaktightness of the reactor building;
(b) Periodic testing of the leaktightness of the penetrations through the reactor building;
(c) Monthly functional testing of the systems for reactor building isolation;
(d) Limited neutron dose of guide tubes for control rods;
(e) Follow-up of deformation and cracking of the beryllium matrix;
(f) Inspection of the vessel in case of replacement of the beryllium matrix.

General regulations on the safety of industrial installations also contain a number of requirements on follow-up of ageing, including the following:

— Periodic inspection of pressure vessels;
— Periodic inspection of steam vessels (i.e. pressurizer and preheater);
— Inspection of electrical installations;
— Periodic inspection of hoisting cranes.

IV–3.2.1. Introduction of the ageing management programme

In the past, most of the test and maintenance actions were decided by the groups responsible for the components, typically using their expertise and judgement. A list of important inspections was available in the safety analysis report.

However, since 2011, ageing management of SSCs important for nuclear safety is addressed under Issue I on ageing management in the WENRA Safety Reference Levels for Existing Research Reactors [IV–10], which stipulates that the utility sets up an ageing management programme.

In the framework of the fundamental expectations of the Belgian Safety Authority for long term operation of the Belgian research reactors, the Federal Agency for Nuclear Control explicitly requested the licensee to develop an overall AMP.

Consequently, the formal AMP (known as plant asset management, or PAM) for BR2 started in 2011. A quite complete inventory and assessment currently exists. Work instructions will be completed when they are needed.

IV–3.2.2. Quality assurance

All documents related to the PAM project are stored in the general document management system. This system gives each document a unique identification. It also keeps track of all changes to a document and a backup is made each day. The documentation will be completed further with older information about certain SSCs.

All classifications are verified by the Department of Health Physics and Safety in accordance with the department's tasks defined in the regulatory framework. Special attention is paid to components that are important for safety.

IV–3.2.3. Ageing assessment

The installation concept management, or ICM, phase of the PAM project defines the additional actions for testing and maintenance of the class A and B components. For these components, a risk based maintenance concept is used. The class C and D components are not subjected to formal ageing management. For class C components, only maintenance and replacement are reviewed, so that they can be executed if necessary. These components are subjected to "run to failure". Class D components only undergo on the spot maintenance, repair or replacement.

IV–3.2.4. Maintenance concepts and risk profiles for class A and B components

All safety related components are analysed using the reliability centred maintenance approach and failure mode, effects and criticality analysis. Time dependent evaluation and ageing is taken into consideration. The following questions are to be answered during the evaluation process:

(a) What are the functions of the SSC? Some SSCs have a single function and others can have multiple functions. A typical example is a pump, which has to provide a specific flow rate and pressure, but which is also part of the pressure retaining boundary.
(b) What are the failure modes for each of the functions of the SSCs?
(c) What are the possible causes for each failure mode? Failure of the considered SSC due to a fault in another SSC is also taken into account.
(d) What are the indicators of each failure mode? There could be several different indicators for each failure, or some failures can remain hidden for a long period.
(e) In what way does each failure mechanism matter? Some failures will only lead to disturbed operation or will stop operation of the installation, while others can

increase the probability of an accidental condition. The probability of failure (depending on the mean time between failure) is taken into account.

(f) Is the technology used by the SSC obsolete or will it become obsolete in the near future? This question is of particular importance because of the age of the installation. A positive answer to the question will have an impact on the maintenance measures. It may even lead to a design modification of the installation, if maintenance or replacement are no longer possible.

(g) What can be done to prevent each failure mechanism? The answer to this question is the definition of a preventive maintenance programme. Where available, codes and guidelines will be applied. However, in a number of cases, engineering judgement needs to be used.

(h) What are the corrective measures that can be taken in cases where preventive maintenance cannot be performed or in the case of unexpected failures? This item defines the requirements for stocks of spare parts or the identification of potential suppliers for replacement parts.

In the questions above, it was assumed that no redundancy is available; it was assumed that the failure of the SSCs leads to abnormal conditions. However, in most cases a certain redundancy is present and the unavailability of certain SSCs for a limited period of time is acceptable. This makes repair possible. The maximum unavailability periods for important SSCs are given in the safety analysis report.

IV–3.2.5. Preventive maintenance tasks

A preventive maintenance task is defined for failure modes with a major impact. The definition in asset classes is further detailed with a parameter that takes the mean time between failures (MTBF) into account. A score for probability of failure (PF) is specified for each failure mode of a safety related asset (see Table IV–1).

The risk score can then be calculated as the product of all scored parameters:

$$\text{risk score} = \text{probability} \times \text{consequences} = PF \times (SS \times OS \times ERS)$$

where

PF is the probability of failure;
SS is the safety score;
OS is the operational score;

and ERS is the replacement score.

TABLE IV–1. DEFINITION OF PROBABILITY OF FAILURE

Probability of failure score	Qualitative meaning	Relation to MTBF (years)
1	Very probable	MTBF ≤ 3
3	Probable	3 < MTBF ≤ 10
10	Improbable	10 < MTBF ≤ 30
30	Very improbable	MTBF > 30
1000	Impossible	MTBF ≈ ∞

Risk Category	**Relation to Risk Score (*RS*)**
Red	$RS = 0$
Orange	$0 < RS \leq 180$
Yellow	$180 < RS \leq 240$
Green	$RS > 240$

FIG. IV–4. Risk categories for failures of class A and B SSCs.

Every different failure mechanism of an SSC may lead to different consequences and so it is necessary to analyse them all independently. When the function that fails because of a specific failure mechanism is redundant (i.e. some other asset of the installation takes over the function), the failure has to be scored as if there is no redundancy. However, the fact that there is redundancy will be taken into consideration, so that the information will be registered and can be used to choose an appropriate maintenance strategy to prevent the failure of the function.

The risk score allows four categories of failures to be defined, as shown in Fig. IV–4.

For those failure mechanisms of SSCs in the red category, all kinds of preventive maintenance tasks are proposed, especially predictive maintenance (which involves condition monitoring, trend analysis and failure prediction), based on or adapted from the guidelines given by the standard maintenance codes. When the standard codes are not applicable or adaptable to the specific case of BR2, preventive maintenance tasks are proposed in accordance with the engineering judgement and experience available within the PAM group and among other BR2 and SCK•CEN personnel.

For those SSCs in the orange category, all kinds of preventive maintenance tasks except predictive maintenance are foreseen in the same way. For failure mechanisms in the yellow and green categories, no dedicated preventive maintenance programme is foreseen.

IV–3.2.6. Documents for the installation concept management phase

All SSCs belonging to class A or class B are reviewed in detail. For each SSC (or type of SSC), an individual assessment is made by the PAM group in cooperation with the maintenance groups. All available information (e.g. ageing mechanisms, consequences, acceptance criteria, construction standards) concerning the SSC is collected and documented. Based on these documents, the maintenance groups develop working procedures.

IV–3.2.7. Use of R&D programmes

Dedicated R&D programmes were only used for two components:

(1) The mechanical properties of irradiated aluminium;
(2) The behaviour of beryllium under neutron irradiation.

The programme for aluminium was necessary as a support to assess the lifetime of the vessel. When the first beryllium core was replaced, knowledge of irradiated beryllium was limited; now sufficient information is available for lifetime determination. For all other SSCs, sufficient information is available and no dedicated R&D programmes are necessary.

IV–3.2.8. Use of experience

Internal experience is documented on two levels. First, each maintenance group keeps a detailed operation history of the SSCs under its responsibility. If an SSC is the cause of a disturbance in operation, the information is documented in the general non-conformity database. Owing to the unique design of the reactor, experience from other installations can rarely be used.

IV–3.2.9. Monitoring, testing, sampling and inspection activities

Monitoring, testing, sampling and inspections are executed in accordance with current standards. The following general standards are used:

(a) Mechanical components

For mechanical components, the follow-up of the SSCs is based on the American Society of Mechanical Engineers (ASME) code. Rules are followed as well as possible in practice. The following inspections are conducted:

— Internal inspection;
— External leakage inspection;
— Internal leakage inspection;
— Indication testing, where the component is monitored using its own instrumentation, such as the position indicator of a valve;
— Valve stroke and pump startup time testing;
— Structural integrity inspection;
— Exercise testing.

These sets of inspections are completed by the set of legally required inspections, prescribed by general legislation or by licence requirements. Further inspections and tests come from supplier recommendations.

(b) Electrical and electronic assets and components

The maintenance approach for electrical assets adopted by BR2 in the framework of the PAM project is adapted from the 2010 edition of Recommended Practice for Electrical Equipment Maintenance [IV–11], developed by the American National Fire Protection Association. The maintenance approach was discussed in meetings with the engineers responsible for the electrical maintenance of the BR2 installation. The maintenance tasks and frequencies are defined for each of the different categories of electrical assets or SSCs, together with a reference to the corresponding paragraph of the recommendation in which the tasks are explained.

As with the mechanical components, this set of inspections is also completed with legal requirements and supplier recommendations.

IV–3.2.10. Preventive and remedial actions

Different types of maintenance concepts are used to prevent the failure of a component. The type of maintenance depends on the classification of the component. As shown in Fig. IV–5, the maintenance measures can be divided into two large groups: preventive maintenance and corrective maintenance. Preventive maintenance measures are those that help to increase the MTBF (i.e. reducing the probability of a failure happening by preventing it), while corrective maintenance measures are those that help to reduce the consequences or the impact of the failure once it has occurred. The colours of the boxes in Fig. IV–5 reflect those of the risk category colour code presented in Fig. IV–4.

IV–3.2.11. Preventive maintenance

A failure can be prevented from occurring using two different maintenance strategies:

(a) Condition based maintenance;
(b) Non-condition based maintenance.

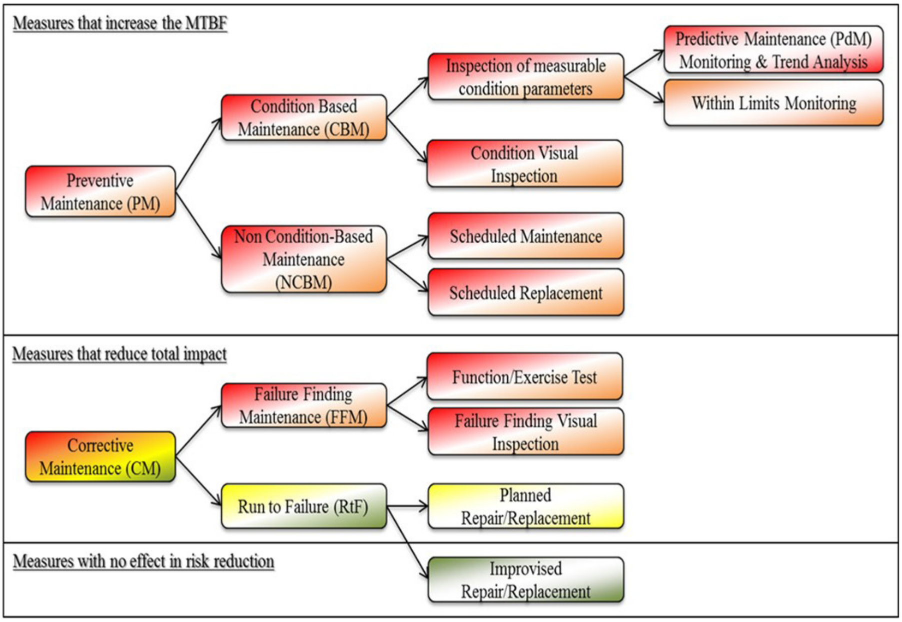

FIG. IV–5. Preventive and corrective maintenance measures.

(a) Condition based maintenance

Condition based maintenance is performed when the need arises. Real time data (e.g. surveillance, monitoring, testing, maintenance) are analysed and the decision to perform maintenance is taken on the basis of one or more indicators suggesting a deterioration in the performance and/or an impending or likely failure. It is helpful in determining the equipment health and in prioritizing and optimizing available resources.

To achieve this, every condition based maintenance task has three action phases:

(1) Detection;
(2) Analysis;
(3) Correction.

In the detection phase, assets in a deteriorating condition that can lead to a future failure have to be identified. For this, a scheduled programme of inspections has to be organized in order to be able to detect or monitor the deterioration processes before the equipment fails. The inspections can be either visual — in which case clearances, settings, physical displacements, discontinuities, imperfections, loss of integrity, lost or missing parts, and signs of corrosion, wear or erosion can be investigated — or based on measurable parameters of equipment condition (e.g. wall thickness, flaw size).

The objective of the analysis phase is to determine the exact condition of the equipment and define the cause of the deterioration. Furthermore, it is in this phase that the decision to restore the equipment to its proper condition is taken. The decision can be taken either by establishing a condition limit that will trigger the maintenance actions once it has been exceeded, or by using the data acquired to analyse the trend of the condition to predict future failure and take action before this happens. This is known as predictive maintenance.

In the correction phase, the real maintenance actions are taken to restore the equipment to its proper condition and eliminate the problem. Corrective action has to be verified to ensure that the problem was actually fixed.

(b) Non-condition based maintenance

Non-condition based maintenance or planned maintenance is a maintenance strategy in which maintenance events or actions (e.g. greasing, painting, dust cleaning, part replacement) are preprogrammed or scheduled in accordance with manufacturer recommendations, legislation or failure statistics. The period between maintenance events is normally extrapolated, for example, from the estimation of running hours or switching limits.

IV–3.2.12. Corrective maintenance

The consequences of a failure can be reduced using two different maintenance strategies:

(a) Failure finding maintenance;
(b) Run to failure.

(a) Failure finding maintenance

Failure finding maintenance is a maintenance strategy that is used to determine whether a hidden failure has occurred in a specific asset. This is normally performed through functional or exercise tests (e.g. testing if a pump starts up or not) or through visual inspections (e.g. observing if a piece of pipe or a junction leaks or not).

Failure finding maintenance does not prevent the failure from occurring or avoid it, but it might help reduce the impact on the plant if the failure is found either before the asset ceases to function (a small leak has smaller consequences than a large leak) or even before the function is actually needed (e.g. finding that a safety valve is not operational before an emergency situation occurs).

(b) Run to failure

Run to failure is a maintenance policy that allows an asset to run until it breaks down, at which point corrective maintenance may be performed. In this approach, the reactive maintenance actions (repair or replacement) can be either previously planned, in which case there is a reduction of the impact on the plant, or improvised, in which case the action has no effect on risk reduction.

IV–4. REVIEW AND UPDATE OF THE OVERALL AGEING MANAGEMENT PROGRAMME

The information contained in the PAM project is kept up to date, although care has to be taken to avoid unnecessary changes. Changes are made only if the scoring is inadequate or when new components are installed.

The state of AMP at the beginning of 2021 was as follows:

(a) The asset configuration management database was considered to have been completed. Changes are possible for new installations (irradiation devices), correction of errors, modification of the installation or for safety revisions.
(b) For all SSCs categorized as class A or B, an installation concept management assessment has been made.
(c) A large number of instructions for work order and management and skills were available. In many cases, existing procedures were reviewed and introduced into the system. The corresponding database is not expected to be complete in the sense that the necessary instructions are developed immediately for every installation concept management issue. For SSCs with very long maintenance intervals, procedures will be developed in due time.

The BR2 reactor is subjected to a periodic safety review every ten years. The content of this periodic safety review is defined in accordance with IAEA Safety Standards Series No. SSG-25, Periodic Safety Review for Nuclear Power Plants (2013) [IV–12]. Ageing management is on the list of items for review.

IV–5. OPERATOR EXPERIENCE OF THE OVERALL AMP

The BR2 reactor has been operating for more than 50 years. Therefore, most of the SSCs have undergone some kind of ageing management, such as replacement, redesign, inspection and testing. A limited number of ageing requirements were prescribed in the licence. Others are listed in the safety report. Some of the SSCs were monitored on the basis of defined procedures, while others were tested and maintained based on the judgement and experience of the responsible persons. The main advantage of the AMP, which began in 2011, is that all information is collected in a systematic manner. In this way it is guaranteed that all SSCs are treated and that all systems important for safety receive the same necessary attention. The legal requirements only concern SSCs that are important for safety. However, it is useful for an operator to take all SSCs into account, and to also consider questions of reliability and cost. This will decrease the operational cost and will limit the unavailability of the reactor. In this case, the AMP guarantees that safety always has priority over economic considerations.

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ABBREVIATIONS

AMP	ageing management programme
AMR	ageing management review
I&C	instrumentation and control
IMS	integrated management system
IRSRR	Incident Reporting System for Research Reactors
ISI	in-service inspection
MTBF	mean time between failures
PAM	plant asset management
RRADB	Research Reactor Ageing Database
RRDB	Research Reactor Database
RRMPDB	Research Reactor Material Properties Database
SSC	structure, system and component
WBS	work breakdown structure

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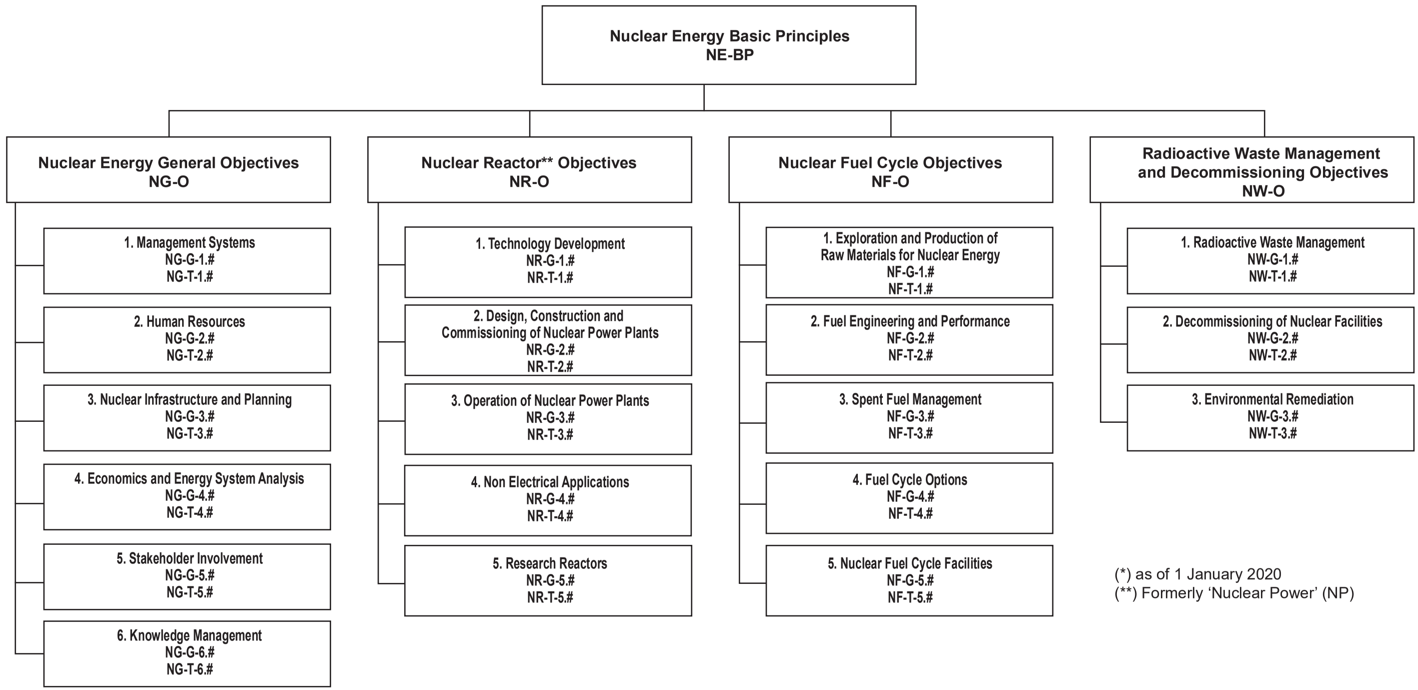

(*) as of 1 January 2020
(**) Formerly 'Nuclear Power' (NP)

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BP: Basic Principles
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Examples

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This publication provides detailed information for operating organizations of research reactors on methodologies to manage existing and potential ageing effects and the degradation of structures, systems and components. Practical guidance is presented on managing the effects of ageing on civil structures, on mechanical, electrical and instrumentation and control systems, and on reactor components important for safety and operation. This publication also provides information on how to establish and implement an effective and systematic ageing management programme, including the management of modifications, modernizations and refurbishments. Several practical examples of successful ageing management programmes executed in operating research reactors are included as annexes.

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