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Long Term Operation of Nuclear Fuel Cycle Facilities

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LONG TERM OPERATION
OF NUCLEAR FUEL CYCLE FACILITIES

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LONG TERM OPERATION OF NUCLEAR FUEL CYCLE FACILITIES

INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

In 2022 the IAEA projected that the global capacity to generate electricity from nuclear power would increase to 715 GW(e) by 2050 in the high case scenario, which corresponds to 11% of global electricity generation projected for 2050. To achieve this high case projection and meet climate goals by 2050, long term operation of existing nuclear power plants (typically beyond 40 years) and a significant effort to build new capacity to generate 500 GW(e) (mainly with small modular reactors) over the next three decades will be needed. At the same time, this could also involve building new nuclear fuel cycle facilities or increasing the capacity of the front end and back end of existing nuclear fuel cycle facilities.

More than 70% of nuclear fuel cycle facilities worldwide have been operating for 30 years or more according to the IAEA's Nuclear Fuel Cycle Facilities Database. Ensuring the safety and reliability of these facilities has become increasingly challenging given the ageing of their structures, systems and components. To address this challenge, several IAEA Member States have implemented ageing management activities, including refurbishment and modernization projects.

A sufficient amount of knowledge exists in Member States about degradation mechanisms and the minimization and mitigation of ageing effects in nuclear fuel cycle facilities. Sharing this knowledge would improve the ability of Member States to develop and maintain systematic ageing management programmes for their nuclear fuel cycle facilities.

This publication provides practical information on factors affecting the ageing of nuclear fuel cycle facilities and its consequences, and mitigating action needed for these facilities in the operational stage, including modernization and refurbishing. The publication also provides considerations for long term operation of a nuclear fuel cycle facility. The information in this publication may be useful to operating organizations, regulatory bodies and other organizations involved in the design, construction, operation and management of safety at nuclear fuel cycle facilities.

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CONTENTS

1. INTRODUCTION

1.1 BACKGROUND

Nuclear Fuel Cycle Facilities (NFCFs) include facilities that provide the nuclear fuels for the nuclear power plants, be it based on natural uranium, enriched uranium, plutonium or thorium (or a combination), and facilities at the back end of the fuel cycle that provide for reprocessing or spent fuel management. Over the lifetime, right from mining, processing of ore, conversion and enrichment, fuel fabrication, reprocessing, and waste management, NFCFs are subjected to wear and tear, by which their safety and reliability may be jeopardised through the effects of radiation, the operating environment, and the use of aggressive chemicals if a proper ageing management programme were not being carried out regularly. Particularly this is very important when long term operation (LTO) or life extension is considered for an extended period of operation of the facility.

The term "long term operation" (LTO) of NFCFs is meant as operation beyond an established time frame defined by the original plant design or license period as per relevant regulations. This term is used to accommodate the different approaches followed in various member states and that is justified by safety assessment, considering the processes that limit the life and features of systems, structures, and components (SSCs).

As per the IAEA database on NFCFs (NFCFDB), there are about 317 facilities in operation worldwide which include facilities for uranium mining and milling, conversion and re-conversion, enrichment, fuel fabrication, spent fuel storage and reprocessing.

The facility's continued usefulness and economics determine its lifetime. For NFCFs, the replaceability of equipment is generally greater in comparison to nuclear power plants due to accessibility. Nevertheless, for some facilities with long operational lifetime, such as spent nuclear fuel storage facilities, reprocessing, hot cell facilities, radioactive waste storage and handling facilities, it would be appropriate to set and justify their extended lifetime within the design.

Most of NFCFs are operating for decades (about 70% facilities worldwide are more than 30 years old) [1,2] in many of the Member States, and many of them have either already exceeded or will be exceeding in near future their initially established design lives. Hence, most of the operating NFCFs are challenged by the negative impacts of ageing of SSCs, which are operating over a considerable time. Since ageing is a process in which characteristics of SSCs change with use or time, equipment including instrumentation and control (I&C) systems' ageing, and obsolescence issues are becoming increasingly more prevalent.

Following the IAEA Safety Standards Series No. SSR–4, Safety of NFCFs [3], Member States have adopted in the recent years various approaches to prepare and implement an ageing management programme for their NFCFs. Many operators of NFCFs have either completed or are in the process of planning large capital projects for refurbishing and modernization, for safety upgradation, to improve performance, or to add capacity to provide new products and services. Such projects can pose unique challenges to NFCF's organizations, which include resource mobilization, both internal and external, shutdown decisions, planning and prioritization, back up plans in case of extended delays.

1.2 OBJECTIVE

The objectives of this publication are to highlight:

- Key issues related to ageing and obsolescence that need to be taken into consideration including modernizing of systems and equipment for consideration in the LTO of NFCFs;
- Strategies that could be employed to address such issues;
- To share good practices for ageing management of NFCFs, so that extension of life of a facility can be considered as a part of its long term operation.

1.3 SCOPE

This publication intends to address a methodology for consideration in the long term operation of a NFCF. This publication provides a comprehensive information for those interested in establishing and implementing a systematic ageing management programme for the long term operation of their NFCFs. The IAEA Safety Reports Series No. 118, Ageing Management for NFCFs [4] provides information on methods, approaches, practices and strategies for ageing management of NFCFs, that can be applied to different types of NFCFs, through all the stages of the facility's lifetime. This publication complements the Ref. 4 by providing detailed Member State experiences and best practices in implementation of the ageing management programmes and further addresses the aspects related to modernization and long term operation of NFCFs.

This publication also focuses on guidelines for addressing associated challenges, such as old design and obsolete components, and the retirement of technical experts on design, manufacturing, maintenance, and operation of NFCFs. The mining and waste management facilities for pre-disposal treatment and disposal are not covered here since separate publications on these specific topics are being published by the Agency. This document also does not address the allied facilities for heavy water and zirconium products and isotope production facilities and decommissioning of NFCFs.

It also needs to be noted that this publication does not provide guidance in relation to the qualification of equipment, as these topics are covered in detail by other IAEA publications (see Section 2.4).

Although this publication is aimed at existing NFCFs and related facilities, the information provided is also useful for designers of NFCFs which includes information on instrumentation and control systems, automation systems and other equipment and new-build programmes. In addition to the operator, this publication may also be used for preparing regulatory requirements, codes, standards, and guidance, for life extension of NFCFs by the regulatory bodies.

1.4 STRUCTURE

This publication is organized into six major sections, including Section 1 comprising of background, objective and scope of this publication. Section 2 lists relevant IAEA safety requirements and guidance applicable to the subjects covered in the publication. Section 3 discusses ageing issues and ageing management covering physical ageing, non-physical ageing, management of technological and non-technological obsolescence covering socio-political issues, economic issues, knowledge management, training and qualification and management issues. Section 4 covers I&C modernization and refurbishing and strategies to cope with equipment obsolescence. Section 5 covers the management of life extension/long term operation. Section 6 contains a summary and conclusions.

The Annexes I and II describe case studies of Member States' practices related to ageing management and modernization of system/equipment of NFCFs. The case studies of events related to ageing management and country examples of best practices in long term are described in these Annexes. Summary of outcome of two technical meetings on, ageing management and life extension held in December 2021 and in October 2022 are provided in the Annex III.

2. RELEVANT IAEA SAFETY REQUIREMENTS AND GUIDANCE

2.1 SAFETY REQUIREMENTS FOR NFCFS

The IAEA Safety Standards establish the requirements for ensuring safety of NFCFs, including the aspects related to ageing and obsolescence. The purpose of this section is to present such requirements that are relevant for long term operation of a NFCF and provide details on the guidance available for meeting these requirements.

2.1.1. Verification of safety

The requirement for conducting periodic safety reviews considering the ageing and other aspects is established in Paragraph 4.26 of SSR–4[1] that states:

"In accordance with national regulatory requirements, the operating organization shall carry out systematic periodic safety reviews of the nuclear fuel cycle facility throughout its lifetime, with account taken of ageing, modifications, human and organizational factors, operating experience, technical developments, new information on site evaluation and other information relating to safety from other sources".

Further, Paragraph 4.27 of SSR–4[1] states:

"The periodic safety review shall confirm that the safety analysis report and other documents (such as the operational limits and conditions and documentation on maintenance and training) remain valid in view of current regulatory requirements or shall indicate where improvements may be necessary. In such reviews, changes in the site characteristics, changes in the utilization programme (particularly for research and development facilities), the cumulative effects of ageing and modifications, changes to procedures, feedback from operating experience and technical developments shall be considered".

2.1.2. Proven engineering practices for the design

The requirement related to the consideration of various degradation mechanism including corrosion, in the engineering design rules is established in Paragraph 6.36 of SSR–4 [1] that states:

“Many NFCFs use aggressive chemicals under harsh environmental conditions, often involving thermal and mechanical cycling and the transfer of materials containing abrasive particulates and, in some cases, complex mixtures of elements and compounds unique to the facility. In establishing engineering design rules and acceptance criteria, the effects of corrosion, erosion and similar processes shall be considered. These effects shall also be considered when establishing monitoring and inspection requirements and, where appropriate, for the management of facility ageing”.

2.1.3. Qualification of items important to safety

The requirement related to consideration of ageing effects in the qualification of items important to safety in NFCFs is established in Paragraph 6.115 of SSR–4 [1] that states:

“The qualification programme for items important to safety shall include the consideration of ageing effects caused by environmental factors (such as irradiation, humidity or temperature) over the expected service life of the items important to safety. When the items important to safety are subject to natural external events and are required to perform a safety function during or following such an event, the qualification programme shall replicate as far as is practicable the conditions imposed on the items important to safety by the event, either by test or by analysis or by a combination of both”.

2.1.4. Design for maintenance, periodic testing and inspection of items important to safety

Requirement 26 of SSR–4 [1] which states:

“Items important to safety shall be designed to facilitate maintenance, inspection and testing for their functional capability over the lifetime of the facility”.

The requirements related to the interface between ageing management programme and the programme for maintenance, periodic testing and inspection of a nuclear fuel cycle facility is established in following paragraphs:

Paragraph 6.105 of SSR–4 [1] which states:

“The design and layout of items important to safety shall include provisions to optimize protection in maintenance, inspection and testing activities. The term ‘maintenance’ includes both preventive actions and corrective actions”.

Paragraph 6.106 of SSR–4 [1] which states:

“Specific attention shall be paid to design for maintenance of equipment that is: Installed in high active areas such as hot cells; To be used in facilities with a long design lifetime”.

2.1.5. Design considerations for the management of ageing

The requirements related to consideration of the magement of ageing during the design of a nuclear fuel cycle facility includes requirement 32 of SSR–4 [1] that states:

“Design safety margins shall be adopted so as to accommodate the anticipated properties of items important to safety, to allow for the effects of materials ageing and degradation processes”.

In addition to the overarching requirement 32 stated above, the other requirements related to the design considerations for the management of ageing in NFCFs include:

Paragraph 6.117 of SSR–4 [1] which states:

“The design and layout of items important to safety, including containment systems and neutron absorbers, shall take account of ageing degradation of materials and the potential for premature failure. Where components provide a safety function, replacement components of equivalent quality shall be provided”.

Paragraph 6.118 of SSR–4 [1] which states:

“Where details of the characteristics of materials whose mechanical properties may change in service are unavailable, a system of monitoring shall be developed in the design to minimize the risks brought about by the effects of ageing, process chemistry, erosion, corrosion and irradiation on materials”.

2.1.6. Ageing management

Requirements related to the management of ageing during the operation of a NFCFs include the following:

Requirement 60 of SSR–4[1] states:

“The operating organization shall ensure that an effective ageing management programme is implemented to manage the ageing of items important to safety so that the required safety functions are fulfilled over the entire operating lifetime of the nuclear fuel cycle facility”.

In addition to the overarching requirement 60 stated above, the other requirements related to the management of ageing during operation of NFCFs include:

Paragraph 9.53 of SSR–4 [1] which states:

“The ageing management programme shall determine the consequences of ageing and the activities necessary to maintain the operability and reliability of items important to safety. The ageing management programme shall be coordinated with, and be consistent with, other relevant programmes, including the programmes for in-service inspection, periodic safety review and maintenance. A systematic approach shall be taken to providing for the development, implementation, and continuous improvement of ageing management programmes”.

Paragraph 9.54 of SSR–4 [1] which states:

“Where details of the characteristics of materials and systems are unavailable and could affect safety, a suitable surveillance programme shall be implemented by the operating organization. Results derived from this programme shall be used to review the adequacy of the facility design at appropriate intervals”.

Paragraph 9.55 of SSR–4 [1] which states:

"The programme for maintenance and replacement of equipment shall be adjusted in accordance with the conclusions of the ageing management programme. The design life of equipment shall be considered in safety assessments for extended operation".

The case studies provided in Sections 3.5, Annexes I and II include the examples of the practices of the Member States which are in compliance with these requirements.

2.2 SAFETY GUIDANCE FOR NFCFS

The recommendations on meeting the Safety Requirements for the different types of NFCFs are provided in the following IAEA Safety Standards Series publications:

- No SSG–5 (Rev. 1), Safety of Conversion Facilities and Uranium Enrichment Facilities [5];
- No. SSG–6 (Rev. 1), Safety of Uranium Fuel Fabrication Facilities [6];
- No. SSG–7 (Rev. 1), Safety of Uranium and Plutonium Mixed Oxide Fuel Fabrication Facilities [7];
- No. SSG–15 (Rev. 1), Storage of Spent Nuclear Fuel [8];
- No. SSG–42, Safety of Nuclear Fuel Reprocessing Facilities [9];
- No. SSG–43, Safety of Nuclear Fuel Cycle Research and Development Facilities [10];

Recommendations on measures for criticality safety in these facilities is provided in IAEA Safety Standards Series No. SSG–27 (Rev. 1), Criticality Safety in the Handling of Fissile Material [11].

2.3 SAFETY REQUIREMENTS RELATED TO LONG TERM OPERATION

SSR–4 [3] does not specify requirements for long term operation of NFCFs. The safety requirements related to long term operation of Nuclear Power Plants are established in IAEA Safety Standards Series No. SSR–2/2 (Rev. 1) [12]. These requirements may be suitably applied for NFCFs by use of a graded approach.

The specific requirements for long term operation of Nuclear Power Plants are specified in Requirement 16 of SSR–2/2[12] which states:

"Where applicable, the operating organization shall establish and implement a comprehensive programme for ensuring the long term safe operation of the plant beyond a time-frame established in the licence conditions, design limits, safety standards and/or regulations."

In addition to the overarching requirement 16 stated above, the other requirements related to the long term operation of Nuclear Power Plants include:

Paragraph 4.53 of SSR–2/2 [12] which states:

"The justification for long term operation shall be prepared on the basis of the results of a safety assessment, with due consideration of the ageing of structures, systems and components. The justification for long term operation shall utilize the results of periodic safety review and shall be submitted to the regulatory body, as required, for approval on the basis of an analysis of the ageing management programme, to ensure the safety of the plant throughout its extended operating lifetime.”

And paragraph 4.54 of SSR–2/2[12] which states:

“The comprehensive programme for long term operation shall address:

- Preconditions (including the current licensing basis, safety upgrading and verification, and operational programmes);
- Setting the scope for all structures, systems and components important to safety.
- Categorization of structures, systems and components with regard to degradation and ageing processes;
- Revalidation of safety analyses made on the basis of time limited assumptions;
- Review of ageing management programmes in accordance with national regulations;
- The implementation programme for long term operation.”

The following IAEA publications between them provide guidance regarding the ageing and obsolescence programmes and associated activities that need to be undertaken during each phase of an NPP’s life cycle:

- IAEA Specific Safety Guide No. SSG–48, Ageing Management and Development of a Programme for Long Term Operation of Nuclear Power Plants [13];
- IAEA Safety Report Series No. 3, Equipment Qualification in Operational Nuclear Power Plants: Upgrading, Preserving and Reviewing [14];
- IAEA Safety Report Series No. 82 (Rev. 1), Ageing Management for NPPs: International Generic Ageing Lessons Learned (IGALL) [15].

2.4 TECHNICAL GUIDANCE RELATED TO AGEING AND OBSOLESCENCE

The following IAEA technical guidance related to long term operation of NPPs, and RRs may be utilized for NFCFs by use of a graded approach in their application.

- IAEA–TECDOC–1402, Management of Life Cycle and Ageing at Nuclear Power Plants: Improved I&C Maintenance [16];
- IAEA–TECDOC–1389, Managing Modernization of Nuclear Power Plant Instrumentation and Control Systems [17];
- IAEA–TECDOC–1147, Management of Ageing of I&C Equipment in Nuclear Power Plants [18];
- IAEA Nuclear Energy Series No. NP–T–3.6, Assessing and Managing Cable Ageing in Nuclear Power Plants [19];
- IAEA–NP–T–3.2, Handbook on Ageing Management for Nuclear Power Plants (2017) [20];
- IAEA–TECDOC–792, Management of Research Reactors Ageing (1995) [21];
- IAEA–TECDOC–1736, Approaches to Ageing Management for Nuclear Power Plants (2014) [22];
- IAEA–TECDOC–1748, Project Experience in Research Reactor Ageing Management Modernization and Refurbishment (2014) [23];
- IAEA–TECDOC–1503, Nuclear Power Plant Life Management Process: Guidelines and Practices for Heavy Water Reactors (2006) [24];

— IAEA–TECDOC–1871, Material Properties Database for Irradiated Core Structural Components for Lifetime Management for Long Term Operation of Research Reactors (2019);
— IAEA Technical Report Series No.43: Understanding and Managing Ageing of Material in Spent Fuel Storage Facilities (2006) [26];
— IAEA Guidance on Ageing Management Programmes for Spent Nuclear Fuel Dry Storage Systems (Final Report of a CRP in progress);
— IAEA–TECDOC– Asset Life Cycle Management of Uranium Mining and Processing Facilities (in progress).

3. AGEING ISSUES AND AGEING MANAGEMENT

Ageing is defined as a "general process in which characteristics of a structure, system or component gradually degrades with time or use" [15]. SSCs are required to operate during normal operation as well as in transient conditions even though the ageing process may lead to degradation of materials' characteristics. The definition of ageing does not include postulated accident and post-accident conditions. The ageing may contribute to the reduction or the loss of the ability of SSCs to function as required by the design intent. It may affect safety, operation and utilization of the facility unless corrective measures are taken to control the ageing process.

The 'bathtub' curve given below in Fig. 1 conceptually represents the ageing phenomena in terms of the probability or rate of failure of a component or a group of components over their life. The meaning of term 'failure' refers to any state where the component/equipment either does not perform as per original intent, or is not fit for service anymore, or it requires remedial steps to make it healthy. The rate of degradation and the effect of accumulated damage on operating margins are determined by the slope and direction of the curve. The three phases of failure are infant mortality phase, useful life or constant failure phase and end of life or wear out phase.

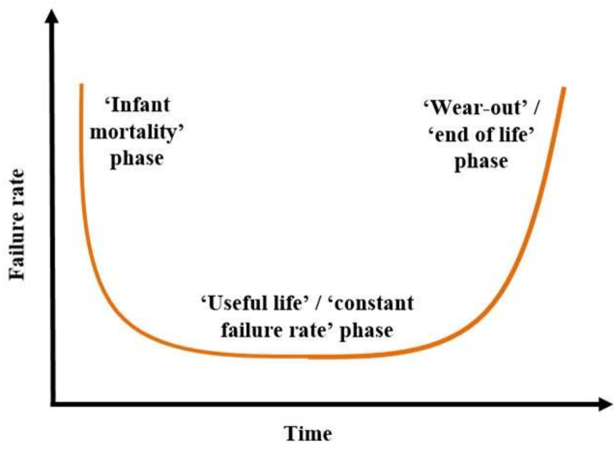

FIG.1. Reliability bathtub curve

The intervention for remedial actions can be beneficial if proactive ageing management is applied at a stage when ageing starts. The figure above indicates that important indicators are approaching design limits and the increasing degradation rates. Definitely an action at this stage provides greater confidence and control in the condition by means of quantitative, frequent inspection and of course non-destructive testing (NDT).

The pro-active ageing management involves revalidation, replacements, major repairs, and refurbishment at various times. The loss of knowledge or history due to retirement of key personnel of the organisation or loss of corporate memory or records can also add to ageing issues. The other issues like obsolescence and a lack of availability of spare parts or non-conformance with current safety requirements, codes and standards and procedures may also further aggravate an ageing process. These issues have been described further in this section.

Like any other facility, NFCFs experience two kinds of ageing: physical ageing and non-physical ageing. NFCFs usually handle large amounts of radioactive material and also corrosive, reactive, and dangerous chemicals. These materials may be abrasive, corrosive, or may contain impurities or other unwanted material depending on the type of facility. In general, NFCFs provide barriers for containment of these materials since failure of such barriers could result in releases of radioactive or other hazardous materials. Hence, in NFCFs, the prevention of release of radioactive and other hazardous materials needs to be addressed. Of course, the service conditions in NFCF are less severe than in NPPs, due to mostly lower temperatures and pressures. The neutron irradiation is not an issue here unlike in NPPs, however, there could be major damage due to heating by gamma radiation. This can vary with the degradation mechanisms and ageing management of the NFCFs with respect to NPPs.

3.1 AGEING IN NUCLEAR FUEL CYCLE FACILITIES

3.1.1 Physical ageing

Gradual deterioration in the physical characteristics of SSCs which results in degradation is called physical ageing, i.e., it is a time dependant process of degradation due to physical, chemical, or biological processes, also called degradation mechanisms. Several ageing related problems occur in NFCFs due to different service conditions. The ageing process, however, gets accelerated if several of these service conditions or mechanisms exist simultaneously.

3.1.2 Degradation mechanisms and ageing effects

NFCFs cover a very large number of nuclear facilities which include mining and milling of uranium, thorium (in some countries), conversion of uranium, enrichment, fuel fabrication, spent fuel storage, re-conversion of uranium hexafluoride, spent fuel reprocessing and associated waste and effluent management facilities (e.g., vitrification), and related research and development facilities. Because of this diversity, the degradation mechanisms and ageing effects may be different for these facilities in different countries depending on the process conditions, environment conditions, temperature, pressure, chemicals used etc. Accordingly, the implementation of ageing management policy and programmes are required to be sized differently.

The most common factors and service conditions that can lead to degradation mechanisms are listed as follows:

- Stress and/or strain;
- Temperature;
- Fatigue;
- Radiation;(including UV radiation);
- Mechanical degradation by abrasion , erosion and wear;
- Humidity;
- Corrosion;
- Vibration;
- Changes in dimensions or position of individual parts of assemblies;
- Inadequate design, improper installation or maintenance;
- Excessive testing;
- Chemical degradation and reaction rate;
- Mechanical properties (fracture toughness, fatigue)

These factors may also affect others in combination and accelerate the degradation process (example stress corrosion cracking (SCC) and irradiation enhanced stress corrosion cracking).

In addition to the above, based on the service conditions, the other important factors that are unrelated to physical or chemical processes which can also lead to ageing effects and may affect the safe and reliable operation of NFCF are obsolescence and are further discussed in Section 3.3.

A detailed list of degradation mechanisms with different factors is given in section 3.2.2.

3.1.3. Degradation of materials characteristics

The process of ageing impacts degradation of materials characteristics. The degradation can be reflected in:

- Changes in physical properties (e.g., density, dimensions, colour, thermal conductivity, electrical conductivity);
- Changes in mechanical properties (strength, ductility, elasticity etc);
- Changes in chemical properties (ionization caused by irradiation, reaction with contacting fluids, molarity);
- Material damage (cracks, surface deterioration, breakage);
- Performance deterioration of SSCs (equipment not delivering design parameters, calibration change of instruments).

3.1.4. Examples of factors responsible for physical ageing

3.1.4.1. Radiation effects

Since the materials in a NFCF are subjected to all or in combination of various types of radiation, e.g., neutrons, gamma, beta and alpha, it may cause significant damage to the crystalline structure of materials. The interaction of radiation with materials is well studied subject matter damage to the material is caused by the interaction of the radiation energy with the nuclei and/–or orbiting electrons. Radiation damage to materials may cause the crystal structure getting modified through these energy interactions leading to changes in the bulk materials' mechanical properties. The gamma radiation related degradation of material is more applicable to back-end facilities including fuel fabrication from recycled nuclear materials than to front end facilities.

Damage due to radiation has been widely studied because of its importance in structural components which are subjected to extreme conditions i.e high temperature, high stress, corrosive environment besides irradiation. It is important to remember that materials used in a NFCFs experience bombardment by different types of radiation simultaneously and therefore the damage sustained can be quite complex. Before understanding the combined damage caused by different radiations, it is essential to understand separately the type of interaction exhibited by the type of radiation and its effects on a material. The type of damage a particular radiation can cause in a material depends on radiations under two broad categories namely ionizing radiations and non-ionizing radiations.

Since the atomic bonding gets disrupted due to ionization, the extent of damage in a material depends on the nature of chemical bonds present in that material. If the material is made up of atoms chemically bonded through covalent bonds, the ionizing radiation, can break up bond pairs of electrons by stripping electrons from their atoms which in turn results in a chemical change due to disintegration old and formation of the new molecules. For an example of co-valent bonding, plastics or rubber (natural and synthetic) or organic compounds such as extractants like tri-n-butyl phosphate (TBP) which are normally deployed on an industrial scale for purification of the uranium raw material and the diluents such as kerosene and/or n-dodecane oils, are subjected to significant damage by ionizing radiation. Gamma radiation induces damage of elastomers and mineral oils in lead glass windows that are used in hot cells causing poor visibility.

In comparison to covalent bond, the ionic bonds are not affected/damaged by the ionizing radiation because in ionic bonds, electrostatic attraction holds together oppositely charged ions in a crystal lattice. When ionizing radiation falls on a material made up of ionic bonds, due to knocking of electron from the atoms, the electrical charge on individual ions may be altered and the knocked out electron may eventually find its way to another electron deficient site and still experiencing electrostatic attraction. However, in case the knocked–out electron become trapped in a crystal lattice it leads to formation of imperfection which can cause changes in colour. It is to be noted that the formation of imperfection has little effect on the mechanical properties of the material and the structural properties are virtually unaffected.

For example, in a spent nuclear fuel reprocessing plant, the gamma radiation beyond a threshold limit damages seal and gasket material, which is generally non-metallic, in valves, piping and equipment. In polymers and elastomers, the gamma and neutron radiation affect cross linking resulting in the change of properties. It is also seen that gasket and O-rings made of neoprene material turn brittle after withstanding a high radiation dose and are mostly replaced before they fail.

In the case of metals on the other hand, due to metallic bonding, the ionizing radiation will have only a transient effect because of the replacement of the stripped electrons with freely moving other electrons. Regarding the radiation damage, metals are reasonably unaffected by ionizing radiation. Therefore, the process tanks and other metallic gadgets used for various operations multiple number of times do not suffer significant radiation damage and the structural integrity will not get affected due to the processing of radioactive material such as natural uranium. The radiation affects the metals mainly due to increase in the yield and the ultimate strength and also reduction in the toughness resulting in embrittlement which under high stress conditions sometimes may lead to a brittle fracture of the material. Under neutron irradiation, the transmutation of aluminium to silica and the resultant change in properties of aluminium is an example in spent fuel storage facility using borated aluminium material

Concrete is commonly used as a shielding material in addition to as a construction material for civil structures of NFCFs. Effect of neutron irradiation on concrete is mainly seen on reinforcement metals and aggregates used in the concrete. Gamma heating could lead to loss of moisture and thereby concrete properties. However, since the concrete is usually not in a very high radiation field in NFCFs compared to NPPs and RRs, severe damage from radiation is not expected under operating conditions of most of NFCFs.

A practical example is the degradation behaviour of concrete walls of spent fuel storage pool. In addition to radiation, they also withstand thermal heat from spent fuel. The pool water heat transfer system is so designed that it can limit the temperature of the inner concrete surface. Although the radiation effect on concrete is very small but it needs to be considered for long term performance of spent fuel storage facilities.

The electrical and electronic equipment (e.g., coaxial and other cables) are normally located in low radiation areas of the facilities. However, some of the detectors for monitoring might be located in higher radiation fields also. It is observed that the insulation of cables or electrical/electronic component deteriorates beyond a threshold value due to radiation. Ageing management programme would therefore consider this and accordingly plan for suitable inspection, testing, and replacement.

Similarly, since all the organic materials and glasses are affected by radiation, they need to be carefully selected and monitored for use in the NFCFs. The mineral oil used between layers of radiation shielding windows (RSWs) undergoes degradation leading to reduced visibility. Hence, these oils require periodical replacement.

Some more examples are given in annex II.

3.1.4.2. Temperature and pressure

All SSCs are to some extent affected by the high temperature. Therefore, it is important to pay attention to have proper cooling of facilities and systems such as cooling of spent fuel storage, high level liquid waste storage tanks, dissolver in a reprocessing equipment, as well as to electrical and instrumentation systems/equipment which are located in hot areas and may not be properly ventilated. There is a temperature limit of 60°C for concrete as higher temperature may cause degradation of concrete by dehydration leading to loss of integrity as well as radiation shielding effectiveness. Elevated temperature in polymers results in hardening or a loss in tensile strength and elasticity.

For example, Cooling and heating cycle for piping and tanks, heating cycles for refractory material used in furnaces.

As another example, a reprocessing facility normally operates at a negative pressure. Therefore, pressure may not be the only factor for high stress on components. Special care is required for devices operating at high temperature and/or pressure e.g., evaporators and vitrification melters in both reprocessing and vitrification plants. Examples of pressure induced degradation are enhancement of creep induced degradation due to increased pressure in combination with temperature and reduction of fatigue cycles due to increased pressures in feeding tanks in reprocessing.

Increased pressure in the process systems may lead to reduction of fatigue cycles, for example in the pressure vessels. Further, increased pressure in combination with temperature may cause enhancement of creep induced degradation. Hence, the SSCs operating at higher temperature and pressure, for example evaporators, need to be monitored for these ageing effects.

3.1.4.3. Vibration and cyclic loading

Loading stresses which may cause material cracking and sometimes a fatigue fracture in general are developed due to vibrations and cycling of pressure, temperature, and flow. Vibrations and thermal stresses induced in steam piping are an example. Steam piping requires supports for protection against vibrations and expansion joints or U-bends for taking care of stresses. Electronic components and instrumentation may get degraded due to vibrations. Vibration associated with the integrity of bonds and seals is an important factor in the premature failure of these components. Change of position or of a set point in instruments is due to vibration is also another phenomenon. Adjacent parts of these components may be subjected to fretting or wear due to repeated relative motions. Vibration may also lead to weakening of structural supports. Vibration would also include ultrasonic devices.

Failure of high speed fans in ventilation systems and compressors/pumps and degradation of conveyers used in fuel manufacturing and vibration / thermal expansion induced degradation in steam / vapor carrying piping are some of the examples physical ageing due to vibration and cyclic loading.

3.1.4.4. Corrosion and erosion

Corrosion is the gradual deterioration of materials and their critical properties by chemical or electrochemical reaction with their surrounding environment. Corrosion takes place in both metals and nonmetals. It leads to material loss with surface degradation, loss of thickness and loss of strength. Corrosion is the most prevalent factor for degradation of materials in NFCFs which may also lead to loss of strength through crack propagation and growth (e.g., intergranular corrosion, stress/strain corrosion, corrosion fatigue). Another effect of corrosion is deposition of particles (corrosion products) in vulnerable places (e.g., valve seat) to impair the function of a component. These particles containing radioisotopes may cause higher radiation dose to the operating personnel. Corrosion of reinforcing bars in concrete cause them to swell, lose in strength and could result in cracks or spalling. The chemicals used at fuel manufacturing and fuel reprocessing facilities include nitric acid, sulphuric acid, formic acid, chlorine, ammonia, caustic lye, TBP, kerosene etc which are highly corrosive in nature. A typical example is that of failure of pipes due to corrosion carrying these fluids. A case study example of corrosion of an evaporator in a reprocessing plant is given in annex II.

The common types of corrosion that SSCs are likely to encounter are:

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

3.1.4.5. Degradation due to erosion, wear and abrasion

Bi-metallic corrosion occurs when two dissimilar metals are in contact with each other in the presence of an electrolyte. This is mainly due to an unfavourable electrochemical potential difference between two metals in contact. Whereas the wear out of material due to action of surface processes such as fluid flow is called erosion. For example, erosion in equipment such as heat exchangers, pipes etc can occur due to the operating conditions of high velocity of coolant fluid, dissolved and suspended matters. Like corrosion, erosion results in deterioration of surfaces and also loss of material, resulting in reduction of the thickness. The environmental conditions such as high winds and sandstorms can also cause erosion in the structures which are outdoor. While corrosion takes place mainly due to the service environment, many other service conditions causing erosion will enhance the process. The erosion processes may also take place where there is a continuous high speed flow of suspended particles via pipelines of mixture of such suspensions. One of the major examples is erosion of carbon steel (CS) pipes from inside carrying secondary cooling water/fluid to and from cooling towers.

3.1.4.6. Other chemical reactions

The deterioration of structure or equipment can also happen due to the conditions through chemical reactions with the chemical environment, e.g., reaction of the structure or equipment with ozone or nitrogen dioxide (NO_2). Use of chemicals such as acids or alkalis typically used in NFCFs may cause damage to equipment if proper measures are not taken during selection of materials as well as during operation. Special care requires to be taken when handling or storage of highly corrosive acids like nitric acid in the conversion, fuel fabrication and reprocessing facilities. Suitable measures such as periodic chlorination of sea water to prevent bio–growth is taken. The underground pipes are specially coated with protective material on outer surface for minimising /eliminating the possibilities of corrosion. Use of fluorides in fuel manufacturing is highly corrosive and can have impact on the life of SSCs for which special care is taken for selection of materials like polyvinylidene fluoride (PVDF).

More details are given in [20].

3.2 NON-PHYSICAL AGEING OF SSCS

The obsolescence due to any of the factors related to either availability, or technology or due to changes in safety requirements, codes or standards, etc is called non-physical ageing where SSCs are becoming out of date (i.e., obsolete).

3.2.1. Obsolescence of SSCs

SSCs becoming obsolete or out of date for further use is considered as obsolescence. This may be due to functional, economic, or physical factors. It may result in a lack of availability of spare equipment due to current knowledge, standards, and technology.

Obsolescence or non-physical ageing occurs due to changes in technology, upgrading of knowledge, revisions in standards or regulations, non-availability of spares, or outdated documentation. It is necessary to predict items which could be obsolete, before the obsolescence can happen, and which can directly or indirectly have an adverse effect on the safe operation of the nuclear fuel cycle facility. The factors of obsolescence are also reviewed during periodic safety review (PSR) or its equivalent. The process of evaluation of the effects of both physical ageing and obsolescence of SSCs is carried out continuously by the operating organisation for safe operation of the facility.

3.2.2. Factors of non-physical ageing

Human factor is one of the most important factors in addition to changes in technology, knowledge management, documentation, changes in regulatory requirement/ standards. The safety and reliability of NFCFs largely depends on the efficacy of the staff who operate the facilities sometimes in hazardous environment in addition to the robustness of the systems they handle.

3.2.2.1. Changes in technology

NFCFs are built according to the industry standards and with the equipment available at the time of construction. For some older NFCFs, over the years, there has been a good progress in the technology, especially in electronics and automation made since their design and construction. Though the life of such components may not be long, and the facility may be operated further, however, due to non-availability of spares or due to increase in efficiency, it may be necessary to modernize the entire mechanical or instrumentation and control system in order to facilitate a proper maintenance programme.

As for example, modern days controlled exhaust system for pressure vessels, reliable monitoring and detection systems of different parameters etc. can replace the old ones. Some other examples that can change the old ones are (i) gaseous diffusion technology to centrifuge technology for fuel enrichment; (ii) change of analogue technology to digital technology in I&C systems; (iii) switch over from wet storage of spent fuel to dry storage of spent fuel. (iv) use of I&C for logging of equipment performance for planning of repair and maintenance (v) single stage U_3O_8 to UO_2 conversion process from two stage process (direct reduction instead of calcination and reduction). (vi) change from batch type dissolution to continuous dissolution in a reprocessing process. (vii)from batch to continuous sintering process for pellets in a FMP, (viii) changes due to advancement in fuel design and (ix) state of art automation technology to improve quality, efficiency, ergonomic and improving safety through reduction of radiation exposure to personnel in field operations.

3.2.2.2. Changes in safety requirements

Many of the Safety Standards may require a revision and can include new safety requirements considering a long period of installation and operation of a NFCF. The modification of the systems or back fitting and the updating of the documentation of the NFCF over a period of operation, are required to be considered. Moreover, the lessons learned from accidents and incidents that might have happened over many decades of operation also contribute to changing the safety requirements. The ageing management programme therefore needs to take this into account.

Over the years, regulations with respect to national and international safety requirements have changed and there are requirements that periodic safety review or its equivalent are carried out normally once in five years as per new requirements of the national/international regulations. Some of the examples are: effluent limits, seismic requirement, dose limits, protection against external event (Tsunami etc), layout for electrical panels for safety systems, secondary control room, occupational (lead glasses for hot cell operators) etc.

3.2.2.3. Out of date documentation

The operational efficiency demands modifications and changes of SSCs which can be reflected in the revision of any relevant documentation. The management system for a NFCF may include a process to ensure that design changes are included in the revisions of any documentation. A good ageing management programme needs to include a comprehensive review of documentation having safety significance, and support the updating of operational, maintenance and safety documents, drawings, specifications, documentation including quality assurance documents. The documents which are made during design, commissioning, and operations may become obsolete when considered for long term operation because of modifications, obsoleteness of equipment, instrumentation, and control. To be able to maintain an updated safety documentation, it is advised to have a structured and modularised documentation system. Since an update of safety documentation normally requires several stages of reviewing and adjustments after reviewing, there is a risk that the lead time can cause conflicts of accessing the editable version. One example is long term projects that might lock the editable safety documentation for updates connected to more urgent, but minor modifications. It is also a risk that different updates of the SSC's impact each other causing the update of safety documentation a challenge.

Hence, out of date documentation may be set aside and new document for operation and maintenance as well as regulatory clearances may be adopted. The documentation would be suitable for matching with new generation.

As an example, drawings from papers can be converted to digital documentation. New IT tools are also required to retrieve documentation. Another example is use of digital documentation directly on the file by workers which includes transmission of the information in real time.

Operator requires to set a frequency to update the documentation, changes of installation layout/purpose etc. The best practice is to update as and when modification or replacement action is completed in the plant.

The suggestive methods to resolve the issue may be the following:

— Establishment of unified database of instructions and R&D documents;
— Recording of video guidelines for personnel training;
— Use of IT tools for automated analysis, AI, and advisory for upgrade of information in the corresponding sections of instructions (when the safety requirements are revised);
— Use of I&C for logging of equipment performance for planning of repair and maintenance.

3.2.2.4. Inadequacies in design

Inadequate design such as selection of improper materials and inaccessibility for inspection and repair could also contribute to accelerated ageing effects. It may be noted that overdesign or under-capacity operations lead to differential conditions in unutilized portion of equipment leading to accelerated ageing.

As an example, when we overdesign an evaporator for a rated capacity, operations can lead to dry heating causing high thermal stresses and damage to the vessel. Similarly, when we operate at higher than the rated pressure, it can lead to vibrations and cause damage to the system. To overcome the effects of inadequate design, the ageing management programme requires to include measures such as changes in the operating conditions e.g., decrease of flow, pressure or temperature in pipes or use of higher thickness pipes to lower the rate of ageing and increase the life or the need for more frequent inspections, tests, and analysis. As an example, for reprocessing, advanced alloy materials are being used for evaporators in nitric acid environment in place of SS 304.

3.2.2.5. Improper maintenance and testing

Any improper maintenance and testing may add to the severity or increased rate of ageing effects. For example, increased pressure on bearings or excessive tensioning of retaining bolts could accelerate wear. Too frequent testing or use of test procedures that are not in accordance with design and manufacturer's/supplier’s recommendations can have detrimental effects on systems, structures and components. Availability of trained staff is very essential. It is very important that records of maintenance, and testing are appropriately generated, maintained, and retained.

For an example, EOT crane requires periodic maintenance and testing. Condition based maintenance in place of time-based maintenance would improve the availability. Monitoring for lubrication also improves availability.

3.2.3. Technological obsolescence issues

Technological obsolescence refers to the situation where a technology or equipment becomes outdated, inefficient, or incompatible with newer advancements. Several technological issues that can arise for a NFCF are ageing technology used in the fuel cycle facility, outdated control systems, ageing instrumentation and monitoring systems, obsolete safety systems, cybersecurity vulnerabilities and newer methods for radio-active waste minimisation. Addressing technological obsolescence issues requires proactive planning, periodic assessments, and investment in research and development. Regular upgrades, modernization efforts, and collaboration with industry experts can help ensure the safe, efficient, and reliable operation of NFCFs.

At many a times, availability of suppliers for spares or equipment changes with time which are needed due to compatibility with other systems. This is more rapid for electronic components and computerised systems where the market is more dynamic. The operating organisation need to identify such components becoming obsolete in advance and make necessary arrangements for suitable replacements.

3.2.3.1. Operating conditions and obsolescence

The factors such as operational or service conditions contribute to ageing through physical and chemical processes (degradation mechanism) can affect material properties and/or functional capabilities.

In addition to these service conditions, the factors unrelated to physical or chemical processes which can also lead to ageing effects and affect the safe and reliable operation of a nuclear fuel cycle facility are:

- Technology changes;
- Safety requirements changes;

— Obsolescence of components;
— Out of date documentation;
— Inadequacies of design;
— Improper maintenance or testing;
— I&C equipment and software obsolescence.

3.2.3.2. I&C equipment and software obsolescence

The safety and reliability of the NFCFs largely depends on I&C system in addition to their mechanical or process function. As an example, a list of items of I&C important to safety in operation and thereby for LTO in a conversion and enrichment facilities are given below:

— I&C related to ventilation;
— Monitoring equipment for ventilation such as differential pressure gauges on filters and between gloveboxes and room;
— Devices for measuring uranium or gas concentration in ventilation system;
— Fan failure alarms/differential pressure (DP);
— I&C related to prevention of explosion;
— Monitoring of ammonium nitrate deposits in conversion facilities;
— Level detectors and alarms for vessels containing nuclear material;
— I &C related to chemical purity of UF_6;
— I&C related to criticality safety;
— I&C related to the process;
— I&C related to gaseous and liquid effluents.

3.2.3.3. I&C equipment knowledge management

Effective knowledge management for instrumentation and control (I&C) equipment in a NFCF is crucial to ensure safe and reliable operation. The following are some steps to consider for I &C equipment knowledge management which can improve safety, operational efficiency, and reliability:

— Documentation and information sharing;
— Training and knowledge transfer;
— Standardization and best practices;
— Maintenance and calibration;
— Obsolescence management;
— Vendor and supplier relationship;
— Knowledge sharing and collaboration;
— Continuous improvement;
— Regulatory compliance;
— Record keeping and data management.

3.3 AGEING MANAGEMENT PROGRAMMES (AMP)

Most of the NFCFs (NFCFs) in nuclear industry are being operated for many decades and in some cases over 50 years [2]. NFCFs generally handle large quantities of radioactive materials as well as corrosive, reactive and hazardous chemicals. To avoid failure during service life due to ageing, a systematic ageing management programme is implemented. At the design stage itself an adequate safety margin is provided for the equipment handling hazardous chemicals or fluid with only single pressure boundary for hazardous fluid. The materials handled may be highly corrosive like acids or alkalis (as in uranium conversion or fuel reprocessing facilities), or abrasive like powders (as in fuel fabrication) or may sometimes contain impurities like silica in yellow cake obtained from processing of uranium ores. There is other undesired material such as some fission products content in the spent fuel feed of reprocessing facilities. These impurities in process fluids in particulate form or their physical and chemical properties may result in corrosion, erosion and clogging of the piping or the equipment.

The objective of ageing management is to address ageing of all the time dependent SSCs of the NFCFs that are critical to safe functioning, in a systematic way. Recording of details regarding the variety of situations and conditions encountered by the systems, structures and components (SSCs) is very essential. This data can be used as an input for defining their periodical testing and maintenance and inspection methodology which would help in timely detection and mitigation of ageing effect of SSCs. A guidance to a systematic approach to ageing management is given in [4].

For effective implementation of ageing management programme (AMP) for any NFCF handling variety of corrosive, toxic, flammable, and hazardous materials in various processes, the important parameters are service conditions, and environment conditions for evaluation during all stages of a facility. The strategies to be followed for managing ageing during design, fabrication/construction/commissioning/operation and decommissioning/dismantling are quite different and have to be applied suitably in order to have an effective AMP.

Some of the consequences of ageing related failures may be leading to fire, radioactivity spread or release or release of hazardous material and in combination due to the following reasons:

- Loss of confinement of hazardous chemicals including radioactive materials;
- Accumulation of radioactive and fissile materials (in vessels, piping, ducts, etc);
- Uncontrolled chemical reactions;
- Unavailability of monitoring and alarm systems;
- Non- availability of safety related utility systems (cooling water, compressed air, steam supply, ventilation, etc).

3.3.1. Elements of an effective ageing management programme

A systematic and formal assessment of the SSCs at periodic intervals as a part of ageing management can achieve the goals of life management of the NFCFs. A graded approach is required in implementing an ageing management programme at a facility for an effective life management and safety. The main elements of a systematic and proactive ageing management programme for NFCFs include the following [4]:

- Administration and organization;
- Screening and selection of SSCs;
- Identification and understanding of applicable degradation mechanism(s);
- Detection, monitoring and trending of ageing effects;
- Collection of relevant data and evaluation;
- Minimization and mitigation of ageing effects;
- Acceptance criteria;
- Assessment and prediction of residual life;
- Corrective actions;

— Review including experience feedback and modifications;
— Documentation and records.

3.3.2. Inspection and assessment techniques

The various inspection and assessment techniques, giving important inputs for an effective ageing management, include in-service inspection, preventative or predictive maintenance, regular maintenance, surveillance, condition monitoring, testing and calibration, fitness for service etc. AMP also involves coordinating various ageing management activities i.e., managing SSC degradation mechanisms from detecting and assessing ageing effects to taking corrective steps for consideration of long term operation of the facility.

One of the methods of understanding and detecting ageing effects is by a suitable non-destructive testing (NDT) which provides a systematic data of a trend to give information about degradation of the SSCs. This information would help during consideration of long term operation of the facility. The common NDT techniques used are namely, visual inspection, ultrasonic testing (UT), eddy current testing (ECT), liquid penetrant testing (LPT), magnetic particle Testing (MPT), radiography, phased array ultrasonic testing (PAUT), time of flight diffraction (TOFD), high voltage spark testing etc. In most of AMPs, the data from condition monitoring, surveillance, and in-service inspection along with the base line data, operation data and maintenance history are used to detect and monitor any degradation. Accordingly, for effective life management of SSCs, suitable mitigating measures like controlling operating parameters, planning maintenance programme, modifications etc. can be taken.

A dedicated ageing management programme (AMP) greatly contributes towards ensuring the safety in operation throughout the service life as well as during the extended period of long term operation of the facility.

3.3.3. Minimisation and mitigation of ageing effects

Considerations for minimisation of ageing effects need to start at the design stage of the facility. It takes into consideration the end of useful life of equipment associated with the material of construction and the operating environment of the equipment. In addition to the design of the equipment, the configuration and physical facility layout is considered for the access to perform maintenance and testing/inspection of the equipment for detecting ageing effects. Advancements in design have resulted in the ability for continuous acquisition of important data which precludes the need for repetitive ‘surveillances’ of equipment such as installation of a data acquisition system which collects, analyses, and trends the data. Also, self-diagnostic features typically in control systems reduce the need for testing and reveal the faults or failures. Decommissioning stage is worth taking into account at the design stage of SSC’s. During shutdown and decommissioning the ageing continues by external factors. During the decommissioning, it may also require running/operation of some SSCs like ventilation, pump or store various media, measurements etc.

Minimization of ageing effects is often accomplished as a part of refurbishment or replacement task including system or equipment specific (see section 4).

Mitigation is applied when a condition is identified as being present where 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, e.g., where a process parameter value is brought back into acceptable limits or altered within the operating range or downgrading the safe working load of a crane to slow down the ageing effects. While minimization and mitigation actions are conceptually different, some minimization activities are also mitigatory in nature. Some general measures for prevention and mitigation of potential degradation mechanisms are operation of SSCs in accordance with specific procedures, corrosion control by chemistry controls, environmental parameter controls, use of improved materials or welding methods, corrosion resistant coatings or surface treatment, in service inspection and surveillance programmes, maintenance and condition monitoring programmes, etc.

An example of a mitigatory action to counter the ageing effects is given here:

A carbon steel pipe, meant for transferring fluid, buried and in direct contact with soil (or encased in concrete) is generally coated with fusion bonded epoxy (FBE) and layers of polyethylene to minimise the corrosion. The corrective action can be taken also based on the ageing monitoring systems. Any failure of that coating likely results in an external corrosion of the pipe and loss of material of the pressure boundary and can eventually result in pipe failure. The application of an ageing management programme prompts the facility to recognize the potential for the onset of an ageing effect to that buried piping because the operating life may already be beyond that originally intended and that there is a potential for failure of that coating (and the potential for a loss of pressure boundary function). Mitigatory action in this case that can be followed is to inspect the coating and replace before the onset of corrosion of the pipe. A few more country examples are given in annex II on approaches to ageing management programme.

3.4 COMMON CAUSE FAILURE

Common cause failure happens when two or more factors are responsible for degradation of a material. A common cause failure in a nuclear facility refers to a situation where multiple components or systems fail simultaneously due to shared cause or event. For example, if multiple pipes or valves suffer from corrosion or wear, they mail fail simultaneously, affecting overall performance and safety of the facility.

To mitigate the risk of common cause failures, NFCFs employ various safety measures, such as redundancy, diversity, and robust design principles. These measures aim to ensure that if one component or system fails, there are backup systems or alternate pathways to maintain safety and prevent accidents.

An illustrative example of common cause failure is given here on cooling water pipes used for carrying cold water to a spent fuel storage pool to take away the decay heat of spent fuels. These pipes may suffer from corrosion due to exposure to the operating conditions and chemical reactions within the system. If the corrosion progresses unnoticed or is not adequately addressed through maintenance and inspection, it can weaken the integrity of pipes. As a result, the pipes may develop leaks or even rupture simultaneously. This would lead to common cause failure, where multiple cooling systems fail due to ageing related corrosion of their respective pipes.

To prevent such common cause failures due to ageing, NFCFs employ various strategies like implementation of an effective ageing management programme through regular inspections, maintenance programmes and proactive replacement or repair of ageing equipment. The non–

destructive testing techniques such as ultrasonic examination or eddy current testing are used to detect corrosion and assess the condition of pipes.

Another example for common cause failure of instrumentation system could be due to shared power supply failure. If there is a single power supply that provides electricity to multiple systems, a failure in that power supply could cause simultaneous or sequential failure in these systems. For example, due to a faulty circuit breaker, power supply all systems connected to it will be affected. This can lead to the loss of essential control functions, such as coolant flow control, safety system activation. To mitigate the risk of common cause failures in instrumentation and controls, NFCFs implement redundancy and diversity in their systems which includes having back up power supplies, redundant control channels and independent safety circuits. Additionally regular maintenance, testing and periodic verification of instrumentation and control systems are conducted to identify and address potential issues before they lead to failures.

3.5 PRACTICAL EXAMPLES OF BEST PRACTICES OF AGEING MANAGEMENT OF SYSTEMS, STRUCTURES AND COMPONENTS

This section describes the best practices on evaluation of SSCs in the framework of ageing management in different categories. These practices are in use in NFCFs to improve the overall ageing management programme. There are few examples of ageing management practices given in annex I and additional number of case studies can be referred in [28].

The practical examples of various activities performed on SSCs in the specific NFCFs are given in following paragraphs.

3.5.1. Civil structures

During the operation of fuel cycle plants, the civil structures will be exposed to harmful chemical fumes, in addition to deterioration and decay due to environment and ageing. The structure so exposed will have tendency for corrosion and affecting serviceability of the structure. The net effect of corrosion is development of faults in structures such as crack, crevice, spalling, de-lamination, cavity, and porosity etc.

In view of the above, it is necessary to inspect the civil structure periodically to assess the acceptability for continued safe operation of the plant or any remedial measures that are necessary.

Following types of the inspections of structures are being carried:

— Visual inspection;
— Non-destructive evaluation (NDE) of structure;
— Evaluation through embedded corrosion sensors.

3.5.1.1. Visual inspection

The visual inspection programme requires to include all structures and its elements. For this, proper approach/access needs to be available which can be part of initial design. Where access is not available, use of powerful binoculars, high resolution cameras, man-lifters, suitable scaffold/staging can be considered, as appropriate to the site condition.

Criteria for visual inspection:

- The visual inspection is required to be carried out as far as practicable for all elements of the building;
- Cracks in reinforced concrete cement (RCC) elements, if any, need to be brought out with type of cracks and possible cause of the crack. The structural and non-structural cracks need to be identified and reported;
- The location and possible reason for discolouring of RCC elements, if any, needs to be brought out;
- The visual inspection requires to bring out, the notable modifications carried out to the structure after the structure is built without proper analysis and approval, which may interfere with safety of the structure;
- The visual inspection needs to bring out any material deterioration which has taken place in structure;
- The visual inspection requires to bring out clearly any structural distress and deterioration;
- The visual inspection of structure to identify any deviation from intended use including misuse and abuse which can result in overloading;
- The visual inspection requires to note any leakage of effluent /acids etc., which are in direct contact with structure;
- The visual inspection can note the damages caused to the protective painting coats at various elements and structures.

The typical schedule of visual inspection of various buildings and structures in a fuel fabrication plant in a country-A are given in Table 1.

TABLE 1 TYPICAL SCHEDULE OF VISUAL INSPECTION

Sl. No.	Description of structures	Typical frequency of visual inspection
1	Building and structures exposed to chemical fumes and acid handling environment (severe and very severe environmental conditions as per National Standard for Chemical Buildings	2 years
2	Building and structures where mechanical engineering activity takes place: Mechanical buildings	5 years
3	Office buildings	8 years

Based on the severity of defects / distress observed, it is desirable to have thorough inspection along with non-destructive testing by expert agencies (see Fig. 2):

FIG. 2. Inspection of civil structures (courtesy of NFC, India)

3.5.1.2. Non-destructive evaluation

Under the non-destructive test, the following tests are carried out in addition to the visual inspection of the structure.

— Rebound hammer test (Fig. 3);
— Ultrasonic pulse velocity test (Fig. 4);
— Core sampling and analysis;
— Half-cell potential measurements (Fig. 5);
— Carbonation depth;
— pH value of powder samples;
— Chloride content.

Core sampling is carried out on members such that the stability of the structure is not hampered. For new buildings, the initial readings of NDT taken after completion of construction are the baseline data. The location of subsequent NDT points will be same as that of baseline data location. The periodicity of NDE tests to be carried out, is generally as follows in Table 2;

TABLE 2 TYPICAL PERIODICITY OF NDE TESTS

Sl. No.	Description of Tests	Description of Buildings	Typical Period
1	All the NDE tests as above	All Buildings	Recommendations
2	– do –	All chemical plants as defined in Table 1 under sl. no. 1	Once in 4 years
3	– do –	All the Plant buildings (other than plants covered under sl. no.2 above) of age exceeding 30 years	Once in 5 years
4	– do –	All the non–Plant buildings of age exceeding 40 years	Once in 8 years

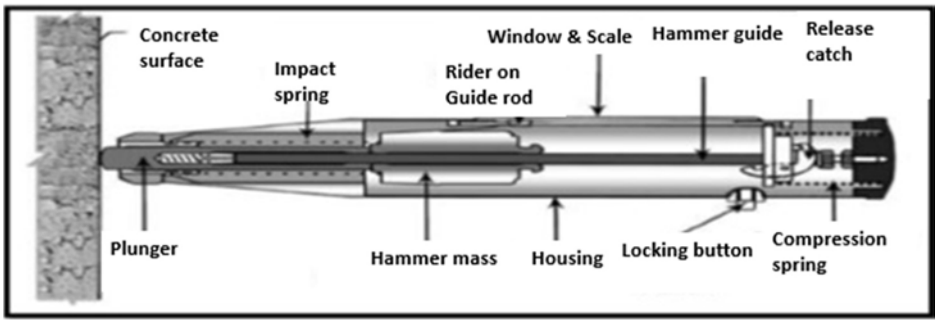

FIG. 3. Components of rebound hammer test (courtesy of NFC, India)

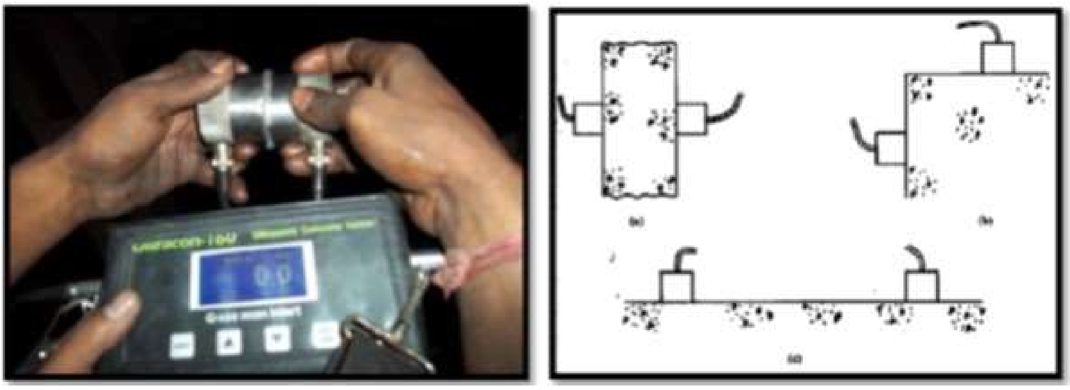

FIG. 4. Ultrasonic pulse velocity Instrument and transducer arrangement in ultrasonic pulse velocity test (courtesy of NFC, India)

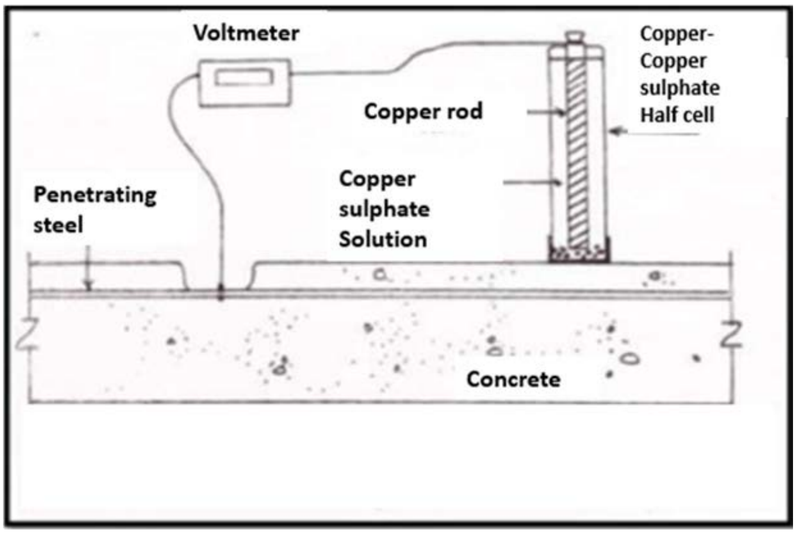

FIG. 5. Copper Sulphate Half-Cell (courtesy of NFC, India)

3.5.1.3. Embedded corrosion sensors

Buildings were embedded with corrosion monitoring sensors. Re-bar potential, corrosion rate and the resistivity of concrete are measured through the embedded sensors. The data analysis of the sensors needs to be done periodically.

In a dry spent fuel storage facility in Lima, Buenos Aires, Argentina, corrosion sensors were installed during the construction of the facility as an ageing management strategy for monitoring and trending the ageing of the reinforcement in the civil structures, which has been planned during the design stage of the dry spent fuel storage facility (see Fig. 6).

The probes for corrosion monitoring were developed by the Corrosion Department of the Argentinian National Atomic Energy Commission. The properties measured by the installed probes are corrosion potential, corrosion current density, oxygen transport, electrical resistivity, chloride concentration, and temperature.

FIG. 6. Installation of probes for corrosion monitoring on steel reinforcement before concrete placement in the Dry Spent Fuel Storage Facility (courtesy of CNEA, Argentina)

3.5.1.4. Evaluation of inspection results

All the test results are evaluated to determine compliance with the acceptance standards. Any inspection findings giving indications of distress / deterioration exceeding the acceptance criteria are to be supplemented by other inspection methods and techniques. Relevant codes and standards are to be referred for the acceptance criteria of visual inspection and NDT methods.

3.5.1.5. Repairs and replacement

The repairs are undertaken to restore the structure to their desired strength, durability and serviceability. The guidelines furnished by national standards authority, if any and by the regulatory authority are to be taken into consideration during repair.

During the construction stage, the type, composition, grade and properties of structural concrete are known and documented. However, for older installations, this information may not be available in some cases. In such cases it can be possible to determine these properties by taking core samples (such as core drilling) and performing measurements in laboratories. Ref. [29] provides more information on concrete ageing. General degradation mechanisms applicable to concrete structures mainly include weathering, loss of moisture content, carbonation, dis-bonding, corrosion of reinforcement bars, etc.

Visual inspection is very commonly performed to make preliminary assessment of the health of the concrete structure. This can be done by a specialist in a methodical and established manner. Special attention requires to be given to the presence of cracks, spalling, mould, fungus, foreign matter, etc.

In case cracks are detected, they are to be evaluated by a qualified expert to determine whether the crack is superficial or deep enough to pose a threat to stability of the structure and whether the crack is stable or growing with time. A periodical check of the crack's length, depth, width, linear or nonlinear etc. is to be made. In case of a crack that is a threat to the stability or that is found to be growing, a repair strategy requires to be formulated and implemented after a thorough review by experts. Beside cracks, attention needs to be paid to differential setting between buildings. It requires to be checked whether these are stable or not.

Another threat is the carbonation of the concrete. It is the reaction of the concrete with the carbon dioxide from the environment. Carbonation can be a serious threat to the reinforcement. The depth of the carbonation requires to be measured through a simple standard test.

In addition, several other inspections, and tests such as chloride and sulphate depths are also conducted to assess the condition of concrete. Ultrasonic pulse velocity (UPV) test, corrosion potential measurement and rebound hammer test to assess the homogeneity of surface concrete, and the integrity of cover concrete can be carried out.

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

Specialist qualified for assessing concrete structures will generally not be present in organizations that operate NFCFs. However, the inspections and follow up of concrete structures can easily be outsourced. Attention is also to be paid to steel structural components like liners or support structures. The condition of the painting to protect against corrosion need to be always checked.

A special case is the contact areas between concrete and other materials. Differential thermal expansion can cause cracks in concrete, while the concrete can be chemically aggressive to some materials such as aluminium.

Many of the civil structures in NFCFs are seismically qualified depending on the safety classification [30] which is again based on quantities and nature of radioactive material being handled and stored there. However, this qualification would have been done at the time of design and construction stage to meet the regulatory requirements prevailing at that time. An ageing management programme would include verification of seismic qualification of SSCs to the current seismicity of the location of the NFCF and to the current safety standards [31] and the structure may require retrofitting to meet the qualification.

An example of corrosion in concrete structure is given in annex II.

Spent fuel pool liners are of special interest to NFCFs. Generally, the liners are made of stainless steel. Many of pool liners have leak detection arrangements typically on weld joints.

However, many of the old pools do not have any liner leak detection arrangement. 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 or eddy current probes could be used to detect such corrosion depending on the design of the pool. Underwater radiation resistant cameras can be used to visually inspect the pool liners with special emphasis on weld joints. Remote ultrasonic testing can be another technique that can be employed. Submarine drones can be used for ultrasonic measurement in storage pools. Monitoring of unaccounted water loss from pool can also indicate the leakage. Leaks in pool liners affect the concrete structure particularly the reinforcement bars. These reinforcement bars, generally made of carbon steel, corrode in the presence of water and tend to swell causing either crack in the concrete or spalling. One of the measures adopted in the current practices is to use the coated reinforcement bars to minimize corrosion due to water leaks. There are several publications on this topic by IAEA including most recent final report of a coordinated research project [32].

3.5.2. Electrical components, Control & Instrumentation:

The life of electrical equipment is seen to be affected due to harmful effects of hostile environment and ageing. Hence, it is necessary to determine obvious damages, wear and tear and other conditions affecting the life and safe use of the equipment and to initiate remedial measures as required. The various inspection and testing techniques, their frequency and remedial actions are described below for electrical components.

Visual and physical inspection need to be carried out as follows:

- Inspection for obvious defects or damage in the accessories, connections, plugs, flexible cords or extension outlet sockets, terminals of battery, contacts of isolators, gaskets of equipment enclosures;
- Check for effective anchoring of flexible cords;
- Checking of operating controls for good working condition;
- Inspection of covers, guards, indicating lamps etc. are secured properly;
- Make sure that the ventilation inlets and outlets are unobstructed;
- Check for damage to painting of the body of the equipment;
- Check for cooling fans and back up battery for panels and PCs.

3.5.2.1. Testing of Earthing Continuity

Earthing protects the equipment, structures, etc due to overloading or short-circuit or from lighting protection as designed. Degradation of earthing can lead to damage of these systems. The earthing continuity needs to be tested for ensuring that the resistance of the protective conductor is sufficiently low for safe operation of the protective circuit.

For fixed and stationery equipment, the earth continuity needs to be checked for the protective conductor from the earth connection point to the earth pit or the earth grid as the case may be. For portable equipment, accessible earthed parts require to have continuity of the protective earthing conductor from the plug earth pin to the accessible earthed parts. For equipment without accessible earthed parts such as cord extension sets, outlet devices and portable residual current devices, need to have the protective earth conductor continuity from the earth pin of connector plug to the earth socket of the earth socket of the outlet.

3.5.2.2. Testing of Insulation Resistance

All equipment needs to be tested for insulation resistance in accordance with relevant standards.

3.5.2.3. Testing of Protective Devices & Circuits

Unusual occurrences in electrical system may lead to electric shock, arc flash and resultant fire. In order to avoid these effects, and to ensure proper functioning of the protection system, all the devices in the protective circuit are to be checked. Checking of protective circuits & devices including relays, HRC fuses, battery systems and control supply for the protective circuits to be carried out for their healthiness. In addition, proper co-ordination of the protective relays needs to be ensured.

3.5.2.4. Testing of Transformer oil

Complete diagnostic testing and dissolved gas analysis as per relevant standards of transformer oil of power and distribution transformers needs to be carried out.

Residual life of a transformer refers to the remaining useful life or remaining operational life span of the transformer. It indicates the period during which the transformer can continue to perform it's intended functions reliably and efficiently.

Determining the residual life of a transformer is a complex task that involves assessing various factors, including the transformer's age, design, maintenance history, operating conditions and environmental factors. It requires a comprehensive evaluation of the transformer's physical condition, insulation system, electrical performance and any signs of degradation or wear. For carrying of residual life assessment (RLA) studies, several techniques such as diagnostic testing, condition assessment, historical data analysis and age and design considerations, are used. At a particular fuel fabrication facility, some of the transformers with 40 years of life service, are still in operation without any problem due to regular inspections and periodic over-hauling of the transformers.

3.5.2.5. Frequency of inspection and testing

Every plant department requires preparing a list of equipment and services under their control for carrying out the in-service inspection. The list needs to contain names of the equipment, month and year of manufacture and commissioning, date and results/observations of last ISI carried out. The criteria for qualifying the inspection/testing also requires to be prepared based on the type of equipment and applicable standards and rules. A typical frequency of inspection and testing of electrical components is given in Table 3.

TABLE 3 TYPICAL FREQUENCY OF INSPECTIONS AND TESTING OF ELECTRICAL COMPONENETS

Sl. No.	Description of Inspection & Testing	Typical Frequency
1	Inspections	Once in 6 months
2	Tests for Earthing Continuity	Once in 12 months
3	Testing of Insulation Resistance	Once in 12 months
4	Checking of Protective Circuits & Devices	As per Preventive Maintenance schedule
5	Calibration Testing of Protective Relays	Once in 24 months
6	Testing of transformer oil	(i) Once in every year for Transformers of 5.0 MVA & above rating (ii) Once in every three years for All transformers of less than 5.0 MVA rating

3.5.2.6. Action based on inspection & testing

After completion of every inspection and testing, the equipment needs to be classified into two categories, viz., (i) non-compliant equipment and (ii) compliant equipment.

The non-compliant equipment/services can be labelled accordingly. Suitable remedial actions need to be taken to rectify the defects of such non-compliant equipment/services. If remedial action is not possible, the equipment requires to be withdrawn from service and disposed. The compliant equipment needs to be labelled accordingly giving details of inspection & testing carried out.

Some of the examples of common electrical items used in NFCFs and the associated maintenance, inspection or testing that are performed for ageing management of electrical items are described. These programmes are established based on applicable codes or manufacturer's recommendations and adjusted based on the operating experience. The list is by no means a comprehensive, and a similar programme need to be developed and implemented for all electrical items in the scope of an ageing management programme.

3.5.2.7. Battery banks

Batteries, used as backup power source in NFCFs, a safety related system, are sensitive to ageing. The facility needs to take care to keep them in good condition such that they can deliver the required power to equipment on demand. As per the plant surveillance procedures, standard battery bank capacity test or load testing (discharge test) is generally conducted annually and it is one of the effective methods to assess the battery bank condition. The regular preventive maintenance like rundown and equalize charging, checks on reference cell (voltage, electrolyte make up, temperature, etc.), terminal tightness and greasing, visual inspection, etc. help in minimizing and mitigating ageing effects. Thermography is an efficient method to detect faults such as bad contacts. Batteries have a limited life and need replacement. The replacement interval is normally specified as part of the maintenance programme. Results of battery bank capacity tests can be used to forecast if the battery's performance is degrading faster than expected. If so, then the replacement schedule needs to be adjusted to ensure that the battery is always capable of supplying the full demand from the postulated design basis accident.

3.5.2.8. Battery chargers, inverters and converters

Environmental conditions such as temperature and humidity are to be controlled as they accelerate ageing of battery chargers and converters. Preventive maintenance including cleaning and tightening of joints, thermography or visual checks for overheating and functional tests are helpful in assuring uninterrupted service. For inverters, vibration and noise of cooling fan, coolant condition, and visual inspection for overheating, and functional tests need to be conducted.

3.5.2.9. Equipment specific DC power supplies

Periodic replacement is advised to be performed due to limited lifespan of typical internal components. Typical frequency for replacement is 8–10 years.

3.5.2.10. Circuit breakers and switchgears

Periodical functional test and cleaning is essential for good functioning and thermography is a useful test to reveal the hot spots.

3.5.2.11. Relays

Periodical cleaning followed by a functional test needs to be conducted according to pre-defined periodicity and it is advised to replace relays important to safety according to a pre-defined periodicity (especially relays that are continuously energized or relays with a high frequency of switches).

3.5.2.12. Variable frequency drives

Replacement of film type capacitor after pre-defined period of use, cleaning of cabinet and fans annually and replacement of fans after pre-defined period of use are typical methods.

3.5.2.13. Electrical motors

Electrical motors drive mechanical equipment and are essential safety component in a facility and are susceptible to ageing during their lifetime. The most common methods of maintenance used are visual inspection, brush and commutator inspection to detect sparking or damaged surfaces, vibration and noise measurements can indicate any incipient failure, motor winding test at pre-determined frequency to determine any damage, thermography to detect excessive heating inside the motor, and current signature analysis.

3.5.2.14. Lightning protection

The lightening protection and earthing material are subjected to environmental ageing. The regular preventive maintenance including visual and resistance measurement and continuity checks for earthing or grounding strips to ensure the integrity of ground path is necessary.

3.5.2.15. Power Cables

Ageing of cables has been studied for all nuclear facilities by various organisations and there are several IAEA and other publications on this topic which can be referred [19,27,33]. Ageing of cables can take place either due to external environment like chemical / heat parameters or can be due to poor design particularly during routing with short radii at bends. Short radii can accelerate ageing of cables at these locations. Visual examination is a common method to detect any cracks in the insulation on the outside, continuity and insulation resistance measurements are used to check the cable integrity. The condition monitoring methods like laboratory and field tests to determine trending of ageing and degradation of insulation e.g elongation at break (EAB), irradiation tests etc are performed on cables from case-to-case basis [20,34].

3.5.3. Mechanical components

Some of the common mechanical items used in NFCFs and their associated maintenance, inspection or testing are given below which are useful for ageing management of mechanical items. In most cases, these programmes are established based on manufacturer's recommendations and adjusted based on the operating experience. The list is by no means a comprehensive, and a similar programme needs to be developed and implemented for all mechanical items in the scope of an ageing management programme [4].

The process equipment that has been under use in a NFCF being operated for more than 20 to 30 years or more are bound to undergo significant degradation and particularly so when they are being used in a chemically severe and harsh environment. Assessment of operating life of the process equipment by suitable means and implementation of necessary remedial measures in such a case not only increases the life of the process equipment, but also gives scope for replacement of components before reaching complete failure. Some of the case studies on ageing management of mechanical components are given in annex I.

To illustrate the advantages of timely assessment and action in extending the operating life of the components and/or of equipment leading to safe operation of plants, practical examples from the operational experience of a leading fuel fabrication facility in India are furnished in the following paragraphs.

The characteristics of a structure, system or component (SSC) gradually change with time or use and lead finally to the degradation of characteristics of materials subjected to normal operation and transient conditions under which the SSCs are required to operate. With the knowledge on the characteristics of materials and their life, it is always possible to extend the life of a particular process equipment by replacing the component with that which has more shelf life. For example, the tube of a heat exchanger used in an ammonia cracker gets deteriorated, due to the nitride scale formation, in the presence of ammonia gas at elevated temperatures. The nascent nitrogen produced during the dissociation of ammonia is very reactive and nitrides the metal as per the following chemical reaction (1).

$$M + n\,NH_3 \rightarrow MN_n + 1.5\,n\,H_2 \qquad (1)$$

Although the heat exchanger stainless steel tubes have a good resistance to nitriding with its consequent formation of cracks and scaling over period, the tube gives way for nitriding because of dissociation of NH_3 at the steel surface and diffusion of the atomic nitrogen into the steel surface at temperatures over say 300°C, resulting in a hard and brittle nitrided layer.

In such cases, the knowledge about the tendency towards nitriding is relatively low for nickel in comparison with other alloying elements such as Al, Ti, Cr and V and accordingly replacing of low Ni alloy (SS 310) tube with high Ni alloy (Inconel 600) tube enhances the life of the heat exchanger tube significantly. Figure 7 shows the nitride scale formation on the outer surface of the tube in contact with ammonia.

FIG. 7. Nitride scale formation on the outer surface of tube in contact with ammonia (courtesy of NFC, India)

During the production of UO_2, green pellets are placed in molybdenum (Mo) boats (Fig. 8a) and sintered in a cracked ammonia atmosphere at elevated temperatures. These pure Mo boats develop cracks and deformation with repeated use over a period from thermal cycles. Change of material of construction to oxide dispersion strengthened (ODS) Mo alloy enhanced the life of the boats significantly (Fig. 8b).

FIG. 8. (a)Pure Mo charge carrier boat (b) ODS Mo charge carrier boat (after 200 thermal cycles) (courtesy of NFC, India)

High efficiency particulate air (HEPA) filters are used for achieving the required levels of ambient air quality in powder material handling areas and other areas. Vibration induced cracks were observed on the wall of the HEPA filter bank room and HEPA filter efficiency testing could not be done. This could be overcome by coating polyurea on concrete surfaces to plug the crack (see Fig. 9 (a) and 9(b)).


FIG. 9. (a)Crack in the concrete (b) Plugged crack (courtesy of NFC, India)

Because of differential pressure across the HEPA filter and flow induced vibration, the filter media bulged out and developed gap between wall and filter frame which was made of polyurethane (PU). As a result of this, the efficiency of HEPA filter dropped down significantly. This problem was circumvented by changing the design of frame of HEPA filter with aluminium mesh above filter media and aluminium frame for sustaining higher differential pressures and protection of filter media (see Fig. 10(a) and 10(b)).


FIG. 10. (a)Old HEPA filter having PU frame (b) New HEPA filter frame having Al mesh and Al frame (courtesy of NFC, India)

In the production of uranium dioxide fuel through ammonium di-uranate (ADU) route, to meet the sintered density and other characteristics of UO_2 pellet, it becomes essential to carry out pre-compaction, granulation and final compaction of the ADU precursor generated UO_2 powder. Prior to final compaction the UO_2 powder need to be admixed with a lubricant. With this lubricant, during sintering of the green UO_2 pellets so generated, over a period of operation formation of a solid layer was observed on the refractory bricks and interior walls of the sintering furnace was forming and hindering the smooth movement of the charge carrier boat. The jamming of UO_2 carrier boats could be avoided by replacing with a new lubricant.

Similarly, during sintering process, the volatile impurities present in UO_2 green pellet emanate at elevated temperatures and form as a layer in the internal surface of the sintering furnace including the surface of alumina bricks which gets thickened and over a period of operation. This led to the degradation of insulation of alumina bricks which in turn led to deformation and/or melting of alumina bricks. This problem could be overcome by suitably changing the dew point of the sintering atmosphere, namely the cracked ammonia gas.

Cracked ammonia gas is used as an atmosphere during industrial sintering process as well as during reduction of ADU and/or U_3O_8 to UO_2. Cracked ammonia is produced from ammonia cracker which is operated at elevated temperature. Refractory bricks of ammonia cracker are supported using mild steel rod which is welded with internal wall of ammonia cracker. Upon ageing, the rod got deformed due to operation at elevated temperature in cracked ammonia atmosphere and the cracker could not be operated. The deformed mild steel tie rod has been replaced with suitable grade stainless steel tie rod and cracker could be put into operation with a prolonged operational life. The heating element wire used in sintering furnace under cracked ammonia atmosphere is of Molybdenum and is constantly subjected to corrosive atmosphere of cracked ammonia and very high temperatures. Under these harsh conditions over a period of operation, the heating element fails due to creep (see Fig. 11 and 12).

FIG.11. Failed pure Mo heating element (courtesy of NFC, India)

This could be circumvented by replacement of pure molybdenum heating element wire by lanthana doped molybdenum heating element, as mechanical properties like creep resistance and ambient ductility for Mo-La_2O_3 material are better than pure Mo material at elevated temperatures.

FIG.12. Amplified failure zone (courtesy of NFC, India)

3.5.3.1. Process equipment and tanks

The process equipment or tanks are generally made of carbon steel, stainless steel or Zircalloy and sometimes it is difficult to approach/replace/repair e.g., especially equipment inside hot cells in a reprocessing plant. Radiation induced damage in fuel cycle facilities is negligible as neutron flux is very low (in fuel fabrication, spent fuel storage and reprocessing) and mainly chemical induced corrosion or process induced corrosion usually determine the life of the equipment. It is easy to predict the effect of individual degradation mechanism, but the combined effect of two or more degradation mechanisms is difficult to assess/predict. It is a good practice to install sufficient number of corrosion coupons at strategic locations at commissioning stage, to get practical information on the degradation suffered with progressive service of the tank but may not be feasible for some of the equipment not approachable to remove or replace the coupons. The NDE techniques like visual inspection, ECT, UT, radiation mapping, etc; can also be deployed.

For tank type chemical equipment, inspection of the tank is an important part of the ageing management programme. The equipment designers need to include provisions for inspection equipment to access both the inside and outside wall of the equipment for critical equipment. Operating organizations may have to schedule special shutdowns including removal of radioactive material to facilitate inspections for ageing effects which could prevent the tank from meeting its design requirements. For the equipment processing nuclear materials, regular control of geometry of machines and tanks need to be performed (confirmation of annular gap, slot width etc). To expedite the checks and to reduce volume of radioactive waste, the sampling of solutions is performed and controlled with graduated sensors.

If the equipment is pressurized, a non-destructive inspection (ultrasonic, eddy current, visual) is required to be done on a regular periodicity (typical 10 year). The change of material properties due to neutron irradiation are to be considered. Pressurized equipment are also subjected to fatigue load. A stress analysis by FEM followed by experimental strain measurements is carried out to estimate the life of the equipment.

Process equipment often get deteriorated upon multiple usage and the extent of degradation can even become huge so much that further usage may be prohibitive keeping in view the safe operation of the process. Therefore, it is always essential to verify the health of the equipment and wherever possible suitable revamping is to be done to minimize the ageing effects.

3.5.3.2. Connections / penetrations

NFCFs like fuel reprocessing, waste processing facilities and spent fuel storage pools have pipe penetrations which are usually welded and due to residual stresses, they are more prone to accelerated corrosion. These penetrations can be inspected together with tank internals.

The replacement preferably be planned during long outage for refurbishment or upgradation. Pressure vessel like evaporators or heat exchanger expansion joints are parts that will need special care, as they are sensitive to thermal fatigue and can be difficult to inspect.

3.5.3.3. Support structures

Other support structures are usually made of carbon steel, SS cladded, aluminium or stainless steel. Regular visual inspection (use of underwater camera) requires to be done. Inspections can include checks for corrosion, deformation, cracks, foreign materials, loose parts, etc.

3.5.3.4. Heat exchangers

NDE (visual inspections, ultrasonic, ECT, radiography) on shells and tubes is based on service conditions. If possible, eddy current testing of tubes in large heat exchangers, cleaning (mechanical/chemical) of tubes/plates where feasible is done. Larger heat exchangers can be cleaned by sponge rubber balls. The condition of heat exchangers can be assessed by trending of maintenance, ISI, and performance evaluation (fouling factor) data. It can help in assessing the residual life. Wherever there is no approach to such equipment for cleaning and testing, e.g., in reprocessing hot cells, the indication of minor leaks from samples' analysis may lead to replacement of such equipment after following a systematic shutdown and decontamination procedure. Figure 13 (a) and (b) below show the corrosion in a heat exchanger.

FIG. 13. (a) Hole in the heat exchanger (b) Rust in the heat exchanger (courtesy of NFC, India)

3.5.3.5. Major pumps

Generally, pumps are easily replaceable except in case of large pumps in high radiation areas. The pumps need to be inspected according to manufacturer's recommendations or its construction/inspection code and based upon experience feedback. For pumps that have a condition-based maintenance, feedback from oil analysis, vibrations, bearing temperatures need to be collected. Trend analysis needs to be done on these data. Visual inspection to assess the condition of supports and foundation. Residual life assessment requires surveillance, performance and maintenance data and modelling. In a reprocessing plant, the process pumps are sometimes remotely maintained or replaced due to high radiation field around the pump.

3.5.3.6. Piping

Piping needs to be inspected according to its construction/inspection code. Visual inspection could reveal external corrosion. For internal corrosion, NDE such as ultrasonic thickness measurement are useful, reference points on the piping for such measurements are to be established including 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, etc. Weld joints need special attention and NDE methods such as liquid penetrant tests, ultrasonic flaw detections are useful.

Pipe supports need to be inspected for any deterioration, in particular where pipe material and support material are different. For painted pipes, a frequency for repainting need to be established. Corrosion is normally the degradation mechanism which governs service life. Modelling of corrosion behaviour is a better technique as compared to linear extrapolation.

Generally, in a reprocessing plant, solution transfer from one equipment to another is through large network of stainless-steel piping using vacuum transfer or pressure transfer method. All active components like pumps etc are located outside the hot cell for maintenance. The failure of any transfer line may be due to chocking of ejectors, failure of pipes or inadvertent operational conditions. Periodic inspections of pipeline network, pneumatic or hydraulic pressure test is advised where the pipe failure is due to corrosion of weld joints or stress corrosion cracking due to aggressive chemicals used in transfer.

Ageing management of deleterious materials such as chlorine transfer piping needs to be inspected periodically for any deterioration. Normally, In Service Inspection (ISI) of the chlorine transfer lines is done periodically (once in two years) by pneumatic testing to verify and ensure the mechanical integrity.

3.5.3.7. Valves

Potential ageing effects as consequence of temperature, corrosion, radiation, cycling (fatigue) and water hammering can become a life limiting factor. Major valves need to be inspected according to its construction/inspection code. In case the valve has an important isolation function, a leak test is required to be done. Non return valves need to undergo regular functional testing. NDE techniques like radiography and acoustic emission help in discovering incipient defects like hinge pin wear.

3.5.4. Instrumentation and control systems (I&C)

In general, I&C systems undergo modernization sometime in the life of the NFCF either due to obsolescence or unavailability of spares or physical ageing. Especially the electronics and software systems are modernized due to obsolescence. In a case study of AREVA NC (now ORANO) reprocessing plant, I&C ageing management involves the main issue of the obsolescence of both hardware and software. Due to the ever developing technology of electronic components, the long term availability (more than 10 years) of these components is a challenging issue. With the support of other major industry, they developed a common platform for reverse engineering, re-fabrication of electronic components and their graft inside the initial and older technology environment [24].

A case study of obsolescence of instrumentation and control system at a fuel manufacturing facility in India provides a method of assessment of risk, impact analysis, mitigation & migration strategies (see annex I).

Given below are some of common examples of I&C items used in NFCFs and the associated maintenance, inspection or testing that is performed and which is useful for ageing management of I&C items. In most cases, these programmes are established based on manufacturer's recommendations and adjusted based on the operating experience. The list is by no means comprehensive, and a similar programme need to be developed and implemented for all I&C items in the scope of an ageing management programme. Ref. [35] provides more information on ageing management of I&C systems.

3.5.4.1. 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. saturation characteristics. Latest computer-based digital systems have self-diagnostic and calibration features. Many NFCFs still have old analogue systems and intend to replace them with computer based digital systems. Ref. [35,36,37] provide necessary guidance for nuclear power plants most of which are also applicable to NFCFs.

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

3.5.4.2. Process instrumentation (temperature, pressure, flow)

The process instruments are to be calibrated periodically including set point check. Typical periodicity is one year. Data are to be recorded, and trend analysis can be performed. This may give sufficient information to detect potential degradation. Noise analysis is another technique used for diagnosis of transmitters. Impulse lines may get blocked due to deposition of corrosion products or may suffer loss in thickness due to corrosion. Replacement during a long outage is a good option.

3.5.4.3. Relays

Life of relays depends on its service conditions such as if it is continuously energised and number of times it is actuated. Although tests such as contact resistance measurement and current signature analysis could reveal deterioration, in most cases, replacement based on its expected life is a better solution.

3.5.4.4. Computer based systems

Use of computer-based systems are now increasing in protection, regulation, and operator information systems such as data acquisition system. The modular concept and software with diagnostic features make surveillance more user friendly. On-line monitoring (OLM), reduction in maintenance effort and ease of maintenance are added advantages. Generally, these systems have built-in programmes to detect malfunctions and the designers/suppliers provide the frequency at which these programmes would be run. In many cases, however, they run automatically at the given frequency and generate a report. Important aspect in such systems is to ensure that latest compatible versions of software are used, and hardware are replaced at periodic intervals. Care needs to be taken to avoid any malwares that can jeopardize the software. Technological advancements make such system more amenable to periodic replacement rather than measures for mitigation of ageing related issues.

3.5.4.5. Radiation monitoring

Radiation monitoring instrumentation requires to be calibrated and set points checked periodically. The frequency for testing will vary according to the manufacturer's recommendation and the importance to safety of the instrumentation. A functional test with a radioactive source provides a good test that can be performed frequently. Data is to be preserved and trend analysis needs to be made to provide sufficient information to detect any potential degradation.

3.5.4.6. Signal Cables

Trending of continuity checks, conductor impedance, the insulation resistance measurement and visual checks provide a good input for the assessment of health of the signal cables. Specific checks like tensile properties, hardness and polymer dis-bonding could be employed to detect deterioration.

3.5.5. Auxiliary systems

3.5.5.1. Ventilation system (containment/confinement functions)

The effectiveness of the ventilation system is to be ascertained and is carried out by periodic performance tests such as air flow measurement and measurement of pressure drop across filter banks. Trend analysis across the long period would indicate signs of degradation. Components for confinement or containment function are required to be tested according to a pre-defined test plan. HEPA and Charcoal filters efficiency are tested on a regular basis to ensure that particles and contaminants are properly removed, and that filter housing integrity is maintained. Vibration and noise testing are useful in detecting the ageing effects on rotating equipment such as fans and blowers.

Acoustic emission tests can detect the leaks from ventilation ducts very effectively, alternately walk downs along the ducts are also useful in detecting corrosion or deposition of dust inside inlet / outlet plenums and ducts; and stacks or chimneys requires to be inspected periodically to detect any degradation.

3.5.5.2. Diesel generators (emergency power)

Most of the plant conditions of operation require periodic testing of emergency power system i.e., diesel generators for ensuring its response on demand. Usually, no-load tests are performed once a week to test the response and load tests are performed once a month to check the full functionality. During this test several important parameters are to be monitored (response time, delivered current, delivered power, frequency). The trend analysis will indicate signs of degradation. Generally, the inspection/maintenance scheme will be defined by the original equipment manufacturer and adjusted based on the experience. Inspection/maintenance of the electrical generators for any ageing effects has to be done periodically and assessment of condition of fuel storage and supply for the engines need to be done periodically. For NFCFs where the emergency diesel generators are operated infrequently, or tested for short periods, ensuring the integrity of the fuel supply is important. Periodic draining, cleaning, inspection and refilling of the fuel tanks could be necessary.

3.5.5.3. Compressors (including air drums/receivers)

The performance of compressors needs to be monitored by several tests. Main compressors are required to be inspected according to its construction/inspection schedule. Testing is advised to verify that air is dry and free from contaminants. When moisture causes corrosion inside compressed air systems, the ageing management programme could lead to replacement of large sections of piping well in time. For compressors that have a condition-based maintenance, feedback from oil analysis, vibrations, bearing temperatures needs to be collected. Trend analysis could reveal any ageing effects. Visual inspection to assess the condition of supports and foundation need to be done and air drums be checked periodically. Pressure relief valves need to be tested according to a pre-defined periodicity. In many cases this periodicity is a legal requirement.

3.5.5.4. Waste handling (liquid, gas, solid)

Radioactive liquid wastes are generally generated during the operation and maintenance of the NFCFs and mostly collected in drain tanks and sumps, even underground, which are susceptible to build up of sediments over time. The design of such components requires to include provision for periodic cleaning, provision for flushing or for redundant sumps to facilitate replacement. Sumps that receive chemical waste need to be monitored more frequently. Visual inspections and pressure hold tests that include leak measurement from the tanks are helpful in detecting the degradation of the tank integrity and containers that store solid waste on-site need to be monitored for corrosion from weathering conditions.

Inspection of storage racks by visual examination are required to be done. Leaks from the pools can be detected by performing hold tests that takes into account loss of water by evaporation. Usually, the trend of make-up rates for pools could reveal any degradation of the integrity of the pools. Water chemistry of storage pool need to be controlled in order to avoid corrosion of spent fuel clad. Inspection of pool liner by visual examination needs to be done to detect corrosion signs; and inspection of stored fuel elements and other assemblies by visual examination with underwater radiation resistant cameras will help determine their status.

3.5.5.5. Water purification

The efficiency of the water purification systems can be followed up by measurement of the pressure drop across the resin beds, service period and by checking the quality of the product water delivered by the system (measurement of pH and conductivity). NDE inspection of tanks can be done, in case these tanks are empty, for any ageing effects. Monitoring of differential pressure across filters and their periodic replacement are to be included in the surveillance and maintenance programme and periodic cleaning of mechanical strainers needs be included in the maintenance programme. Periodic surveillance and calibration of all instruments has to be carried out to observe trend for maintenance or replacement.

3.5.5.6. Cranes and material handling devices

Cranes and other material handling devices for transfer and handling of loads are important equipment for NFCFs and need constant and careful regular maintenance and testing programme. A set of pre-handling checks are required to be available before taking up the loads. Due to faster wear and tear of mechanical or electrical components, a rigorous maintenance programme is established as per manufacturer’s instructions or as a part of plant procedures specially for cranes handling critical loads like shipping casks for spent fuel. On regular basis data records have to be kept, as they can reveal ageing issue (same faults are found during several inspections) and in most countries, load handling devices need to be tested periodically (typically annual) by an accredited agency. Such tests include thorough inspection of components, brake testing, current measurements on test load, and deflection measurements on test load. These tests can reveal any ageing effects on the component and structure of the crane.

3.5.5.7. 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 done by the supplier or a specialized agency. Fire water feed can be tested by the fire department responsible for the site (internal or external) to meet safety code requirement. In this way, the tests are part of their exercises. Fire water pipes usually have stagnant water and hence are more prone to corrosion. The piping needs to be inspected periodically including non-destructive examination. Flushing of fire systems demonstrates adequate flow, unobstructed flow paths, and assists in removing debris from the system. Fire detectors, and alarm systems are to be tested at regular intervals to reveal any ageing issues. A practical example of ageing related degradation of fire water system from a fuel manufacturing plant in Brazil is given in annex I.

3.5.5.8. Tanks and vessels

Visual inspection from inside and outside (if accessible) to check for any corrosion or damage or leak requires to be done. Integrity checks (hydro-test or air-hold test) needs to be done on tanks with special emphasis on leaks from weld joints. Supports and foundations are to be inspected for any deterioration and NDE techniques such as ultrasonic thickness measurement or flaw detection are very useful for tanks and vessel inspections.

3.5.5.9. Cooling towers

Periodical cleaning of cooling tower basins is advised. Visual examination of its components for corrosion, deposition and algae growth are to be done. Chemistry control to minimize corrosion including addition of algaecides help to extend cooling tower's life and performance checks of cooling tower reveals any sign of degradation.

3.5.5.10. Hot cells equipment

Hot cell windows require follow up as they degrade due to irradiation. In order to limit this damage, high active sources require 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 advised. Light efficiency test with a monochromatic source is an effective way to monitor the deterioration in the glass. The manipulators used for remote handling objects inside the hot cell are also subjected to degradation due to dust accumulation, radiation damage to its gaskets and seals or electrical switches. These are periodically maintained by bringing out the equipment in a dedicated maintenance area. The ventilation, air cleaning by filters (HEPA, active carbon), is to be monitored frequently. Measurements (purge flow) are to be taken, and trend analysis done in order to detect degradation well in time.

3.5.5.11. Fuel handling equipment, transport system for SF and other radioactive material

Spent fuel storage facility fuel handling equipment consists of spent fuel handling at the fuel storage areas. The fuel handling can be manual or automated. Maintenance and inspection of fuel handling and fuel transfer equipment need to be periodically done to detect any signs of ageing and most of the NFCFs qualify the equipment before use through dummy runs. A practical approach to ageing management of a dry spent fuel storage facility in Czech Republic is given in annex II.

3.6 NON-TECHNOLOGICAL ISSUES

Non-technical issues include knowledge management which is dependent on documentation, replacement and training and leadership and organisation. The issues are mainly related to socio-political reasons for stakeholder engagement and public perception, economical reasons for resource allocation, organisational culture and knowledge management, training and qualification of operating staff and overall management for long term planning and decision making. These issues can impact the overall safety, regulatory compliance, and long term sustainability of the facility. Addressing these issues requires a multi-disciplinary approach involving collaboration among various stakeholders, including facility operators, regulatory bodies, experts, and the public.

3.6.1. Socio -political issues

In some countries, socio-political issues take a lead over putting up a new industry, particularly for nuclear facility. NFCF having a potential risk of both radiological and chemical hazards poses additional risk of more land acquisition, disturbing population etc. In such cases, instead of shutting down an existing facility, life extension or long term operation with additional safety measures and scrutiny of records of ageing management would be preferred.

On the other hand, continuation of an existing facility beyond its design life may attract an objection from nearby population questioning the safety of them. These concerns can be partially addressed technically with proper risk assessment and management that the LTO consideration is based on technical review and extension of life up to a certain period will not pose any additional risk to the society.

3.6.2. Economic issues (new vs. refurbishing)

Economic issues play a crucial role in the decision-making process for ageing management of a nuclear fuel cycle facility. One key economic issue is determining whether it is more cost effective to build a new facility/system or to refurbish and extend the life of an existing one. The some of the economic considerations for this decision making are capital costs, operating costs, licensing and regulatory requirements, construction time and schedule, project risks and long term economic viability of new build.

The economic evaluation of capital costs, operation costs and other factors are important to take decision on new build or refurbishing. Factors such as the condition of existing infrastructure, availability of skilled labour, supply chain considerations and potential cost overruns need to be considered during the analysis.

3.6.3. Organisation and management

Project management planning, budgeting, scheduling, implementing, and review are important management aspect for an effective ageing management programme. More details are described in section 4.

3.6.4. Knowledge management

Preserving institutional knowledge and maintaining a strong safety culture are vital for an effective ageing management. It involves ensuring effective communication, training, and knowledge transfer between experienced personnel and new staff members. Fostering a culture that prioritizes safety, continuous learning, and open communication is crucial for addressing non-technological challenges.

The following are some of the approaches for knowledge sharing, organization can adopt within, or outside organisation based on their culture, resources and specific needs to foster a culture of continuous learning and knowledge exchange:

- The OEF programme providing information on operations and maintenance;
- External networking;

— Transfer of knowledge by regular team meetings, departmental meetings or cross functional discussions, documentation and knowledge repository;
— Training and workshops;
— Mentoring and shadowing.

IAEA's publications [1,2] on fuel incident notification and analysis system (FINAS) is one of such databases which shares information of incidents/accidents in fuel cycle facilities among the members of the database.

3.6.5. Training and qualification

Training and qualification of operating personnel are crucial for ageing management in a NFCF for reasons of safety in operation, maintenance and inspection, diagnostic and testing procedures, and regulatory compliance.

To ensure the training and qualification of operating staff for ageing management, several steps which can be taken are:

— Training needs assessment;
— Training programme development;
— Qualification and certification;
— Continuous training and professional development;
— Collaboration and knowledge sharing;
— Performance monitoring and feedback.

The training topics needs to concern particularly training of new operators or contractors involved in ageing management giving awareness on concepts of ageing management and for existing technologies used in NFCFs.

The experience in engineering staff training calls for tight cooperation between the NFC facilities and academia including the skills tools, extensive practical on-site training of elder students and consolidation of knowledge of elder students with the engineering staff by participation in R&D, engineering projects and case studies.

3.6.6. Management issues

In ageing management, there are several management related non- technological issues that need to be addressed to ensure effective management of ageing infrastructure and equipment in a NFCF. These issues involve organizational, strategic and regulatory aspects, such as following:

— Ageing management programme development;
— Risk informed decision making (risk vs cost analysis);
— Financial planning and budgeting;
— Regulatory compliance and licensing;
— Human resources and competence management;
— Change management and organizational culture;
— Stakeholder engagement and communication;
— Performance monitoring and continuous improvement.

Managers need to comprehend how the risk has changed from its initial state as a result of ageing and how it might evolve in the future. The risks that will escalate if they are not addressed by a certain period need to be identified and made obvious. It is necessary to periodically verify the responsibility holders' competence through high-calibre training and performance. For efficient ageing management, a programme for the competence development of suppliers and contractors for new designs and technology is required.

4. MODERNIZATION AND REFURBISHING

4.1 INTRODUCTION

All SSCs, including the I&C systems are subjected to ageing and obsolescence. Reasons for modernization are mainly due to end of their shelf life or deterioration in quality of their performance or use of outdated technology. During operation and maintenance, it is likely that the required components are no longer available either from original equipment manufacturer (OEM) or from other manufacturers for the components from market, or not able to fabricate inhouse, meeting the specifications. The systems will probably need to be modernised on multiple occasions during the course of the NFCF's life, even during extended operation.

IAEA NP–T–1.4 [35] states that: *"A long term modernization strategy should also be created, which takes into account the remaining life of the plant as well as any future upgrades."*

Since modernization or refurbishing involves a wholesale change of system, a well-planned long term strategy is needed to implement the modernization scheme based on technical basis of determination of end of life of SSCs. The strategies which may be considered during the modernization are given as below.

The project stage for designing a new NFCF is the most important time to plan for changes to SSCs caused by physical ageing or to lessen their effects. In any case, the defence-in-depth concept need to be strictly applied by taking these mechanisms into account when defining the safety barriers. The previous experience from construction and operation of similar facilities, or from available data of others will help in this regard.

All the issues require to be addressed in the preparation of a draft project report well in advance to enable obtaining the approvals from the regulator in a timely manner.

4.1.1. Automation in operations and management

NFCFs need to pay attention to use of automation to minimize human intervention for safe operation of plants. Operations with PLC and SCADA need to be ensured wherever possible. CCTVs are required to be placed at vantage points for critical operations to monitor the same for safety. Accessibility of these images to decision makers from their laptop/mobile phone and provision to see previous footage whenever required will help to review the decision-making process. Image capture and analysis tools have to be developed and used where required, particularly in areas like active material stores, chemical operations involving handling/generation of corrosive/toxic/flammables, less manned areas, etc. Where data acquisition is not possible, pre-decided manual data entry at local stations nearer to the machines will be helpful in data analysis compared to logbook entries. Digitization will also have the benefit of data storing and retrieval as and when required. Apart from the usage of digital technology in plant operations, it is also used for better management of the overall operations. While going for digitization, it is advisable to invest in data storage for sufficient duration e.g. 90 days or more before the data is overwritten. This will help in retrieval and analysing the data in case of need. Some of the systems suggested for automation / digitization are like, material management system, RFID based container movement within the stipulated boundaries, RFID based TLD tracking system in monitoring the exposure to the person, portal monitor with data acquisition for restricting the movement of persons with contamination and image capture, doorway monitors to control movement of active material outside the designated areas, etc. These modules help in uninterrupted plant operations with safety and security, easy retrieval of information, and effective inventory control. The e-office aims to support plant management in more effective and transparent manner. The advantages of having an electronic office include increased transparency, the ability to track files and have everyone aware of their status at all times, assurance of data security and integrity, promotion of innovation through the release of staff time and energy from ineffective processes, and greater workplace collaboration and efficient knowledge management.

The most common reason found in any accident investigation is that of inadequate training, coaching, behaviours etc. Generally, training programme requires assembly of identified personnel in the training division. This is found to have resistance from managers to release the persons from duty spots. To overcome this, digital screens / dash boards can be installed in various designated places in the plant areas to provide training preferably in local languages wherever applicable. Training video modules on various topics of relevance can be prepared and played in selected areas. On specified date and time, identified persons from the plant's job areas assemble in the area along with the faculty and the videos are played. Faculty will help in discussion / clarification among the audience to understand the topics and enhance their awareness. This will minimize the non-availability period of persons in the workplace.

4.2 STRATEGIES OR OPTIONS

The strategies or options for modernization would need through a decision-making process on choice of technology, interfacing issues, and replacement with similar equipment.

4.2.1. Decision making process

The decision to be made on modernization based on 'end of life' estimation may come from periodic safety reviews (PSR) or its equivalent, economic considerations or changes in technology as functional requirements. Generally, these decisions are taken after due review process is followed at plant level which includes competent personnel and all relevant stakeholders from operations, maintenance, engineering, finance and support contractors.

Finally, when considering modernization strategies, a holistic approach is to be adopted to consider the effect of modernization rather than a system in isolation over an extended period of time. Taking this approach will allow for optimization and harmonization of solutions over the longer period. However, it is important to mention here that any strategy finalized would remain valid for long term operation of the facility.

All system interfaces (internal and external) are required to be identified when choosing to employ a partial or full replacement modernization strategy including adding new functionality so that system performs as per the desired specifications.

Most of the time, interface changes are not needed when I&C equipment is updated by replacing electronic circuit board components, modules, racks, or chassis in a current I&C

system. But this is not likely to be the case when I&C equipment, sections, and cabinets are being replaced as part of modernization. An example is changing analogue equipment with digital equipment will require additional interfacing capabilities for exchange of data information.

It may also be necessary to carry out modernization of interface equipment in order to meet modern cybersecurity requirements. Guidance regarding this is provided in [38].

4.2.2. Solution Justification

Due to continuous technological advancement, most of the I&C systems would need to be re-modernized every 10 to 15 years including systems' in-built electronics with mechanical systems. It is therefore advisable that adequate planning is done for the deadlines of the implementation stages of the modernized system, retention of original functionality and/or extending functionality and the choice of modernization strategy to employ. It is essential to get critical components / spares from the supplier during installation stage itself for the design / expected life. A salvage approach for the redundant equipment that considers the risks and costs involved in physically removing the original equipment is also crucial. This plan ought to take into account if it is necessary to preserve the original equipment in order to sustain or extend the life of other systems.

4.3 CHOICE OF TECHNOLOGY

The choice of appropriate technology for modernization is influenced by number of factors which can vary depending on the specific objectives, constraints, and the requirements of the project. Following are the key factors that can influence the choice of technology for modernization or refurbishment:

- Operational efficiency to improve productivity, reduce downtime, optimise processes, and improve overall performance;
- Cost effectiveness in terms of initial investment, ongoing maintenance, operational expenses, and the long term return on investment (ROI);
- Compatibility and integration with existing systems;
- Scalability and flexibility of the technology to accommodate future growth, changing needs, and emerging requirements;
- Safety and regulatory compliance to meet stringent safety requirements and comply with relevant regulations and standards with enhanced safety features and improving overall safety performance;
- Technological advancements for innovation, enhanced automation, better data and analytical capabilities;
- Expertise and skill requirements for additional training and resource mobilisation;
- Stakeholder inputs from operating and maintenance personnel, engineers, and management for the decision making process.

4.3.1. Use of same technology

When creating the technical specification for a modernization programme that does not call for the addition of new functionality, NFCF operators need to consider the question that follows: 'Is it feasible to implement the required functions, with the required integrity, employing the same technology that is used in the existing system?' This may certainly be the best technological path to take if the answer to this question is yes and the technology would be easily available for the foreseeable future, especially if a 'replace with similar' modernization plan has been chosen. This is the most economically justifiable solution. This strategy may also consider that even if the basic process remains same, there could be improvements in process efficiency, ergonomics, safety, or other factors with the advent of newer technology. While going for modernization in highly radioactive areas like in reprocessing plants or waste immobilization facilities, economical factors of replacing the equipment need to be considered such as the cost of decontamination, radiation dose during work inside hot cells, loss of plant output during replacement, etc.

An example of evaporators replaced with improved materials in a fuel reprocessing plant in France is given in annex I.

4.3.2. Scale of modernization

The scale of modernization can depend on whether the outdated technology is still produced or accessible. In these situations, technology changes typically involve swapping out outdated process systems with more modern ones and integrating them with other plant systems. It may also involve a switch from analogue to digital technology or from one digital technology generation to another. The difficulty of updating obsolete digital I&C systems is one that many NFCFs are already dealing with.

Examples of modernization at a fuel manufacturing plant in India and Russian Federation is given in annex II.

4.3.3. Benefits of modernization

The benefits of modernization include increased safety, better productivity, improved quality and cost effectiveness. implementation of latest industrial practices. Other benefits are availability of spare parts and consumables, availability of engineering support from OEM (or their representatives) and knowledge management of the new technology.

Modernization may also be necessary in cases where national regulators demand that safety-related systems be implemented in different ways. For the cooling water system of a pool type spent fuel storage facility, for instance, two redundant pumps may need to be provided with two different power systems.

Implementation of providing a redundant control room to operate the major safety related systems in the event of an external event e.g., flood, earthquake and a secondary control room for NFCFs for crisis management in a recycling facility in France after a thorough stress tests review by regulatory body subsequent to Fukushima event is an appropriate example of improved safety as benefits of modernization.

4.3.4. Technology choices

Once a justifiable decision is taken on change of technology, the next important part of decision making is to decide on the technology. This will depend on factors like required technological benefits, economic and market driven decisions, patents and IPRs, and relationships (country to country and company to company). Sometimes, it is necessary to take consent from customers for choice/change of technology.

An example on choice of technology of I &C system is given below:

It needs to be decided whether to replace the field programable gate arrays (FPGA), which are now used by I&C systems in NFCFs in place of the programable logic controllers (PLCs), as the most prevalent type of freely programable devices, or to adopt wireless network technology. Low power consumption compared to a PLC with comparable performance, high speed, a large number of embedded input/output ports, no operating system (resistance to cyberthreats), high reliability, independence from external memory, and availability from several lead suppliers are some of the benefits associated with the use of FPGAs.

The use of wireless network technology in NFCFs is relatively limited as compared to other industry due to the stringent safety and security requirements associated with these facilities. The nuclear industry prioritizes robust and highly reliable communication systems to ensure safe operation and control of NFCFs. The wireless technology poses certain challenges and concerns in nuclear industry despite huge advantages it offers significant savings through reduced cable use and can be placed in locations where there is limited space for cables. The challenges include interference from other equipment, structures and components, cybersecurity risks, signal range and penetration through shielded thick walls and compatibility and regulatory compliance such as electromagnetic compatibility (EMC) and electromagnetic interference (EMI). However, it is worth noting that there are certain areas within a nuclear facility where wireless technology may find limited use, such as non-safety-related applications or for communication between personnel in non-hazardous areas.

4.4 INTERFACING ISSUES

The interfacing of new technology with existing plant's equipment including I & C i.e., the compatibility with the existing system is an important factor. A detailed analyses of both the systems is to be carried out before deciding on the replacement due to ageing for considerations of further safe operations.

It is advised that sufficient interfaces' issues with other plant systems/subsystems to be made during future modernization programmes. As an example, addition or replacement of a new equipment for a process, also needs integration with plant control and instrumentation system.

4.5 REPLACEMENT WITH SIMILAR EQUIPMENT

The replacement with similar equipment strategy for modernization projects involve upgrading or replacing existing equipment with newer version or models that provide enhanced capabilities, improved performance, or increased efficiency. This strategy focuses on maintaining continuity in operations while leveraging the benefits of updated technology. This strategy allows for a smooth transition from the aged equipment to updated versions while maintaining operational continuity. However, it is essential to carefully evaluate the cost effectiveness, compatibility, and the performance improvements offered by the replaced equipment to ensure the success of modernization project. The major factors to be considered for this strategy are:

- Assessment of existing equipment performance;
- Identification of upgrades and replacement;
- Compatibility and integration with existing infrastructure and systems;
- Improvements in performance and functionality;
- Safety and regulatory compliance;

— Training and familiarisation of operating personnel;
— Planning for implementation and testing to minimise downtime and disruptions to operations;
— Establishment of robust maintenance and support system;
— Monitoring of performance and evaluation on a continuous basis.

4.6 INTEGRATING ISSUES

4.6.1. Repair/Upgrade vs. Replacement

When deciding between repair/upgrade and replacement options for equipment, several integrating issues need to be considered. These issues involve evaluating various factors that involve overall feasibility, cost effectiveness, and impact of each option. Some of the integrating issues to be considered when making this decision are as follows:

— Equipment condition and age;
— Cost analysis of two options;
— Technological advancements and benefits;
— Compatibility and integration;
— Reliability and safety improvements;
— Downtime and operational disruption;
— Long term strategy and future needs;
— Considerations for environment including minimisation of radioactive waste generation.

Integrating these issues into the decision-making process will help evaluate the pros and cons of repair/upgrade versus replacement options more comprehensively. It allows for a well-informed decision based on the factors given above. The economic viability of replacement vs maintenance can be evaluated through this process to help in taking the management decision.

4.6.2. Other integrating issues

In addition to the integrating issues of repair or replacement, several other factors need to be also considered when undergoing modernization project. These additional integrating issues can help ensure the successful implementation of modernization initiatives and maximise their benefits. Some of the key integrating issues to consider are:

— Stakeholder engagement;
— Project management;
— Regulatory compliance;
— Data management and integration;
— Training and skill development;
— Change management;
— Performance monitoring and evaluation;
— Supplier and partner collaboration;
— Asset lifecycle management.

These are required for engaging relevant stakeholders throughout the modernization process which includes personnel from various departments such as operations, maintenance, engineering and management and solicit their inputs and feedback, to implement effective project management practices for smooth execution of the modernization project, to ensure that all modernization activities adhere to applicable regulatory requirements and standards; to evaluate how modernization will impact data management and integration within the facility, Identify the training and skill development needs for personnel involved in operation, maintenance and managing the modernised system or equipment; implement a robust change management process to facilitate the transition to modernized systems or equipment, Implement a robust change management process to facilitate the transition to modernized systems or equipment, to establish mechanisms for monitoring and evaluating the performance of the modernized systems or equipment, to collaborate closely with suppliers and partners involved in the modernization project, and to consider the impact of modernization project on the overall lifecycle management of assets within the facility, respectively.

4.6.3. Considerations in ageing equipment management

The current trend in NFCFs is a shift from time-based maintenance to condition-based maintenance. Utilising sensors and advanced data analysis, the aim is to precisely identify which equipment requires immediate maintenance, upgrades, or replacement. Instead of deciding to replace equipment every specified number of years, operators can examine results and more easily address deficiencies before the equipment fails.

Reverse engineering strategy is sometimes adopted when there is a difficulty in availability of replacement equipment, which requires having sufficient information about an item of equipment and may include examining the original equipment and reviewing associated design documentation. Reverse engineering is also done when the catalogues and drawings are lost, and the OEM is no longer in the market to support the customer. Reverse engineering techniques can be used to provide obsolescence solutions that are functionally equivalent to the original equipment in the absence of a complete set of original design drawings and manufacturing information.

Before implementing a reverse engineering solution, it is suggested to conduct a thorough risk and cost assessment considering critical design attributes, legal considerations related to IP controls, quality assurance requirements, procurement plan, availability of material, supply chain, inspection and testing requirement including prototype testing.

4.7 PARTIAL OR FULL REPLACEMENT STRATEGY

When choosing between a partial or full system replacement strategy, the following factors need to be taken into account:

- Whether a complete system replacement is required, or is a subsystem upgrade possible;
- Whether is it required that the new system or subsystem to be added, changed to provide the same functions as the existing system or subsystem;
- What interfaces is the current system/subsystem equipped with;
- How will the modernization be carried out (in stages or all at once).

It is suggested that a partial replacement modernization strategy be thought about when new functionality needs to be added, when performance changes are needed, when the physical condition of part of the system is deteriorating faster than desired, when certain subsystems can't add the new functionality that is needed, and when information is available about how the original equipment worked and how it was made.

Replacing the entire system seems to be the easiest modernization solution from a technical perspective. Such modernization aims at resolving all the problems associated with the existing deficits and realizes all the necessary new functions. In addition, modern equipment can reduce operating and maintenance costs significantly. The high cost of wholesome replacement may force the modernization strategy to be applied only in cases where no other strategies that were considered earlier can solve the problems that necessitate this modernization. Even if the operating organization has sufficient financial resources, this strategy is advised for use only in those cases where, in addition to compensating for existing deficits and introducing new functions, it is planned to extend the life of the NFCF by at least ten to fifteen years. Only under such condition, a complete replacement will be economically justified by increasing the overall operational reliability of the NFCF and reducing operating costs.

The important activities involved in partial or full replacement are given below.

4.7.1. Technical specification

A comprehensive technical specification is needed to be prepared to ensure that an appropriate technical solution for partial or full replacement modernization project is developed. The technical specification needs to cover detailed description of the functions and performance requirements, reliability and integrity requirements, operating life, power consumption, interfacing requirements with other plant systems, limitations on size, weight and operating environment, quality assurance requirements, installation and commissioning requirements, equipment support requirements, maintenance requirements, spares and consumable requirements, documentation and training requirements.

4.7.2. Manufacturer selection

The success of implementing a partial replacement modernization plan is improved by choosing the original OEM because it has sufficient design knowledge, including on compatibility with the system's other components. This tactic is also helpful when separate organisations support distinct system components, which could result in disagreements over interface responsibilities and liability.

Contracting the original OEM, however, would not be feasible or desirable from an economic point of view if they have already closed. In such cases, a new vendor development step will need to be taken.

4.7.3. Testing

Inspection and Testing need to be carried out according to a specially designed QA programme. It is either prepared by the NFCF operator or by the equipment manufacturer and approved by the NFCF operator. The testing programme involves testing of raw material quality, testing during various stages of manufacturing, functional testing at manufacturer’s shop and after installation at site for the functional and qualitative characteristics of the equipment including interlocks and controls. It is also beneficial for operating personnel to participate in the testing as this enables better familiarization of the new system.

At the same time, it is advised to organize a training programme for the O&M personnel either at manufacturer’s workshop or at NFCF site depending on the complexity of the system, cost and convenience for the operators.

It needs to be noted that sometimes it is possible to commission the old subsystem in the event of a complete failure of the new subsystem and thus dismantling of old system is postponed till successful completion of the trial operating phase of new system. Another benefit by having the old subsystem available is that it is often possible to run the two systems in parallel to assist in building confidence that the new system is functioning correctly.

4.8 RETROFITTING ISSUES

Retrofitting of a system in many instances may not match or function as intended leading to mismatching and various troubleshooting problems. A systematic and detailed analysis is to be carried out prior to selection of new equipment including I&C system that are to be installed for replacement or modernization of existing units as a part of ageing management or LTO programme.

4.9 PROJECT MANAGEMENT

The different aspects of a project management involve project delivery schedules, project scope definition, project delivery method (phased delivery or lump sum delivery), strategies for selection of vendors and contractors (single or multiple). These actions will depend on the scale of modernization and experts' availability within the organisation and economical aspects.

The execution of projects needs to take into account the necessity to implement temporary or bridge solutions to support final project delivery, which involves concurrent activity at various work fronts.

4.9.1. Pre-engineering phase

Given the complexity, novelty, and other risks involved, it is advised that pre-engineering work be done to assess project risks and uncertainties to make sure that all available solutions are properly explored before the main project delivery phase begins. Making such decisions while having little or no understanding about the consequences can result in the project falling short of its goals or requiring costly revisions later.

The final delivery contractor is involved in this stage. Design studies and bids from various suppliers, the prototyping of technologies and designs, the testing of methodologies and processes, restricted scope modernizations with post-implementation assessments, and the choice of various design solutions are a few examples of pre-engineering activities. It is also advised to involve customer or regulator early in the process if major changes are expected. As an example, the qualification process can cause unnecessary long lead time if identified late in the project.

Compilation of a comprehensive and clear technical specification is an essential pre–engineering activity which involves all relevant stakeholders and disciplines to collate, review and verify the specification. The clear-cut ownership/responsibility for production and production schedule for the documentation needs to be clearly identified between vendor and client organizations, including schedule for delivery and inter dependencies aligned with project milestones or phases.

4.9.2. Contract strategies

Since all modernization projects of any complexity will involve contract(s) with vendors, success or failure will be greatly influenced by the choice of an appropriate contractor and contracting strategy. Multiple contract strategies either singly or in combination, are possible and each have their own advantages or disadvantages. These are generally not discussed here as there is adequate guidance available in other documents. Nevertheless, establishing a close and ongoing working relationship with the contractor assists is one of the most important factors to consider. Overall efficiency and risk need to get divided between the contractor and the NFCF operator and payments term requires to be properly defined in advance to make sure that the delivery is fulfilled.

4.9.3. Life cycle synchronization and hold points

Within a modernization process there are many separate life cycles which are being followed which are often conflicting and at certain points interact either positively or negatively. Life cycles encompass various stages such as plant operational life cycle, contract life cycle (consisting of phases, payment milestones, and hold points), regulatory life cycles (involving safety case submissions, permissions, and regulatory hold points), project delivery life cycle (including conceptual design, detail design, implementation, installation, and closeout), security life cycle (comprising assessments and mitigations), and design life cycle (consisting of specification, design, implementation, test, and so on). It is necessary to define all life cycles at the beginning of a modernization project, and this requires a clear understanding of the ownership and purpose of each.

4.9.4. Change management and configuration management

Complex projects of modernization running over many years encounter unexpected changes for a variety of reasons. An effective management of change is essential for the success of the project. The original project specification would provide clear requirements to establish what have changed from the original intent. The impacts of change on safety, cost/delivery and function need to be clearly understood. The specifications are derived in such a way that the requirements are traceable. For example, a requirement can be traceable from a design drawing or a testing requirement. A clear mechanism needs to be established by the project implementing organisation to review these changes based on the requirements of the project and their impact on the project. An impact analysis, regression analysis and regression testing can be considered as part of change management when change is introduced to improve the quality of the modernization project.

4.9.5. Design and construction

Design completion is a very important step which is approved by the operating organisation either in a single step or in a phased manner depending on the complexity of the system. The construction can only be started after the step of design completion phase. Sometimes the vendor produces prototypes for demonstration of the designs or 3-D simulation techniques is used. To avoid delays between design and construction due to long delivery times, modernization projects need to give consideration to completion of high-level design work and detailed design as different phases. As an example, the general arrangement drawings are approved so that construction can start in parallel with detailed engineering. The replacement systems need to be designed in a way that facilitates inspection for ageing management as a means of avoiding future modernizations such as adequate illumination, accessibility, and the ability to see wires or circuit boards that are important for inspection. Modularization helps in easy movement of equipment without the need for breaking of building or structures inside. It is also advisable to use a modularisation approach where subsystem could be easily replaced or upgraded in the future to support long term operation. One key element is to have clear interfaces between subsystems. This strategy holds good both for mechanical and electrical equipment such as PLC's. It also advisable to make sure that there are some additional spaces available for future upgrades or upcoming need for additional equipment. As an example, there might be equipment and technology in the future that improves quality or productivity. Another example to consider is to avoid implementing to many applications in the same PC. There is a risk that applications or the PC needs updates at different times causing challenges to get all applications to work continuously.

4.9.6. Factory test and commissioning

For testing of equipment or a system, access to the plant may not be feasible as modernization projects are introduced into an operational plant, unless the plant is subjected to significant outage with nuclear safety considerations. The modernized system needs to be designed in such a way as to facilitate the testing outside the site to maximum extent. The use of mock ups and other test rigs may be helpful here.

A testing programme is required to be developed combinedly by both operating organisation and vendor at the stage next to design completion. This testing programme clearly defines the stages of test and demonstrate how testing will cover all the functionality/requirements of the modernized system. To eliminate gaps in testing, the strategy needs to explain how test steps overlap (e.g., unit test, subsystem integration test, installation test, commissioning).

The other important aspect on testing is about scope of testing, time or resource requirements, shortage of which may lead to incomplete task with risk of having defects remaining with the modernization project.

4.9.7. Installation

The installation of modernization projects need to be carefully well planned and executed. An installation procedure is required to be prepared by the vendor and approved by the NFCF organisation.

Other aspect to be considered is about movement of large/heavy equipment throughout the plant to their final locations which include load restrictions or access opening, complex piping etc. These are sometimes accomplished by way of walk downs or through use of a 3D modelling software.

4.9.8. Spares and long term support

Considerations for spares and long term service support are to be taken at the stage of finalisation of specifications or before finalisation of contract otherwise it becomes costlier affair at a later stage as negotiation at this stage are easier. Alternatively, a strategy may be adopted by the NFCF operator to take care of spares and maintenance in house based on the availability of spares and qualified manpower. Sometimes the contracts are in-built to provide for upgrades of the system on periodic basis which will avoid further modernization projects to be undertaken due to new technology. Sometimes the warrantee periods are extended to take the advantage of negotiation.

Prior to taking over the modernised system, it needs to have the necessary operating, maintenance, and training manuals in place for the NFCF operator to maintain, fault-find, and repair it. The required spare parts are also to be made available to the NFCF operators. It is important to think about spare parts in terms of commissioning spares (those needed to fix problems discovered during commissioning), operational spares (those needed during normal operation to repair the equipment), and lifetime spares (those needed or anticipated to be needed over the system's lifetime). A systematic review of spares required for each phase of the modernization project is required to minimise the cost and inventory of spares.

There are several strategies that can be evaluated for the purpose of managing the spares inventory of a modernised system over the long term. These are periodic provisioning at a planned frequency for low intensity of demand and long delivery items, provisioning at an emergency during breakdowns, and continuous provisioning for maintaining a minimum spares inventory level for repairable parts.

4.9.9. End stages, close out and hand-over

This sub section deals with the issues that need to be taken into account when project's actual works are done and the project is in the closing phase, A responsible person nominated by the end user organization who will take over the project product (system and documentation) will ensure that all planned work is done in all respect. A check list needs to be prepared by the NFCF organisation to check that all necessary training in the new system has been received and users are competent in its operation and maintenance, that all project specific special deliverables (e.g., specific training, special tools, etc.) are handed over and all necessary documents have been handed over.

4.10 MINIMISATION OF RADIO-ACTIVE WASTE GENERATION

No NFCF can avoid generation of radio-active waste in either liquid/ gaseous form or solid form or in combination during variety of processes involved and/or even wastes could be generated otherwise that constitute a non-process waste. For smooth functioning for long term, it becomes essential for the NFCF to look for suitable methodologies of handling the radioactive waste for disposing the process and/or non-process wastes meeting the statutory requirements in all respects as per guidelines of the respective regulator or other agencies. An example of good practices followed for minimization of radioactive generation is given in following paragraphs.

As a part of the management of wastes at fuel manufacturing facility in a Member State, a fully mechanized and automated ultrasonic decontamination facility (Fig. 14(a)) and active incineration facility (Fig. 14(b)) are to be set up for decontamination and incineration of non-process waste respectively. Similarly, volume reduction facilities for decontaminated non-combustible, compressible active wastes before final disposal in engineered trenches, hydraulic drum compaction unit (Fig. 15(a)), shredder (Fig. 15(b)) for cutting of used sheets, hand gloves, and polythene melt densification units (Fig. 15(c)) are also required to be set up.

FIG. 14. (a) Automated decontamination facility (b) Active Waste Incineration Facility (courtesy of NFC, India)

(a) Hydraulic Drum Compaction Unit *(b) Industrial Shredder* *(c) Polythene Melt Densification Unit*

FIG. 15. The systems of waste treatment at a nuclear fuel manufacturing facility (courtesy of NFC, India)

Another example of new processes being developed to minimise the radio-active waste generation in MOX fuel fabrication is highlighted here. A simplified pellet fabrication process has been developed in JAEA, Japan to reduce MOX fuel fabrication cost drastically. In this method, plutonium nitrate and uranyl nitrate are mixed to form a solution, which is then converted to MOX powder with adjusted plutonium content using the microwave direct de-nitration method. The flowable MOX powder is then directly pelletized without the addition of conventional flowable powder additives. By introducing this process, it is possible to eliminate the powder preparation steps such as ball-milling in the conventional process and thereby reducing generation of radio-active waste. Several developments have taken place at Sellafield’s, UK and JAEA, Japan, also for residue/scrap management of Pu powder in MOX fuel fabrication or from reject pellets, grind dust, residue from filters etc to minimise the radio-active waste.

5. LONG TERM OPERATION MANAGEMENT

Long term operation refers to use of a facility after its intended lifespan has passed. The procedure used to identify and regulate SSC’s degradation and failure from deterioration owing to the environment and/or the SSC's age for consideration of long–term operation is known as ageing management, as explained in Section 3. In order to make it simple to decide whether to operate the nuclear fuel cycle facility for the long term, all the ageing management actions need to be coordinated through an ageing management programme inside a total asset management plan.

5.1 CONCEPT OF LONG–TERM OPERATION MANAGEMENT

Following three top–level ageing and obsolescence management techniques, as shown in Fig. 16, can be used to extend the functioning lives of systems according to an extended classical bathtub curve.

— Retain and sustain equipment;
— Wholesale equipment replacement;
— A combination of the above as shown in the figure.

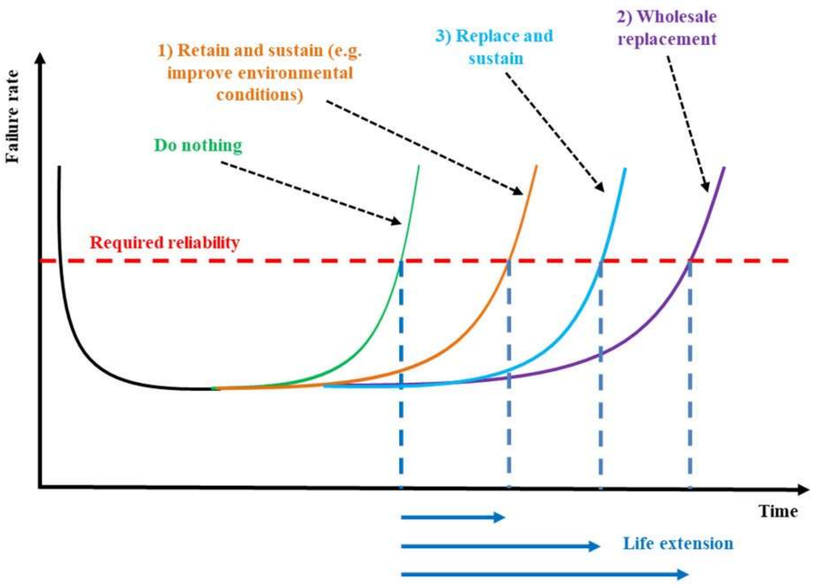

FIG. 16. Main top-level ageing and obsolescence management strategies reproduced from [39].

Strategies that involve the substitution of newer, more advanced technology (especially smart technology) for older, less effective technology can boost system performance. Enhancements like these can be seen in areas like efficiency, safety, reliability, and reduced O&M expenses. The following difficulties, however, are associated with the upgrading of systems and equipment:

— New degrading mechanisms and effects, understanding of new designs;
— Evolving methodologies for identification of ageing in complex technology-oriented systems;
— Identification of suitable equipment technology for replacement;
— Suitable methods to replace equipment while ensuring safety;
— Integration of new technology replaced systems with older systems;
— Training and qualification of operating/maintenance personnel for the replacement systems/equipment.

The lifetime of a nuclear fuel cycle facility, as stated earlier, is usually determined by the facility's continued usefulness and by its economic viability. The replaceability of equipment in the front-end NFCFs is generally greater in comparison to nuclear power plants and back-end facilities. It would be appropriate to set and justify their lifetime as defined by the design for facilities such as spent nuclear fuel storage facilities, reprocessing, hot cell facilities, radioactive waste storage and handling facilities. Generally, from experience, it is observed that 15–20 years is the useful operating life of equipment in the facilities handling corrosive chemicals (e.g., chemical operation equipment in a reprocessing plant).

The lifetime of new NFCFs (as required by national legislation) includes the consideration of the cumulative ageing effects, requirements for application of examination techniques for certain groups of equipment, and measures to be taken if a lack of ability for continued operation is identified. For the SSCs with low or no possibility of replacement, unless sizable modifications are carried out, e.g., building structures and tanks buried underground without any approach, specific consideration needs to be given to SSCs. The periodic safety review process or suitable safety analysis assesses the ability for life extension of operation of NFCFs.

The long term operation (LTO) decisions involve considerations of many factors. The ageing management throughout the life of Nuclear Fuel Cycle Facility (NFCF) is the most important factor to be considered for long term operation of a fuel cycle facility, which is very diverse in nature depending on the various processes involved at the front end and back end of the fuel cycle facility. The economic viability and plant safety are also major factors to be considered for taking decision for long term operation. The decision for LTO, an extension of the life of the facility for further operation safely, beyond its design life is taken based on the data from ageing management and other considerations.

With proper implementation of the ageing management programme as outlined in Section 3, and ageing analysis as outlined in section 5.4, the lifetime of a nuclear fuel cycle facility would get extended as a part of long term operation.

5.2 PROGRAMME FOR LONG TERM OPERATION

The broad programme for long term operation or life extension involves a combination of technical, regulatory, and economic initiatives aimed at ensuring the safe and efficient operation of NFCFs beyond their originally planned operational lifespan. Some of the key programmes commonly implemented are as follows:

Periodic safety review (PSRs) or an equivalent safety review process are comprehensive assessments conducted at regular intervals to evaluate the safety of nuclear facilities. These reviews involve assessing the plant’s systems, structures and components, considering updated safety standards, regulatory requirements and technological advancements.

Plant modernization and upgrades programme involves implementing technological advancements and upgrades to enhance safety, reliability, and efficiency. It may include replacing or refurbishing critical equipment, improving control systems, implementing digital instrumentation and control (I &C) systems, enhancing safety features, and incorporating new operational strategies and procedures.

Ageing management and maintenance programme focuses on understanding and mitigating effects of ageing on plant components and systems. It involves monitoring, inspecting, and assessing the condition of structures, equipment and materials, and implementing appropriate maintenance and repair strategies.

License renewal programmes involve obtaining regulatory approval to extend the operating license of a nuclear fuel cycle facility beyond it’s original expiry date. This typically requires a comprehensive assessment of plant’s safety, environmental impact, and operational performance including demonstration of the ability to manage the ageing related issues.

Safety culture and training programmes are vital for the long term operation of nuclear facilities. Safety culture initiatives promote a proactive approach to safety, effective communication and continuous improvement and training programmes ensure that personnel have the necessary skills, knowledge, and competence to operate and maintain the facility safely and efficiently.

Environmental and radioactive waste management programmes address the minimisation, safe handling, storage, and disposal of radioactive waste generated by the nuclear facility and compliance with environmental regulations.

Regulatory compliance and oversight programmes involve maintaining compliance with the evolving regulatory requirements and engaging in ongoing communication and collaboration with regulatory authorities.

Stakeholder engagement and public outreach programmes are crucial for maintaining public confidence and trust in the long term operation of nuclear facilities.

5.2.1. LTO programme implementation

The long term operation programme needs to be executed by the operating organisation in compliance with technical and licencing requirements set by the national regulatory body and other relevant national regulations. It is generally carried out in following broad steps:

- Periodical assessment of SSCs after longer periods and then after a duration of shorter period based on periodic safety review, or its equivalent (periodicity may vary from Member States (MSs) to MSs);
- Ageing management programmes development, implementation and review including addressing technological obsolescence;
- Evaluation of remaining life of reinforced cement concrete (RCC) structures, and underground system needs special emphasis;
- Performance evaluation of process systems, auxiliary system which are non-replaceable;
- Performance evaluation of replaceable systems and components.

The licencing basis currently in place may encompass the design basis information specific to the plant, as detailed in a safety analysis report. This report typically includes analyses of ageing that are time limiting. However, it is imperative to consider reports from periodic safety reviews or their equivalent, as well as other plant documents related to operations, when considering long term operation beyond the plant's original design life.

An example of best practices for management of long term operation of a dry type spent fuel storage facility in Czech Republic is given in annex II.

5.3 EVALUATION OF LONG TERM OPERATION (LTO) PROGRAMME

5.3.1. Evaluation of scope of modification, modernization and refurbishing

Periodic safety reviews or comparable analyses need to be conducted to examine the cumulative impact of ageing and obsolescence on the safe continuation of operation of a nuclear fuel cycle facility taking into account the scope of modification, modernization, and refurbishing project.

5.3.2. Ageing management review for long term operation

The changes in regulatory requirements, codes, and standards, evolving knowledge and operating experience feedback would have to be taken into account during the review for ageing management for long term operation for the intended period.

The following issues are to be considered during the ageing management review:

- Identification and comprehension of any new ageing impact or degradation process that may occur during the projected long term operation duration;
- To determine whether any major rates of deterioration or places that are vulnerable to these mechanisms are likely to alter during the anticipated long term operation period. Include operational experience and research findings that are pertinent;
- Create efficient ageing management programmes well in advance of the SSCs' loss of functionality in order to detect and reduce the effects of ageing that the ageing management review highlighted.

The ageing management review would clearly show that ageing impacts would be recognised and controlled for each structure or component included in the scope of long term operation for the anticipated length of time.

5.3.3. Equipment qualification

The equipment qualification is the important aspect for lifetime extension/long term operation of the facility in a risk informed manner. This needs to demonstrate that the equipment will be capable of performing its intended operation and safety functions, throughout its qualified extended life. The operating organization has to develop and maintain a programme for long term operation in consistence with the generic attributes of the ageing management programme, if any modifications are intended to enable or could have an impact on long term operation.

5.3.4. Plant programmes and ageing management programmes for long term operation

A comparison and review of the current plant programmes utilised for ageing management and existing ageing management programmes is necessary to confirm their continued effectiveness for the intended duration of long term operation. This evaluation will be based on the outcomes of the ageing management for long term operation. The purpose of this review is to assess the plant programme and determine any necessary modifications or new programmes are required so that the structures, systems, or components will perform their intended functions during the period of long term operation.

5.3.5. Documentation in support of long term operation

The findings of the ageing management review need to be properly documented in a report for long term functioning. The understanding of ageing, monitoring of ageing, and prevention and mitigation of ageing impacts need to be covered in the report. To apply the findings of the ageing management review to plant operation, maintenance, and design, recommendations need to be provided.

An updated version of the safety analysis report and other documents required by the licencing procedure that reflect the presumptions, actions, and outcomes of the plant programme for long term operation need to be included in the documentation. If relevant, documentation of the revalidation of the time-limited ageing assessments or the safety analysis for the duration of long term operation would also be included in the update to the safety analysis report.

To adequately manage ageing effects during long term operation, the documentation of the demonstration needs to contain the list of identified effects and mechanisms that need ageing management. Once identified, specific programmes or activities need to be developed for each structure, component, or commodity grouping. These programmes and activities need to be described in detail to ensure effective management of the ageing effects and degradation mechanisms.

5.3.6. Regulatory review and approval

The operating organisation has to demonstrate the regulatory body that the nuclear fuel cycle facility will be safe for long term operation in accordance with safety standards and national regulatory requirements.

The regulatory body needs to be demonstrated for verification of long term safety, including expected ageing effects based on past studies and plant modifications to improve safety when necessary. Items important to safety need to be in focus throughout the operational stage of the facility, and subject to safety assessment. Also, items other than items important to safety, which could impact the further operation of the facility such as those that are part of service systems (energy, gas, heat, water or other supplying systems), have to be considered. With proper implementation of the ageing management programme, the lifetime of a nuclear fuel cycle facility may be extended. Assessment of SSCs after first longer periods and then after shorter periods based on periodic safety review or its equivalent (it may vary from Member States to MS's regulatory requirements) based on the review of ageing management programme giving emphasis on performance evaluation of process systems and auxiliary systems which are both replaceable and non-replaceable and of RCC structures.

An example of review of ageing management plan in a recycling facility in France is given in annex II.

5.4 TIME LIMITING AGEING ANALYSIS (TLAA)

This concept of time related ageing analysis (TLAA) is extensively used in long term operation (LTO) of NPPs. IAEA has also published several technical guidance and safety reports on this subject [15]. For NFCFs, some Member States like UK apply this concept for life extension of fuel cycle facilities and others are following a strict regime of ageing management programme (AMP) followed by PSR or its equivalent to license the facilities beyond their original design life.

Based on the collection of data for detection and trending of ageing effects, design margins, and minimization and mitigatory actions, an assessment of residual life of the SSCs need to be made for consideration of long term operation. However, it is to be kept in mind that the ageing effects need not be extrapolated linearly. Often the combined effects of various degradation mechanism(s) may not be the same as if a single ageing mechanism was present. An example is the effect of radiation or stress on corrosion. Time-limited ageing analyses (also called safety analyses that use time-limited assumptions) show that ageing effects will not affect a structure or component's ability to perform its intended function(s) over an assumed period of long term operation.

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

One such evaluation tool, an index for technical condition, for evaluating the equipment condition for long term operation, has been in practice in Russian Federation (see annex II).

One or more of the following ageing analysis methods are used to estimate the residual life of a component/material of an SSC. These are standard mechanical testing methods and details can be found in respective national standards.

- Low cycle and high cycle fatigue analysis (e.g. fatigue analysis of cranes, steam tubes)
- Crack growth analysis;
- Corrosion allowance and rate of corrosion;
- Creep analysis;
- Thermal ageing and stratification;
- Fracture toughness analysis (e.g. flaw tolerance calculations due to thermal)
- Environmental qualification of EE&I components;
- Concrete strength analysis (due to creep and shrinkages);
- Foundation settlement due to soil movement.

The determination of time-dependent parameters involves analysing the plant's operating history and projecting it until the end of the intended long term operation period. The objective is to establish a parameter value that either applies to or sets the limit for the expected parameter value at the end of the planned long term operation period. The time-varying parameter relevant to the extended duration of operation will be utilised for reassessing the ageing that is restricted by time.

6. SUMMMARY AND CONCLUSIONS

Most NFCFs (NFCFs) across the globe have been in operation for several decades, and the ageing of structures, systems, and components (SSCs) is a significant concern for ensuring the safe and dependable operation of a facility beyond its intended design life. Many NFCFs, particularly chemical facilities, deal with dangerous, poisonous, and combustible fluids, and function in a corrosive environment. In addition, there exists only one pressure boundary that separates the hazardous fluid from the surrounding environment. Therefore, it is crucial to ensure that all safety-related systems and components that contain hazardous fluids are maintained in optimal condition to prevent failure during their service life. Additionally, these SSCs need to be designed with sufficient safety margins. A systematic and formal assessment of the SSCs can be accomplished through the implementation of an ageing management at regular intervals. A range of inspection and assessment techniques are utilised to detect and evaluate the effects of ageing. These techniques include testing and calibration, preventative maintenance, predictive maintenance, surveillance, condition monitoring, in-service inspection, and fitness for service. The afore mentioned techniques are crucial factors that contribute significantly to the development of a successful ageing management programme during the operational phase of the facility. A standard ageing management programme for an operational facility involves the coordination of ageing management activities for SSCs, management of degradation mechanisms, detection and assessment of ageing effects, and implementation of corrective measures.

Life management (or lifetime management) for long term operation of NFCFs (NFCFs) includes optimising the operation, maintenance, and service life of structures, systems, and components, maintaining an acceptable level of performance and safety, and maximising the return on investment over the service life of the facilities.

The NFCFs need to consider the unique characteristics of NFCFs, as opposed to NPPs, for LTO, such as the nature of hazards that include both nuclear and chemical environment. An independent ageing management philosophy needs to be devised for each type of NFCFs to function over the long run. The distinctiveness of designs, frequent advancements in equipment design performance, safe and dependable uninterrupted operation of the facility, operational experience, and sharing of best practises in related industries can all combat the chemical processes that can cause deterioration over time.

The operator needs to constantly assess operating experience from various sources, including both domestic and international, to make informed decisions. The sources of information considered for long term operation (LTO) include plant-specific experience, experience from similar plant designs, experience from similar materials, operating conditions and systems, structures and components, and relevant experience that contributes to the judgements on acceptability for LTO, irrespective of plant type. The identification of ageing-related degradation through adverse operating experience can aid in the recognition of new ageing phenomena that necessitate ageing management during LTO. This can be viewed from the standpoint of either new ageing mechanisms or new locations of known mechanisms.

A thorough evaluation of the operators' ageing management programmes, with a focus on their effectiveness, can offer objective evidence that the effects of ageing are being managed appropriately and will continue to be managed throughout the LTO period. This evaluation would consider any previous corrective actions that have led to enhancements or the implementation of additional programmes or activities.

Positive operating experience plays a crucial role in ensuring safe long term operation (LTO) by identifying any potential degradation related to ageing. The implementation of first-of-a-kind or one-time examinations to support LTO, or similar practises, can provide valuable insights into the proper functioning of the plant. This positive operating experience can broaden the knowledge base and enable the refocusing of resources to areas that may require more attention. It is necessary for the operator to assess their operating experience in order to extract valuable insights and detect any potential precursors that may lead to unsafe conditions.

The purpose of this technical document is to outline a set of strategies and best practises for managing long term operation through effective management of physical ageing and obsolescence throughout the entire lifecycle of a facility, from its initial design to its eventual decommissioning and dismantling. The design of a specific nuclear fuel cycle facility (NFCF) is a crucial step in predicting changes to the structures, systems, and components (SSCs) and mitigating the effects of physical ageing that may occur over time. The concept of defence in depth needs to be meticulously implemented, considering these mechanisms. During the operational stage of the NFCF, the primary goal is to establish a proactive maintenance approach within an organizational framework that captures and maintains a record of the facility's operation and maintenance history. Obsolescence management is categorised based on the type of obsolescence. The primary factors to consider for the long term operation of a facility are changes that impact technology (including hardware and software) and may cause maintenance issues for SSCs, changes in current standards and regulations, and obsolescence of documentation. The safe long term operation of nuclear facilities containing fissile materials requires special attention to the management of obsolescence.

The International Atomic Energy Agency (IAEA) has developed a range of safety guides and technical guidelines to ensure the safe operation of nuclear power plants (NPPs) and NFCFs (NFCFs). These resources specifically address the life and ageing management of structures, systems, and components (SSCs). The publications have been included in this TECDOC based on their level of significance. This document outlines the necessary steps for developing and executing a successful life management programme within the facility. It also offers guidance on the critical factors that need to be taken into account when conducting a comprehensive evaluation of the safety-significant components' ability to perform their intended functions in accordance with design specifications.

It is crucial to understand, identify, and alleviate the impacts of ageing for executing an efficient life management programme that considers the long term operation of NFCFs.

APPENDIX.
DEGRADATION OF EQUIPMENT AND COMPONENTS

The following Table 4 provides an overview of the degradation mechanisms with physical changes of ageing (consequence/failure), which may be induced by specific service conditions on materials, components, and systems of a NFCF.

TABLE 4: AGEING MECHANISMS AND EXAMPLES REPRODUCED FROM [27]

Ageing Mechanism	Examples
Civil structures	
Ageing of concrete (chemical attack, carbonation, effect on past deficiencies of construction quality and corrosion of embedded steel)	Ageing of concrete structure, creep due to high temperature during operation, moisture corrosion, chemical corrosion, radiation effect
Shrinkage and creep	Undue displacement and decease of structural strength
Loss of material (scaling, cracking and spalling) due to freeze-thaw processes	Loss of concrete elements. Anchorage, changes of design condition, embedment, vibrations
Mechanical components	
Corrosion (chemicals, hot spots), stress corrosion	Corrosion of vessels and interns, piping, welding Corrosion under insulation in pipes/buried pipes, SS liner in pools/hot cells
Irradiation	Changes in strength, ductility, swelling, Irradiation of organic compounds (confinement tightness) Glove box window/front face/glass windows
Stress fatigue due to mechanical cycles, thermal cycles or vibrations	Fatigue failure of vessels and interns, piping, welding
Erosion	Erosion of hopper, chutes, pipelines and machines
Microbial influenced corrosion	Corrosion of service water system, heat exchangers, diesel generators, wet storage of SF
Mechanical wear, fretting	Fretting of rotating equipment
Binding and wear	Of components within pumps and valves
Electrical and Instrumentation and control components	
Insulation degradation	Due to irradiation changes in insulation resistance, degradation of cables, motor windings, transformers
Partial discharges	Discharge of batteries
Oxidation	Oxidation of relay and breaker contacts, lubricants, insulation materials associated with electrical components
Process degradation	
Irradiation	Decomposition of chemicals e.g. TBP
Plugging	Plugging in pipes and transfer systems (steam ejectors)
Deposits	Deposits in vessels, pipes, process equipment
Other	
Neutron absorbers	Degradation of neutron absorber for storage vessel, pits
Non-physical ageing: obsolescence	
Equipment including hardware	Lack of spare parts e.g., I&C. Old design with impact on occupational exposure (especially during maintenance) e.g., design of glove boxes
Software	Loss of supplier support for the maintenance and modification of software e.g., out of date programmeming language, lack of hardware or upgraded PLC and software
Deviations from current regulations	Regulatory changes e.g., standards related to fire safety, design basis earthquake
Process	Old process compared with more recent ones that eliminate one hazard e.g., dry conversion process versus wet process, centrifugation versus gas diffusion enrichment
Knowledge management documentation	Deficiencies in the data collection and record keeping elated to ageing management. Loss of knowledge if not properly captured and updated on-time e.g., engineering diagram, safety justifications, operational feed back
Knowledge management replacement and training	Loss of operational know–how e.g., associated to industrial reorganisation or staff retirement
Leadership and organisation	Deficiencies of organisation in the management of ageing.

TABLE 4: AGEING MECHANISMS AND EXAMPLES REPRODUCED FROM [27]

Ageing Mechanism	Examples
	Lack of integration between safety and quality systems and oversights e.g., deficiencies in operational safety from lack of communication, weak safety culture (learning process)

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ANNEX I.
AGEING MANAGEMENT PRACTICES AND CASE STUDIES

I–1. METHODOLOGY FOR AGEING MANAGEMENT REVIEW OF A DRY SPENT FUEL STORAGE FACILITY IN ARGENTINA

I–1.1. Introduction

Argentina has number of NFCFs from mining, fuel production to spent fuel storage and final disposal. An example of their implemented methodology for ageing management at a dry spent fuel storage facility consists of (see Fig. I–1):

- — Scope setting;
- — Grouping of SSCs with similar construction, function, materials and operating conditions, an example given in Table I–1;
- — Identification and assignment of ageing related degradation mechanisms (ARDM) i.e. corrosion, leakage, concrete cracking, etc.;
- — Development and implementation of ageing management programme (AMP);
- — Reporting of results of the activities carried out, documenting that the ARDM and their effects are being addressed;
- — Expected lifetime of spent fuel pools is 40 years.

The AMP includes a defined scope, preventive measures, detecting, trending and monitoring techniques, acceptance criteria, corrective and mitigating actions, feedback from operating experience and quality control and documentation steps. The AMP is reviewed on a periodic basis to find opportunities for improvement. The periodicity may be fixed by the operator needs or set by the regulatory requirements.

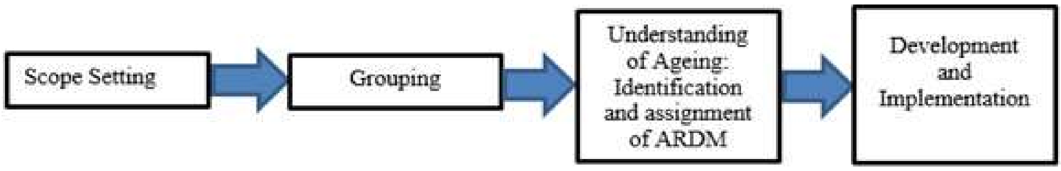


FIG. I–1. Ageing management plan flow chart

I–1.2. Grouping

Components similar in construction, function, materials, and operating conditions are grouped together for example manual valves for cooling water system as given in Table I–1 and Table I–2.

TABLE I–1 GROUPING OF MANUAL VALVES FOR COOLING SYSTEM

System	Cooling system
Components	Manual Valves of cooling system
Description	Manually operated ball valves(SS) with DM water. The valves are welded to the system pipes. The welds are considered part of pipes.
Components ID	3400–V1,3400–V20,3400–V2, 3400–V32, 3400–V54
Intended Function	Keep integrity to allow the flow of liquid and avoid loss of refrigerated water
Material	Valves are constructed with Stainless Steel type 304
Operating conditions	Internal operating condition: DM water at 25^{0}C and 15kPA External operating condition: Controlled air
AM-ID	AM–1001 Manually operated valve with DM water

TABLE I–2 IDENTIFICATION AND ASSIGNMENT OF ARDM

AM -ID	AM group	Definition	Intended function	MOC	Service condition	ARDM/effect	Critical location	Material	AMP
AM 1001	Manually operated valves with DMW	Includes manually operated valves or that don't need to operate, SS	Keep integrity to allow flow without leakage	SS FKM	DMW @ 25^{0}C and 15kPa	Crevice corrosion/ loss of material Compression set/loss of mechanical properties, leakage	Crevices Gaskets/O-rings	SS FKM	Water chemistry programme Periodic replacement
AM 3001	External building walls	Civil structure of the building	Keep integrity to provide support to other SSCs and shielding function	RCC	Atmospheric weather/controlled air	Corrosion of steel bars/loss of material and mechanical properties, cracking of concrete	Reinforced steel	CS	Steel corrosion monitoring

I–1.3. Methodology for implementing an AMR in a NFCF in Argentina

Ageing management is an activity carried out to prevent effects of ageing that could affect safety related function of systems, structures, and components (SSC). The development and implementation of an ageing management review (AMR) allows to coordinate the different activities executed in different facilities of the nuclear fuel cycle. The methodology described is developed to be implemented at dry spent fuel storage facilities in order to have access to updated information on the state of SSCs and to be able to adequately report the results and make periodic reviews on ageing.

Argentina counts with two dry spent fuel facilities i.e., the ASECQ (Almacenamiento en Seco de Combustibles Quemados) a dry spent fuel storage facility under construction in Lima, Buenos Aires, and several storage silos in Embalse, Cordoba. Currently the methodology for implementing an AMR is under development and the main objective is to monitor ageing since the design stage.

For implementing an AMR, the first phase is to set the scope. The scoping process is carried out to determine which SSCs are important to safety, and which are not.

There are two general approaches to determine whether or not an SSC is important to safety:

- Safety systems approach: (systems with critical safety functions or safety support functions);
- Spatial interaction approach.

For SSCs belonging to safety systems, it is analyzed whether they are necessary to fulfill the functions of the system to which they belong. If they are, they are considered important to safety, to be identified. The spatial approach requires that safety systems for SSCs, whether they belong to a safety system or not, it is analyzed if due to their spatial disposition, they can affect the intended function of the SSCs important to safety. If so, they are considered important to safety.

There are three stages of the process of scoping and grouping which are described (figure I–2) below:

Stage 1: identification of safety systems

The objective of this stage is to identify NFCF's safety systems, to analyze which systems have safety functions, which systems have support functions and which systems are not important to safety.

Systems that either have one of the following fundamental safety function:

- Containment;
- Heat removal;
- Reactivity control;
- Control of chemical products.

Or systems with support function (i.e., compressed air systems, lubrication) are considered safety systems.

Stage 2: Scoping and grouping of SSC safety systems

The objective of this stage is to determine which SSCs are important to safety, considering how they contribute to the safety or support to safety function of the system to which they belong.

Each of the safety systems identified in the previous stage is taken, and a detailed analysis is carried out at the level of its SSCs. In this analysis, the technical information of the system is used (design documentation, status and life evaluations, flowcharts and plans, manuals, etc.) to determine which SSCs are necessary to meet the functions assigned to the system.

The SSCs necessary to fulfill the safety function of the system are considered important to safety and therefore within the scope of the ageing management.

For each SSC identified as important to safety, its intended function is defined. The intended function is the one which contributes to the fundamental safety or support functions of the safety system. For example, a pump that drives a coolant does not fulfill the decay heat cooling function itself, but its intended function: to pump a certain flow rate; it does contribute to fulfill the cooling function of the system to which it belongs. Finally, grouping is carried out, which consists of associating each SSC to a predefined AM Group.

Stage 3: Scoping and grouping of SSCs with a spatial interaction approach

The objective of this stage is to identify those SSCs (whether they belong to a safety system or not) that, due to their spatial arrangement, may affect, through a consequent failure, the intended function of the SSCs important to safety identified in the previous stage.

This task is executed by conducting walkdowns, which can be organized by system or by building rooms as appropriate. In the walkdowns it is analyzed how all the SSCs surrounding the safety important SSCs can affect the performance of their intended function.

For each SSC identified at this stage, its intended function is defined. If the SSC already had an intended function (because it belongs to a safety system), it is analyzed if it is necessary to modify it by adding additional functions. The result of the scoping process is a set of SSCs important to safety with their intended function, which are considered within the scope of the ageing management. And a set of SSCs not important to safety, which are considered outside the scope of ageing management. The whole process is documented through a scoping report. The results of the scoping and grouping are documented by elaborating a list of all SSCs indicating whether each one of them is in or out of scope of ageing management (AM).

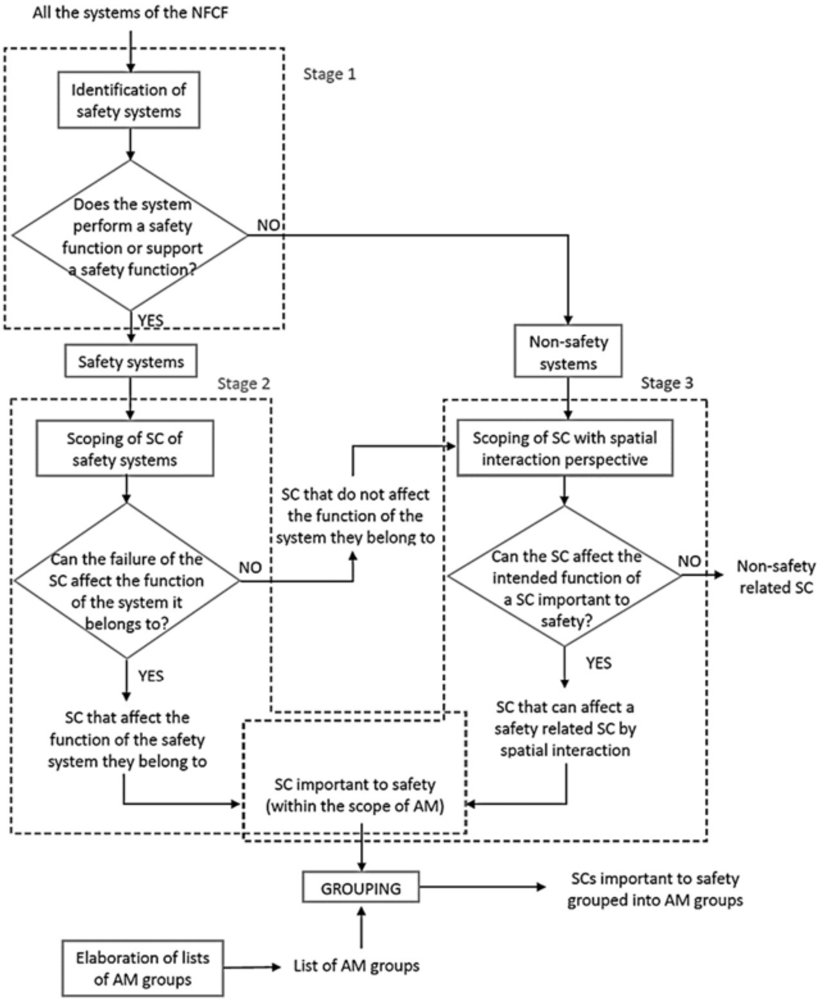


FIG. I–2. Scoping and grouping process

The grouping process is carried out only on the set of SSCs included within the scope of ageing management, which are assigned to different ageing management groups (AM Groups) according to their characteristics.

An AM group is a set of components that share similar ageing characteristics (functions, ageing related degradation mechanisms, applicable ageing management strategies, etc.). These groups are defined in a standardized manner to prevent conflicts in grouping in order to carry out AM and they constitute one or more lines of the ageing management review (AMR) table.

The definition of an AM group implies the development of the following fields:

— Name of the AM group;
— ID code;
— Scope;.
— Type of component (for example: valves, pipes, concrete structures, etc.);
— Physical limits;
— AM area (mechanical, electrical and I&C or civil);
— Material;

— Medium (environment);
— Function (it is the expected function that needs to preserve due to its impact on safety).
— Type of function (It is the type of intended function fulfilled by the SSCs assigned to the group. They can be passive and/or active functions).

For each AM group, ageing related degradation mechanisms (ARDM) that could affect the intended function are assigned. Also, its analyzed witch are the susceptible locations of the SSCs for each ARMD and its effects. The ARDM are standardized for consistency of the management of the information.

After all these processes are completed an AMR chart is built containing the following fields: AM group, scope or definition of AM group, Intended function, material, service condition, ARDM / effect, Critical location, AMP. In the table I–3, the structure of the AMR table is given. The AMPs are plant programmes that coordinate and collect the information and results of the inspections and maintenance tasks carried out on the SSCs. Periodically reports together with the generation of indicators gives the implementation results of the respective AMP.

An AMP include a defined scope, address preventive measures, identified detecting, trending and monitoring techniques, establishes an acceptance criterion, states corrective and mitigating actions. The programme also include feedback from operating experience, proper quality controls and documentation.

TABLE I–3 EXAMPLE OF A LINE OF AN AMR TABLE

AM Group ID	**AM Group**	**Definiti on**	**Intended function**	**Material**	**Service conditions**	**ARDM/ef fect**	**Critical location**	**AMP**
ID code	Name of the AM group	Definiti on and scope of the group	The intended function that needs to be preserved	Main constructi on material	External/ internal medium	Name of the ARDM and Effects on SSCs	Susceptible location of the SSCs	AMP of the NFCF that control the ARDM

Each line of the AMR table represents an AM group, with its respective ARDM and then the plant activities and programmes have to been analyzed, to determine if they are sufficient to control each identified ARDM, and to identify which additional AMPs need to be developed and implemented.

This whole process needs to be reviewed periodically in order to achieve improvements. The results of AMPs and other plant programmes would be evaluated through ageing assessments, to verify that the AMPs and plant programmes are effective and that all ARDMs have been taken into account.

I–1.4. Ageing management in a spent fuel storage facility in Argentina

An example of common cause failure for a spent fuel storage pool, a through-wall cracks that developed in a fuel storage pool (FSP) stainless steel pipe during service is illustrated here.

There are three factors that generally interact to determine whether a cladding or stainless-steel components will suffer impaired durability. These factors can influence the corrosion behavior of stainless-steels, fuel cladding or fuel storage components:

— Metallurgical conditions, degree of sensitization;
— FSP water chemistry;
— Stresses facilitating in Inter granular stress corrosion cracking (IGSCC) or other cracks phenomenon.

The key elements that lead to age related degradation or failure is shown in Fig. I–3.

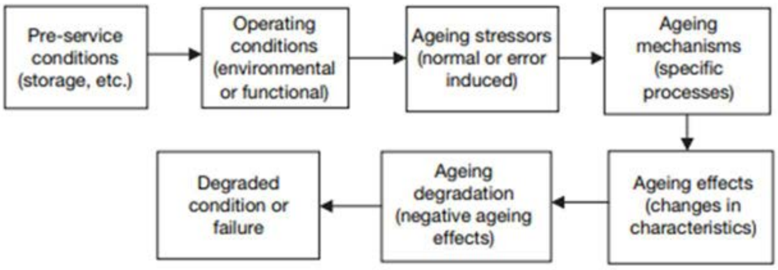


FIG. I–3. Ageing sequence

The sensitization of welds due to improper weld procedure, the use of borated water at about 30°C and possible contaminants along with stresses in weld area created a ripe condition for intergranular stress corrosion cracking (IGSCC), a mechanism of ageing. The ageing effect was a through-wall crack leading to degradation of pipe wall in the heat affected zones and ultimately leading to the failure of pipes. Table I–4 provides factors, degradation mechanism and ageing effects in a spent nuclear fuel storage facility.

TABLE I–4 AGEING EFFECTS IN A SPENT FUEL STORAGE POOL (COURTESY OF CNEN, ARGENTINA)

SSCs	**Caused**	**Ageing Mechanism**	**Ageing effect/ failure**	**Picture**
Pool Liner (SS 304)	Water chemistry	Corrosion	Crack, leakage	 

TABLE I–4 AGEING EFFECTS IN A SPENT FUEL STORAGE POOL (COURTESY OF CNEN, ARGENTINA)

SSCs	Caused	Ageing Mechanism	Ageing effect/ failure	Picture
Pool structure	Concrete	Humidity, salinity	Crack, leakage	
Basket/racks	Water chemistry	Corrosion	Deterioration of strength	
Fuel Handling	Water chemistry	Corrosion	Leakage	

I –2. AGEING MANAGEMENT AT FUEL FABRICATION PLANT IN BRAZIL

I–2.1. Introduction

Currently, Brazil has been operating NFCFs (NFCFs) for more than 30 years in a safe manner. At the beginning of development, the NFCFs were designed and constructed when ageing was not yet a major consideration. The ageing management for nuclear installations has been getting more attention in recent years.

I–2.2. Brazilian Nuclear Policy

The Constitution of 1988 of the Federal Republic of Brazil states that the Union (Brazilian Federal Government) has exclusive competence for managing and handling all nuclear energy activities, including the operation of nuclear power plants. The Union holds a monopoly on the surveying, mining, milling, exploration, and exploitation of nuclear minerals, and the activities related to the industrialization and commerce of nuclear minerals and materials. The Union is also responsible for the final disposal of radioactive waste.

Brazil has established and maintained the necessary legislative and regulatory framework to ensure the safety of its nuclear installations, including irradiated fuel, radioactive waste management, and transport of radioactive materials.

The Brazilian nuclear programme industry includes different stages of the Nuclear Fuel Cycle: mining and milling processing (large uranium reserves), conversion, enrichment, UO_2 powder and pellets, fuel elements, power generation, and spent fuel storage.

I–2.3. Brazil's Regulatory Approaches

Nuclear installations are subject to a nuclear license, issued by the Brazilian Nuclear Energy Commission (CNEN). The Brazil regulatory approach provides a continuous assessment and review that ensures safety throughout the period of facility operation. Facility safety is maintained, and aspects are improved, by a combination of the ongoing CNEN regulatory process, oversight of the licensing basis, license renewal, and licensee initiatives that go beyond the regulations.

In Brazil, the authorization to operate a nuclear fuel cycle facility (NFCF) is not limited to a given duration, and it depends on the type, scale, characteristics, state of installation, and records of the operation.

The following Figure I–4 summarizes the nuclear licensing process conducted by CNEN:

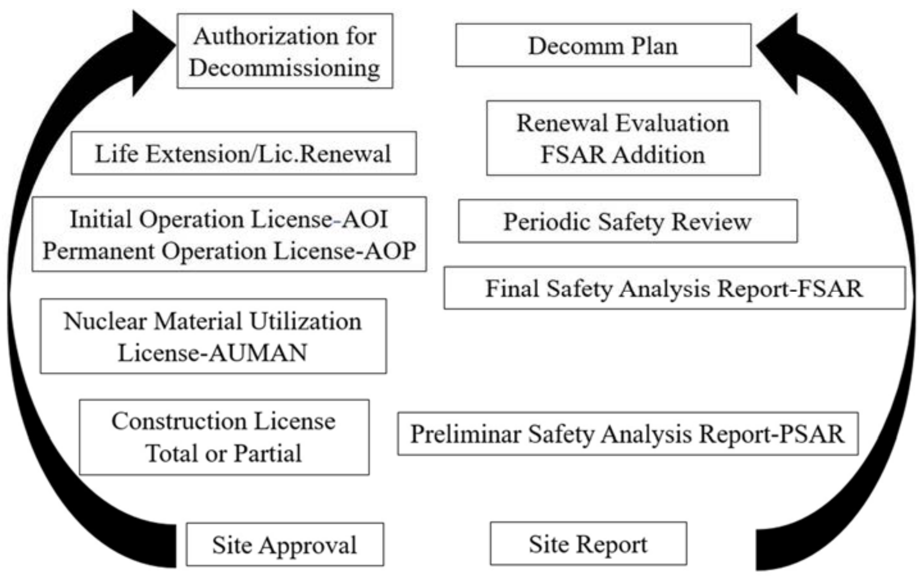


FIG. I–4. Brazilian nuclear licensing process

The management of the life of fuel fabrication facilities is based on:

- Periodic safety reviews (PSR) or its equivalent, considering the processes that limit the life and features of systems, structures, and components (SSCs);
- Economic considerations;
- Experience management;
- Due to changes in technology as functional requirements.

Periodic safety reviews assess the cumulative effects of the facility modifications. Design modification of the site structures, processes, systems, equipment, components, computer programmes, and personnel activities in a NFCF in Brazil have to be approved by Brazilean regulatory body (CNEN).

The CNEN carries out regulatory activities that constitute a process providing ongoing assurance that the NFCFs licensing bases provide an acceptable level of safety, and the effects of ageing are appropriately managed. This process includes inspections (both periodic regional inspections as well as daily oversight by the resident inspectors for some facilities), audits, investigations, evaluations of operating experience, and regulatory actions to resolve identified issues. This is a continuous process for facilities that receive a renewed license to operate beyond the original operating license.

Brazil fuel cycle facilities have a formal documentation process that governs the design and continued modification of the site structures, processes, systems, equipment, components, computer programmes, and personnel activities. These documentation processes typically provide reasonable assurance for the disciplined documentation of the engineering, installation, and commissioning of modifications; the training and qualification of affected staff; the revision and distribution of operating, test, calibration, surveillance, and maintenance procedures and drawings; post modification testing; and review. Additionally, it is important to know that any design and continued modification of the site structures, processes, systems, equipment, components, computer programmes, and personnel activities in a NFCF in Brazil have to be approved by the regulatory body (CNEN).

CNEN standards require fuel cycle facilities to define the safety important items list. By requiring NFCFs to define a comprehensive safety important items list, the CNEN sought to improve safety through a risk informed and performance based regulatory approach that included the performance of safety important items to identify potential accidents at the facility and the items relied on for safety and the implementation of measures to ensure that the items relied on for safety are available and reliable to perform their function when needed.

The safety important items include all the structures, systems, and components specifically designed and operated for preventing the occurrence of initiating events, detecting them, and mitigating the radiological or chemical consequences of incidents or accidents for the workers, the public, and the environment.

The concept of safety important items list implementation leads to the identification of structures, systems, and components important to safety (SSCs) which are those barriers specifically designed and operated for preventing the occurrence of initiating events and for mitigating the consequences of an accident if prevention fails. The safety important items list is routinely updated and revised to reflect new information or consider facility process changes and the safety important items have priority periodic evaluations and maintenance. During operation, the conditions Safety Important Items are recorded and are used as input for defining the maintenance or replacement, spare parts, periodic testing, and inspection regime that provide for timely detection and mitigation of ageing effects.

As in many countries, Brazilian fuel cycle facility licensees are responsible for the safety of their facilities. This responsibility is embedded in their license and in the CNEN's regulatory infrastructure.

I–2.4. Physical ageing, a case study on degradation of mechanical components

The first firefighting system (piping and valves) have been installed in the Nuclear Fuel Facilities Plant (enrichment, reconversion, and pellets) in Brazil in 1997. Since then, the firefighting system has been suffering mechanical degradation of its components due to the natural ageing process. The firefighting system has an excellent operation record without any serious for more than 20 years.

The replacement of the firefighting system was necessary, as the pipeline, buried for the most part, were deteriorated due to corrosion and no longer admitted corrective repairs. This fact increased the frequency of leaks and consequently the loss of water and pressure in the firefighting system. Maintenance procedures ensured systematic identification of corrosion, leakage, degradation and identified a decrease in lifetime.

In 2020, the licensee prepared a modification project for the future replacement of the firefighting system. The new firefighting system installed consists of an aerial part on concrete supports where there is no vehicle traffic, and part inserted in channels □ built in reinforced concrete structures with a concrete bottom and lid, at street crossings and building entrances.
Currently, the new and modern firefighting system project is implemented and commissioned by the licensee and approved by the Brazilian regulatory body (see Fig. I–5 and I–6).

FIG. I–5. Old firefighting system (corroded condition)

FIG. I–6. New firefighting system

I–2.6. Conclusions

The Brazil regulatory approach provides a continuous assessment and review that ensures safety throughout the period of facility operation. This process carries out regulatory activities that constitute a process providing ongoing assurance that the NFCF's licensing bases provide an acceptable level of safety, and the effects of ageing are appropriately managed.

Additionally, it is important to know that any design and continued modification of the site structures, processes, systems, equipment, components, computer programmes, and personnel activities in a NFCF in Brazil need to be approved by the Brazilian regulatory body.

I–3. FITNESS FOR SEVICE PROGRAMMES FOR AGEING MANAGEMENT OF NFCFS IN CANADA

Canada has several uranium mines and mills, uranium refining and conversion, facilities (Fig. I–7), fuel fabrication facilities and spent fuel interim storage facilities, both dry and pool types. The perspective to ageing management is based on a ‘fitness for service programme’. Fitness for service covers activities that impact the physical condition of structures, systems, and components to ensure that they remain effective over time. This includes programmes that ensure all equipment is available to perform its intended design function when called upon to do so.

It includes the scope and frequency for periodic testing, calibration, and maintenance of facility’ SSCs and is a part of service programme. Regulatory body assess “fitness for service programmes” and conducts inspections to verify compliance of the maintenance, testing and control activities with the programme.

The AMP includes following steps:

- Establish enterprise-wide asset management;
- Identify the safety-significant structures, systems, and components (SSCs);
- Implement a preventative maintenance programme to ensure that SSCs remain effective over time;
- Implement periodic inspections and testing of SSCs;
- The extent and frequency of the maintenance, periodic inspection and testing depends on the safety-significance of the SSCs.

FIG. I–7. Port Hope conversion facility (courtesy of CNSC, Canada)

There exists no separate guidance document on “fitness for service programme” for NFCF. The licensee’s fitness for service programme is assessed by regulator to ensure that they detail the preventative maintenance, in-service inspection and periodic inspection and testing requirements for equipment. The regulator conducts inspections to verify that the equipment maintenance and periodic inspection and testing activities have been completed as required.

I–4. MANAGEMENT OF LONG TERM OPERATION OF SPENT FUEL STORAGE FACILITIES IN CZECH REPUBLIC

The Czech Republic has several facilities for spent fuel storage both dry (Fig. I–8) and pool type which are quite old and need special attention towards ageing management and life extension. The country has made safety specific requirement on ageing management for ensuring safety. The AMP includes:

- A list of SSCs to be subject to AM process;
- A list of degradation mechanisms and impacts of ageing;
- A list of monitored parameters and condition indicators that are used for the monitoring and determination of the development of the impacts of ageing;
- Rules for the monitoring and determination of the development of the impacts of ageing;
- A list of the acceptance criteria for monitoring parameters;
- Rules for assessing the monitoring parameters, assessing the current state of SSCs selected for ageing management and predicting the future state of these SSCs;

— A list of corrective measures in respect of a failure to meet the acceptance criteria for monitoring parameters;
— Rules for the monitoring of the efficiency of measures in operation and maintenance of SSCs selected for AM to mitigate or eliminate the impacts of ageing and the effects of degradation mechanisms on these SSCs;
— Description of the provision of feedback in order to measure the efficiency of the ageing management process;
— Rules for assessing the efficiency of the AM process;
— Rules for documenting the activity in the framework of the ageing management process.

FIG.I–8. SF Dry storage containers (courtesy of SUJB, Czech Rep.)

The documentation to be provided for licensing of operation of a nuclear installation include management system programme, limits and conditions of safe operation, in-service inspection programme, list of selected SSCs, operational safety analysis report and operational ageing management programme. The following process chart (Fig. I–9) for AM and long term operation describes the steps followed by operating organisation and regulatory body.

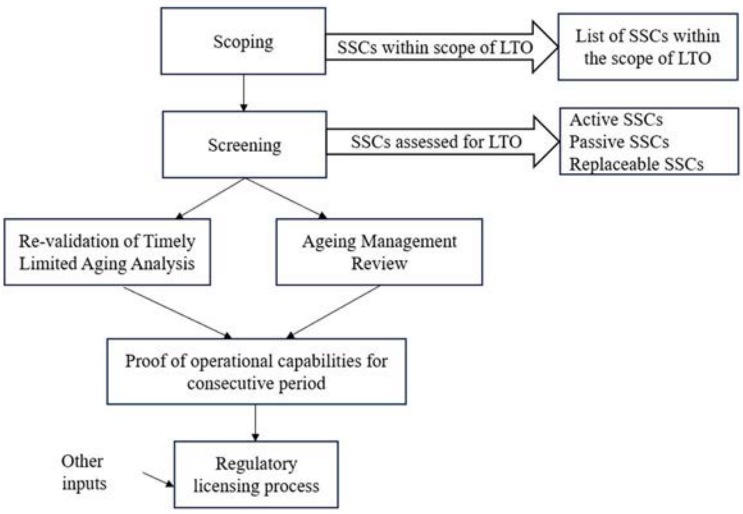


FIG. I–9. Ageing management programme flow chart (courtesy of SUJB, Czech Rep.)

A comprehensive list of SSCs within the scope of long term operation is prepared in the scoping exercise with their identification. The screening of these SSCs is done in next step to identify them in three categories i.e. Active SSCs e.g,. monitoring system, passive system e.g. casks and regular replaceable SSCs e.g. valves etc.

In an AM review, the description of technological unit (e.g., facility for storage of SF), identification of common groups (e.g. casks, monitoring system components, shock absorbers, transport wagon, etc.) with detailed description, degradation mechanism identified from international practices and operating experience feedback (e.g. surface corrosion, mechanical stress. etc.) and their comparison, finalised AMP (e.g., visual controls, leakage tests etc.), already implemented AMP with the reference to specific maintenance, test, and control programmes and summary of recommendations for each commodity group and for the whole technological unit (reflected in health report) are provided.

Some of the AM activities for LTO are carried out in a period of every year:

- Scoping (database for AM);
- Annual report evaluating the managed ageing area;
- Inputs to the health report;
- Update of operational safety case.

The AM activities for LTO which are carried out in a period of 5 year:

- Assessment of the state of ageing management (TLAA);
- Assessment of the state of ageing management of machinery (e.g. storage casks; AMRs, system by system);
- Structural ageing management status assessment (e.g. DCSF; AMR reports, by building/structure);
- Electrical ageing management status assessment (e.g. monitoring system of storage casks and DCSF).

In a dry storage facility, the SSCs like transport and storage casks, temperature and pressure monitoring system and shock absorbers, cables, electric equipment etc are classified as safety relevant SSCs for LTO. The surface corrosion, material fatigue of cask resulting in cask untightens, ageing effects concerning replaceable parts (seals etc) are not subject of AMP as they are managed within regular preventive maintenance programme. AMP can be performed by standard maintenance, testing and control methods (DPC), no specific AMPs are considered for DCSF.

Based on the nature of the DCSF operation and the parameters of the medium (temperature up to 40°C, pressure up to 0.5 MPa), it is not forseen, that the development of fatigue_as a degradation mechanism will impact DCSF operation. The possible manifestations of this degradation mechanism would be detected within the framework of operational control programme. The possible occurrence of cask surface corrosion would be detected during visual inspections according to operational control programme. From an ageing management point of view, the condition is adequate, and no further measures need to be introduced. Any leaks would be identified by the pressure checks. In addition, any leaks are monitored by the cask intermediate space pressure measurement system, the data are transmitted from the measuring unit to the central radiation control information system, where the data are continuously checked, and measured pressure value is archived once a day. Specific for transport and storage casks, periodic re-licensing (every 10 year) including revisions of safety reports and operational maintenance, testing and control manuals are carried out. For DCSFs no AMRs and TLAAs are envisaged.

I–5. EVALUATION OF AGEING MANAGEMENT PROGRAMME FOR NFCFS IN FRANCE

The ageing management activities for LTO which are carried out mostly in a period of 5 years are:

- Review and assessment through time limited ageing analysis (TLAA);
- Review and assessment of the state of ageing management of machinery (e.g. storage casks; AMRs, system by system);
- Review and assessment of status of structural ageing management (e.g. reports related to building/structure);
- Review and status assessment of electrical ageing management (e.g. monitoring system of storage casks and DCSF);
- Review and assessment of I&C ageing management.

I–5.1. List of equipment

The list of equipment in a recycling plant whose compliance is reviewed every 10 years as part of the periodic review is given in Table I–5:

TABLE I–5 LIST OF EQUIPMENT IN A RECYCLING PLANT FOR PERIODIC SAFETY REVIEW

Theme	Equipment
scavenging air: risk of radiolysis	air bottle or tank / Piping / filters / sensors / flow meter / temperature measurement / speed measurement / pressure switch / compressors / boosters / pre-assembled sets
nuclear process control	counting pot / sensors / probes / activity measurement / neutron or gamma counter / alarm system / online concentration measurement
radiation protection control	monitor / beacon / iodine trap / neutron, gamma or beta measurement channel / alarm network
power supply	chargers / electrical cabinets / distribution cabinets / electrical panels / inverter / tracing lines / batteries
pulse devices	air tank / sensors / valves / flow meter / pressure switch / piping
containment enclosure	Walls / filters / Valves / hydraulic guard / valve guard
civil engineering	slabs, hoppers, berths, reinforced concrete, blocks, casemates, hatches, cells, then, crossings, portholes, doors, tele manipulators, slides, sampling bench, anchors, foundations, raft, beams, posts, joints, thermal protection or insulation, elastomer supports, plates, dowels, casing, roofs, drains, rainwater drainage, paint, retention, waterproofing membrane, heavy concrete brick
chimney	sensor / flow meter / anchors / drums
fire	detector / extinguishing network / alarm network / valves / fire dampers
handling / lifting	shock absorbers / handling device / lifting bridge / ferry / trolley / motion sensors / presence sensors / limit switches / grippers / slings / load cell / anti-fall structure / anti-fly-off structure
chemical storage and supply	tanks / retentions / cut-off valves / Level, flow, pressure sensors / lifting pumps / sealing / agitator
cooling systems	air coolers / heat exchangers / pumps / pipes / expansion vessels / sensors
pneumatic conveying network	barrels / filters / suction box / valve / passage detector / hydraulic guard / sliding bag / bellows / piping
backup power supply	diesel groups / fuel tanks / distribution cables / box / control panels / backup panels / cross-failure panels / cabinets

TABLE I–5 LIST OF EQUIPMENT IN A RECYCLING PLANT FOR PERIODIC SAFETY REVIEW

Theme	Equipment
ventilation	air intakes / heating grilles / de-icing resistors / ventilation ducts / filters / filter boxes / fan / dampers / flow measurement / exchangers / heaters / condensers / demisters / washing columns
video surveillance system	camera
sensors and control-command	logic, analog or digital sensors / automation / certain equipment for shaping and restoring a signal / control loop / seismometers / weight measurement / analyzer
equipment	tanks / retentions / sumps /vessels / pressure equipment / water reserves / double envelopes / safety geometry equipment / racks / sampling devices
mechanical materials and structures	berths / casings of storage pools / cofferdams / baskets / nacelles / shears / special equipment / calciners / furnaces / presses / shock absorbers / mechanical devices for closing drums / shutters
transfer devices	pumps / valves / dosing pumps / vacuum pumps / airlifts / ejectors / siphons / check valves / siphon breakers / pipes / manifolds / ducts / holders
process equipment	dissolver / evaporators / tray columns / mixer-settler / chutes / tanks / calciner / precipitator / mixer / pulsed columns / laboratory equipment / electrolyzer / filling hoppers / compactor / leak detection pots / condenser / demister / centrifuge / boiler
internal transports	packageing / containers / mobile enclosures / loading and unloading stations / tractors / docking device / tightness control device / seals / bellows / securing ears / wedging equipment / locking system / braking system / hitching system / fixing pin
various other devices	earthing of equipment / protection against lightning / anti-whipping devices / protective covers / means of pumping effluents

I–5.2. Examples of best practices

I–5.2.1. Wear

Some chutes ensuring the transport of shells and sheared fuel assembly end-pieces show a phenomenon of wear. Wear is checked regularly by visual inspections and thickness checks. Chutes whose thickness reaches a critical threshold are repaired using repair plates.

The phenomena of wear by the fines present in the solutions are studied and monitored. The thickness of the walls of equipment sensitive to the risk of corrosion are subject to monitoring programmes.

I–5.2.2. Safe geometry equipment

Controlling the ageing of equipment for which the criticality control mode is the geometry is approached along three axes:

— A material study which evaluates the risk of ageing by corrosion and wear and defines a consumable thickness to be taken into consideration;
— A mechanical study which verifies the static and seismic resistance, the conservation of the geometry, the absence of fatigue and creep taking into account the thickness of the walls possibly consumed;
— A safety-criticality study taking into account the ageing mechanisms and the effects observed.

In addition, materials are subjected to specific studies aimed at demonstrating the maintenance of their neutron absorption capability over time.

I–5.2.3. Protection against lightning

ORANO uses the International Electrotechnical Commission (IEC) standard "IEC 62305 – protection against lightning" to bring its lightening protection systems up to standard. Inventories of existing protective devices and equipment to be protected are carried out during periodic reviews. Standardization studies are carried out and implemented according to the principles defined in the standard.

I–5.2.4. Effect of radiation

The effect of radiation is mainly taken into account in the ageing of polymer materials such as seals or seismic pads. Studies list the different ageing processes according to the materials used, such as the glass transition temperature, the chemical ageing process, the order of magnitude of the resistance to irradiation before degradation as well as the sensitivity of the material to physical ageing or chemicals.

I–5.2.5. Fault criteria on anchors

A list of fault criteria for anchors is given in Table I–6 below:

TABLE I–6 EXAMPLE OF FAULT CRITERIA FOR ANCHORS

Type of defects	Description of defects
superficial corrosion	The corrosion of the components does not call into question the mechanical properties of the anchorage. On scraping, the steel appears sound.
pronounced corrosion	The corrosion of the components is such that the sound section of the anchor cannot fulfill its role of mechanical strength
absence of bolts	A bolt, screw, stud or nut is missing.
	Anchors: the sleeve is in place but the screw is missing or the nuts and washers are missing
	Stem sealed: the stem is in place but the nuts and washers are missing
defective bolts	The thread is defective. The bolts are deformed or broken.
defective dowel	Missing dowel The thread of the screw is defective The dowel moves freely The sleeve is extracted from the concrete The dowel does not fulfill its role of mechanical strength
defective rod	Missing rod The sealed rod is no longer linked to the concrete The rod is broken The rod does not fulfill its role of mechanical strength
poor tightening	All the elements are in place (sleeve, screws, washers, nuts...) but the nut is not tight on the screw.
	All the elements are in place (rod, washers, nuts...) but the nut is not tight on the rod.
crack or defect in civil engineering	A crack in the concrete is induced by the anchorage Degradation of the concrete
defective wedging of the plate	The plate has a detachment from the concrete
lack of anchoring system	anchoring systems on the equipment is missing

I–5.2.6. Development and use of drones

Miniature and modular drones are developed in order to access previously inaccessible areas. they are equipped with various means of inspection, measurement, and control.These drones are a walking type drone capable of operating in an hot cell and overcoming obstacles (pipes, drip tray, etc.).

There are drones that can be introduced into a hot cell through a 100 mm diameter endoscope hole. These are able to be deployed and flown to perform visual inspections. They are also intended to carry out ultrasonic measurements.

I–5.3. Ageing management monitoring and control at La-Hague, France

France has wide range of NFCFs from ore processing, fuel enrichment, fuel fabrication, spent fuel storage, reprocessing, vitrification and interim waste storage. The La -Hague reprocessing facilities (UP 3 and UP 2–800) were initially designed for 30 years of operation and their operating life span was extended to 40 years to process spent fuel with increased burn ups. This had an impact on occurrences of equipment fouling issues particularly on fuel shearing plant and dissolution facilities.

The ageing management focussed on issues with ageing of equipment resulting in long term outages of plants. The critical equipment necessary to operate including transport were identified to avoid unplanned outages. A common reason was observed for ageing of materials (SS304L) with aggravating factors linked to design or implementation.

A sustainability method/process inspired by advanced process 913(AP913) methodology was used which aims to achieve excellence in terms of equipment reliability (Fig. I–10). This approach is based on lessons learned. The goal is to identify failure modes and anticipate their detection by strengthening and centralizing equipment monitoring. It has limited operational impacts with preventive tailored actions along with robust action plan in the long term with risk management indicators. This approach has four main tasks: identification of equipment and risks, monitoring and supervision, securing and feedback. It also addresses needs in terms of analysis, trouble shooting and repair.

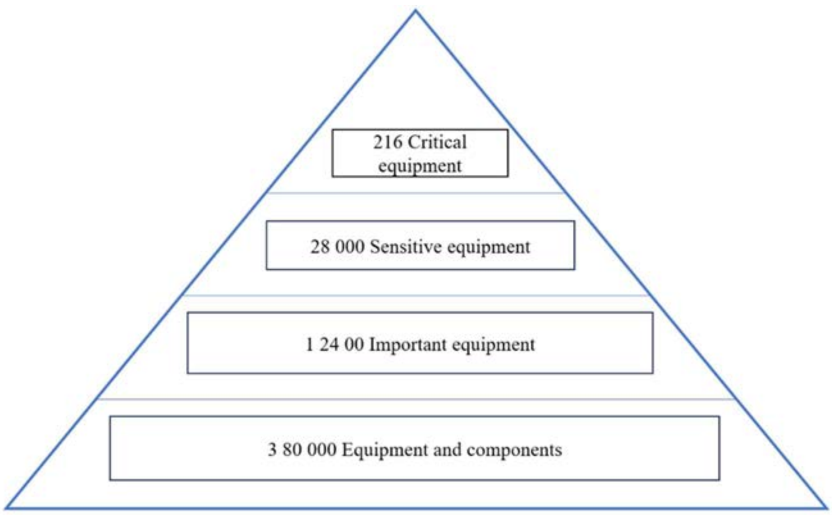


FIG.I–10. Screening of critical equipment at La-Hague (courtesy of ORANO)

For the ongoing process of monitoring and supervision, KASEM, a proprietary software, is used which monitors scheduled operations, such as the assessment of minimum operating duration of equipment subjected to corrosion. The centralised equipment monitoring in KASEM aims at detecting and alerts on drifts and controlling risks by monitoring their evolution. This software has smart sensors using IOT taking inputs from PLCs and analyses process history from process stored data and also does analytical control from laboratory analysis results. It provides automatic feedback of measurement and analysis data, automatic calculation of process parameters in addition to continuous monitoring of these parameters and giving real time alarms. For example, the increase in torque at the ends of calciner could lead to the shutdown of calciner, but due to sensors connected can measure the low rotation speed and generates alerts and KASEM software analyses these alerts and can anticipate the need of cleaning and visual inspection before the calciner is completely shut down.

It can be estimated from the thickness available for corrosion and the corrosion rate. Based on this assessment, a new project for new units of concentration of fission products has been envisaged to replace three evaporators at the La Hague site.

There are 400 on-going investment projects at La-Hague, 40% of them related to ageing management (sustainability). Innovative technologies are introduced for ageing equipment control, such as walking drones, telescopic arms etc. mainly for use in hot cells. The operational process for controlling sustainability is structured based on a network of sustainability correspondents, experts and using a digital tool called BURO (Unique Base for Operational Risks) which provides risk monitoring and Governance and quarterly coordination specific to each operating unit.

A proactive obsolescence management system (POMS) service software is also available to identify, prioritize and address obsolescence issue of spare parts. This system is functional since 2021 at La-Hague with 20000 items integrated with the system (Fig. I–11).

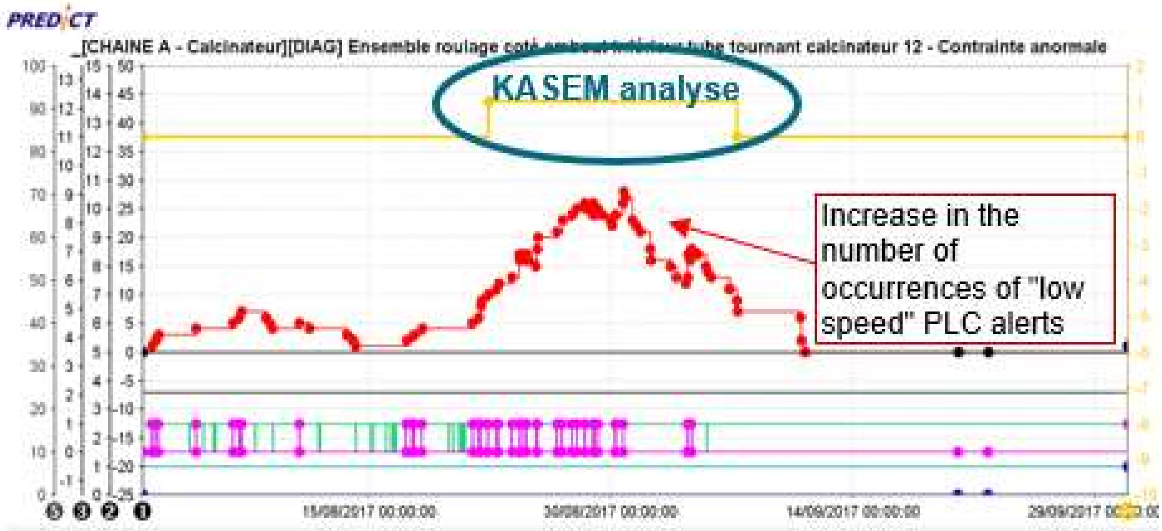


FIG. I–11. KASEM monitoring of health of equipment (courtesy of ORANO)

The minimum operating duration (MOD) of equipment subjected to corrosion can be estimated from the thickness available for corrosion (E) and the corrosion rate (Vcorr) of its most penalizing zone in terms of corrosion by following relation.

$$MOT\ MOD = \frac{E}{N\,Vcorr}$$

The thickness (E) is the difference between the initial nominal thickness and the useful thickness for mechanical strength (E_{lim}).

The factor N is the number of faces exposed to the corrosive environment (N = 1 if corrosion on one face, N = 2 if corrosion on both faces). For equipment subject to periodic thickness measurements (pressurized nuclear equipment for example), the corrosion rate is determined from the successive measurements carried out, according to the diagram. (Fig. I–12).

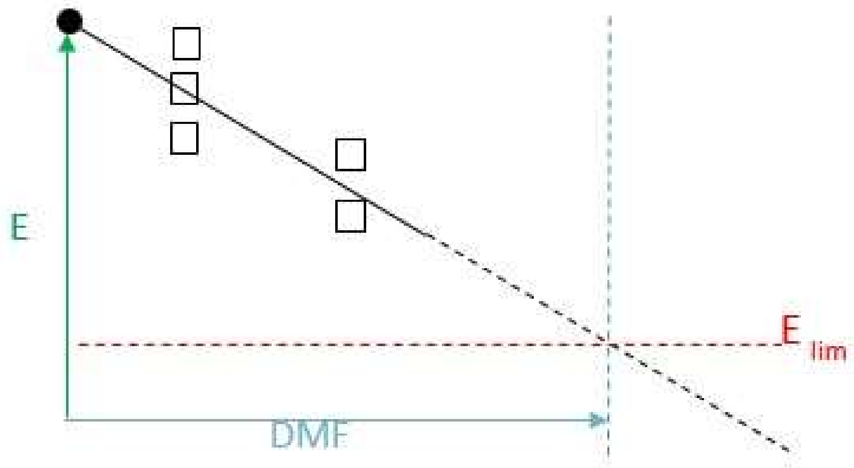


FIG. I–12. Minimum operating thickness (courtesy of ORANO)

I–6. CASE STUDY OF CORROSION IN FISSION PRODUCTS EVAPORATORS AT LA HAGUE, FRANCE

I–6.1. Introduction

The evaporators ensuring the concentration of fission products on the La Hague site, designed for an operating period of thirty years, were commissioned in 1989 and 1994. The first thickness measurements of this equipment were carried out in 2012 by ORANO at the request of Nuclear Safety Authority (ASN), as part of the first ten-year periodic review of the UP3–reprocessing plant. ORANO supplemented these measurements in 2014 and 2015. The results showed corrosion of the evaporators faster than expected during their design.

These results were likely to invite question mark on the safety of the facility in the medium term. Indeed, the resistance of this equipment to the pressure, heating circuits or to earthquakes could be called into question in the future and specially for the most degraded evaporator.

In view of these developments, ASN has decided to provide a regulatory framework for the continued operation of this equipment in 2016. Requirements have been imposed to the licensee on the following main issues for safety of these evaporators:

- Definition of criteria for the definitive shutdown of this equipment;
- Reinforcement of evaporator thickness controls (work to extend control areas, annual controls of sensitive areas, annual hydraulic test of the pressure resistance of heating circuits);
- Implementation of measures to limit the phenomenon of corrosion (limitation of temperature and pressure, measures to make solutions less corrosive, and regular rinsing);
- Reinforced monitoring of scheduled shutdowns for evaporator maintenance;
- Preparation for the management of an emergency resulting from the drilling of an evaporator;
- Transmission of a periodical report giving an account of the results of all these measures.

ORANO then implemented an action plan aimed at responding to the requirements of the authority for the existing evaporators and at sustaining the fission product concentration function by replacing the corroded evaporators and improving their resistance to corrosion, their accessibility and control.

I–6.2. Design and history

The evaporators, as shown in Fig. I–13 consist of a boiler (in which the solution of fission products is brought to a boil) surmounted by a plate column, where the vapors undergo initial decontamination. The heating of the boiler is ensured by water overheated to a temperature of approximately 145°C and a pressure of approximately 10 bars circulating in circuits made up of half-tubes welded to the external surfaces of the boilers.

FIG. I–13. Evaporator at ORANO UP–800 facility (courtesy of ORANO)

These evaporators were made of a stainless steel chosen by the operator having resistance to corrosion. During design, the operator also took margins for the thickness of the walls of the evaporators, to demonstrate their good resistance to earthquakes and the pressure resistance of their heating coils, even after corrosion. Evaporators are also located in individual reinforced concrete casemates, inaccessible to the personnel due to the high level of radioactivity.

The thickness measurements of the walls of the evaporators and in particular of the boiler were therefore carried out by means of poles articulated equipped with a measurement probe which are manipulated through one of the walls of the casemates. Only a limited part of the evaporators is thus accessible to measurement.

I–6.3. Replacement of the evaporators

The main measure taken was to replace the evaporators and place them in new buildings. The process and the buildings were designed to take into account latest safety requirements, new French regulation of nuclear pressure vessels and its control requirements including post-Fukushima lessons learned measures.

The measures taken to improve the service life of the new evaporators are as follows:

- Lifespan of approximately 30 years of operation and 3 years of rinsing;
- Increased corrosion thickness at the level of the boiler in contact with the solutions of fission products;
- Change in the design of the junction between the boiler and its cooling system;
- Increase in the frequency of the thickness measurements;
- Initial survey of thicknesses, internal and external surface conditions and welds;
- Control of corrosion by injection of a complexing chemical and determination of injection points for better efficiency;
- Monitoring of deposits and evolution of rinsing procedures.

The measures taken to improve the accessibility to the evaporators to control or repair them are as follows :

- 3D modeling of cells, equipment and access for maintenance;
- Modification of the layout of the pipes in order to make all the walls of the evaporators accessible;
- Optimization of endoscope sheath positioning using virtual reality;
- Development of corridors or intervention rooms around the cells containing the evaporators;
- Development of areas dedicated to in-service inspection;
- Installation of guide tubes for the internal visual inspection of the evaporators;
- Verification of the ability for inspection of the heating pipes (incoming and return lines, coils);
- Definition, development and testing of inspection tools (cameras, lighting, poles, US measurement.

The following Fig. I–14 shows in green the areas of accessibility to the external walls of the evaporators.

FIG.I–14. Evaporator accessible areas (courtesy of ORANO)

The safety of new evaporation units is enhanced by integrating regulatory changes, feedback from Fukushima and provisions for monitoring the ageing of evaporators into the design. Feedback is taken into account to make improvements in terms of safety, availability, monitoring, and durability of process equipment.

I–7. AGEING MANAGEMENT WITH RESPECT TO LIFE EXTENSION AT A FUEL CYCLE FACILITY AT BARC, INDIA

I–7.1. Introduction

It is of utmost importance to understand, analyse and manage ageing-related phenomena of the facility. Ageing in this context is understood to mean the changes in the characteristics and properties of mechanical components, electrical, I&C system and civil structure of the facility during service period. Unlike the civil structure, the other systems like mechanical, electrical and I&C can be replaced at any given point of time to extend the safe service life of the reprocessing facility. As no civil structure can be extended considerably beyond its design life, hence it becomes the controlling component for deciding its service life. The extension of the service life of civil structure can be achieved by regular surveillance and maintenance during its lifetime. Also, the assessment of healthy and strength of the civil structures needs to be determined by NDT and structural analysis after its design life. This information systematically can be used for taking adequate measures to extend their service life.

Good practices such as close monitoring of systems, structures & components, effective surveillance & preventive maintenance schedules, timely corrective actions and detailed root cause analysis for the failed equipment, systems and components help to improve ageing management programmes with increased plant availability, safety and reliability along with reduced man-rem exposure.

Performance analysis including trend monitoring of operating parameters of the system gives key inputs for further developmental activities which can help in increased performance as well as in reducing waste generation and its radiotoxicity. Effective ageing management programme gives process modifications, improved mechanical design of equipment, innovative practices, and implementation of state of the art technologies.

In one such experience, detailed analysis of a failed thermosyphon evaporator indicated that it was not only the design deficiency but also the probable cause of base metal failure was due to severe operating environment.

Decommissioning (partly or completely) of old facilities is also one of the most important activities of ageing management strategy as it plays an important role w. r. t. radiological safety of environment which depends on choice of decommissioning strategy and the strategy for execution. In one of its own kind of activity is in-situ fixation of an underground decommissioned civil structure where entombment can be a better option for effective decommissioning of the facility. This will result in reduction in personnel radiation exposure and the requirement of near surface disposal facility.

It is important to understand, analyse and manage ageing–related phenomena of the facility. If ageing management is addressed at each stage of a plant's lifetime, i.e. in design, construction, commissioning, and operation, it helps to increase plant availability, safety and reliability along with reduced man-rem exposure.

I–7.2. General philosophy for ageing management

Early identification of deterioration/failure of structure /component is the key for effective ageing management programme. The general philosophy adopted for both structures and components consist of following:

I–7.2.1. Condition monitoring

Condition monitoring involves assessing the functional parameters and condition indicators of the component and structure for detecting, monitoring and trending their ageing degradation. An assessment of the capability and practicability of existing monitoring techniques to measure these parameters and indicators with sufficient sensitivity, reliability and accuracy needs to be ensured. Periodic evaluation or review of monitoring methods based on the operational experience and research results are to be taken up for ensuring effective condition monitoring.

I–7.2.2. Periodic health assessment

Periodic health assessment gives valuable inputs for planning of preventive maintenance schedules which helps in avoiding any breakdown maintenance and thus increasing operational availability of the facility.

I–7.2.3. Data interpretation for predictive health assessment

Analysis of the database generated during periodic condition monitoring helps to analyze the overall health of the component and structure and also gives a measure of rate of its deterioration for planning of the further course of corrective action. State of art data evaluation techniques for recognizing significant degradation and for predicting future performance of the structure/component play a vital role for data interpretation.

I–7.2.4. Refurbishment/augmentation for enhancing safe service period/life

Corrective actions are based on the analysis of the database of the periodic health assessment of system, structure and component. The refurbishment, modification or replacement of the structure or component as a result of periodic health assessment of system result in extending the service life of the facility, as an outcome of an effective ageing management programme.

I–7.2.5. Regulatory control for safety during service period of the facility

Regulatory control on the operating facility plays a crucial role for the safe operation of the facility. Based on the guidelines (which are regularly updated) laid by regulatory authority for licensing of plant/facility need to be established for operation, safety, and ageing management. These are to be prepared and reviewed periodically by the facility. Regulatory bodies ensure implementation and effectiveness by various inspections and assessments. Periodic safety review of the operating facilities is one of such methodology, for granting the permission for regular operation of the facilities, carried out by regulatory bodies.

I–7.3. Ageing management of systems & components

Unlike the civil structure, the other systems and components like mechanical, electrical and I&C can be replaced at any given point of time to extend the safe service life of the reprocessing facility. Performance analysis including trend monitoring of operating and safety parameters of the system gives key inputs for further developmental activities which can help in increased performance as well as reduced waste generation, not only w. r. t. volumes but also the radiotoxicity.

Good practices such as close monitoring of systems & components, effective surveillance & preventive maintenance schedules, timely corrective actions and detailed root cause analysis for the failed equipment, systems and components help to improve ageing management programmes with increased plant availability, safety and reliability along with reduced man-rem exposure and costs. The surveillance of the components helps to identify deterioration / failure of the component at early stage. Periodic inspection of the critical component and continuous monitoring of the operating parameters gives indication of healthiness of the component. The master maintenance schedule for planning of preventive maintenance of all the critical components plays an important role in ageing management. The in-service inspection of the components helps to analyse its condition and rate of its deterioration. Timely replacement of component can avoid breakdown maintenance thus increasing the plant availability and reducing the man-rem expenditure.

In cases of breakdown maintenance like failure of equipment, the detailed analysis of the failure helps to improve the design and operating procedures to address the failure in future.

I–7.4. Few examples of component ageing management

I–7.4.1. Replacement of aged rotating equipment like exhaust fans in view of non-availability of spares and enhancement of capacity with state-of-the-art technology.

Obsolescence of SSCs i.e., their becoming out of date in comparison with current knowledge, standards and technology, calls for their replacement with state of the art technology. Aged rotating equipment having huge capacity and continuously operating for decades are one such example of mechanical system getting obsolete (Fig. I–15).

Effective ageing management programme gives process modifications, improved mechanical design of equipment, innovative assessment methods, standard operating procedures and implementation of state-of-the-art technologies.

FIG. I–15. Replacement of aged rotating equipment like exhaust (courtesy of BARC, India)

I–7.4.2. Failure analysis of Thermosyphon evaporator

Failure of equipment that needs replacement under breakdown maintenance not only reduces plant operating capacity but also results in higher personnel radiation exposure. Redundant process routes are hence provided to avoid such incidences. Thermosyphon evaporators are the most failure prone process equipment in backend facilities. As a part of ageing management programme for such failed thermosyphon evaporator detailed root cause analysis was carried out on all occasions that gave valuable inputs for improved designs, fabrication techniques and modified operating procedures. Pneumatic leak test, bisection of the heat exchanger for inspection of tubes, dye penetrant test for tube to tube sheet joint, and thickness measurement of the tubes was carried out during detailed analysis. Change of material of construction was also suggested as an outcome of the analysis after a thorough experimental research activity (Fig. I–16).

FIG. I–16. Tube thinning in failed TSE (courtesy of BARC, India)

I–7.4.3. Ageing management / Enhancing service life of civil structure

Unlike the mechanical/electrical components, life of civil structure cannot be extended considerably beyond its design life, hence it becomes the controlling component for deciding its service life. The extension of the service life of civil structure can be achieved by regular surveillance and maintenance during its lifetime. Also, the assessment of healthy and strength of the civil structures needs to be determined by NDT and structural analysis after its design life. This information systematically can be used for taking adequate measures to extend their service life.

Effective surveillance schedule helps in identifying signs of deterioration of civil structures at an early stage. Periodic health and strength assessment of civil structures is taken up by NDT and structural analysis during its design life, if need arises, that gives indication of condition monitoring and predictive health assessment.

Systematic analysis of these test results helps in planning of pro-active measures to extend service life. As per the analysis and predictive health assessment results, necessary repair / refurbishment of civil structure is taken up as timely corrective action for controlling the deterioration & enhancing the service life. Figures I–17 (a) and (b) show the pictures of the stack before and during the repair respectively.

(a) *(b)*

FIG. I–17. Structural repair of the stack (courtesy of BARC, India)

I–7.4.4. Developmental studies to improve performance

Based on the data collected during condition monitoring, periodic health assessment, system performance analysis and operating parameters trend monitoring, an improvisation of the existing structures, systems and components is carried out. Implementation of state-of-the-art technologies and innovative practices help in delaying the degradation of the systems and components.

Performance analysis including trend monitoring of operating parameters of the system gives key inputs for further developmental activities which can also help in increased performance as well as in reducing waste generation. Effective ageing management programme gives process modifications, improved mechanical design of equipment, innovative practices, implementation of state-of-the-art technologies. Following are such examples:

— Deployment of salt–free process to reduce radioactive waste volumes and their radiotoxicity;
— Partitioning of high-level liquid waste to reduce long term radiotoxicity of vitrified waste;
— Recovery of important radionuclides from HLLW for societal benefits.

—

I–7.5. Conclusion

The facilities in back-end fuel cycle are mostly radio chemical plants where the structures, systems and components are exposed to various types of chemicals as well as high radioactive environment. Hence, the deterioration of SSCs is much faster as compared to other facilities, demand a systematic ageing management programme to enhance the life without compromising the productivity, safety of plant and personnel. The operating experience feedback from operating plant plays an important role in ageing management and can ensure safety, reliability and rated capacity throughout the service life of a radiochemical plant and its life extension.

I–8 ASSESSMENT OF RISK, IMPACT ANALYSIS, MITIGATION & MIGRATION STRATEGIES OF OBSOLESCENCE OF CONTROL AND INSTRUMENTATION SYSTEM AT A FUEL MANUFACTURING FACILITY IN INDIA

I–8.1. Introduction

Due to various factors like technological advancements in electronics, software, network technologies & sensor technologies or due to changes in process or due to changes in regulations, the I & C systems become obsolete very fast. The most common examples are; newer PLC hardware, new versions in HMIs and SCADA, faster & newer communication technologies, development of new sensors with web enables servers and internet of things (IOT) for industry. The obsolescence is inevitable and affects safety, productivity, quality and efficiency.

I–8.2. Risk assessment

A risk management strategy is applied for the management of obsolescence of I & C systems and components. Initially, each component/subsystem needs to be categorized into grades of very high, high, and medium or low risk. The approach to ascertain the category has 3 steps i.e. i) categorization and listing of components, ii) shortlisting/removing items with spares availability or low consumption rate or which have equivalent functional replacement available and finally iii) to apply risk analysis to find number of components having very high risk. First find risk factor by carrying out a risk tree analysis i.e., better suited to a proprietary component, consumption rate, years to end of life (YTEOL), expected time till failure and spares availability (see Fig. I–18 and I–19).

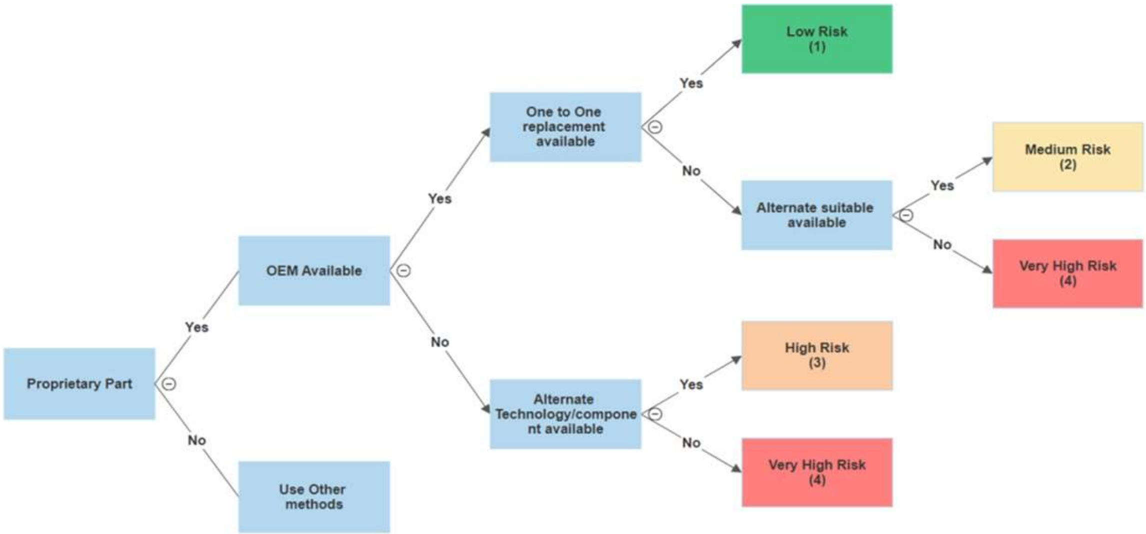


FIG.I–18. Risk analysis diagram (courtesy of NFC, India)

For non-proprietary items, the risk score P1 from 1 to 5 is assigned based on original equipment manufacturer (OEM) declared end of life and the next step is to calculate risk score P2; the probability of failure considering age of components, history, literature survey, manufacturer's data and duty cycle (utilization). Table I–7 gives the risk score based on years of failure.

TABLE I–7 Risk score

Years	< 1	2	3	5	7
Risk Score P1	5	4	3	2	1
Risk Score P2	5	4	3	2	1

The two risk factor K1 and K2 need to be calculated.

K1 is a function of probability of failure and YTEOL as shown in the matrix, where value 1 is for low risk and 4 is for very high risk.

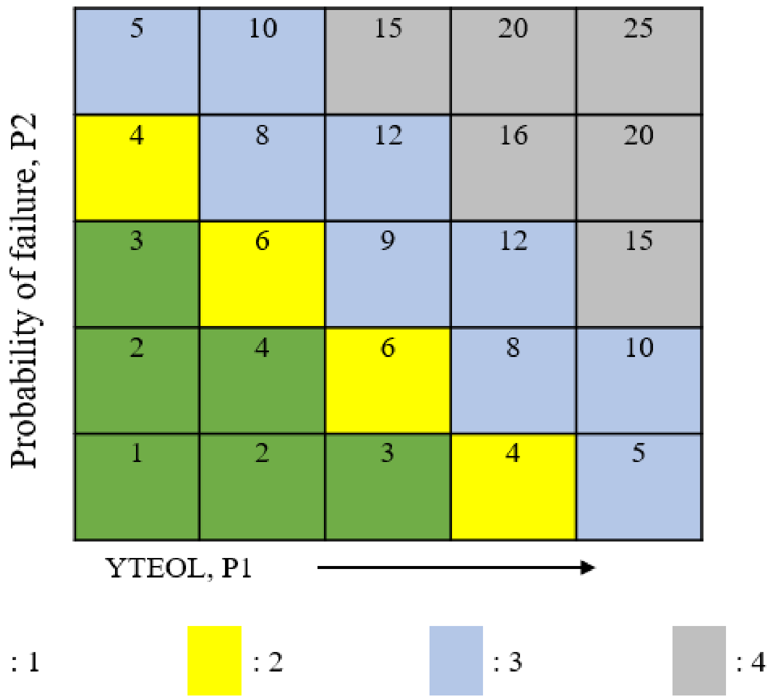


FIG. I–19. risk factor K1 (courtesy of NFC, India)

Risk factor K2 is based on consumption rate in Table I–8.

TABLE I–8 RISK FACTOR K2

Consumption Rate	Low	Medium	High	Very High
Risk Factor K2	1	2	3	4

Combined Risk Factor CRF is then found as sum of K1 & K are given in Table I–9:

TABLE I–9 COMBINED RISK FACTOR (CRF)

CFR, R	8>R>6	6>R>4	4>R>2	R < 2
Risk Factor K2	Very High	High	Medium	Low

Similar approach is used for strategy selection for reactive approach, pro-active mitigation and proactive migration. The weightage points are given for life expectance of plant, remaining life of equipment, number of alternate equipment available, number of high risk components (R), cost of migration, mean time to repair (MTTR) and mean time between failure (MTBF). The mitigation factor (M) is a sum of all these weightage points. Based on the value of this 'M' value a strategy decision on mitigation approach can be taken.

I–8.3. Refurbishing of I & C systems of a vacuum arc remelting furnace (VAR)

A VAR furnace was installed about 30 years back for fuel component manufacturing operations. The furnace had a number of control system components declared obsolete by

OEMs (see Fig. I–20). The described strategy was applied to the VAR control system and the decision was arrived for suitable migration. Accordingly, the system was revamped with latest PLC & SCADA based system, communication interfaces, and distributed racks with control loops erstwhile realized in electronic hardware moved to software-based loops. The exercise has given a fresh lease of life to equipment and improved the performance. The system's configuration will be periodically reviewed to ascertain the obsolescence and applicable mitigation strategies.

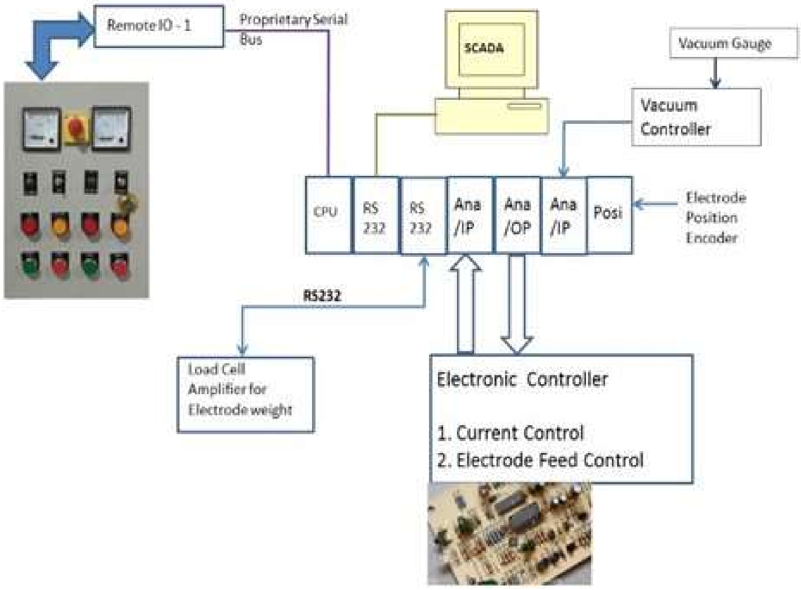


FIG. I–20. Control scheme (courtesy of, NFC, India)

Control systems of a pilger mill, since the vacuum arc furnaces are more than 30 year old, have suffered with problems such as difficult trouble shooting and logic modification, control system based on old card based controller, non-availability of proper documentation, non–availability of spares, difficulty in future expandability and interface not operator friendly. This was circumvented by revamping of control system with latest PLC & HMI based system. After revamping the system, the features available in the system are alarm generation and online diagnostics of PLC, logic modification can be done easily, modular structure of PLC has eased future expandability, documentation and spares are easily available (see Fig. I–21 (a) and (b)).

FIG. I–21. (a) Card based controller I/O(Old) (b)MCCP panel (courtesy of NFC, India)

In the pilger mills feed clutch engagement and dis-engagement leading to frequent breakdowns almost once in a week. Equipment availability reduced due to increase in down time of the mill. This problem was circumvented by installation of soft starter leading to smooth engagement and dis-engagement of the feed clutch. This change has resulted in improvement in clutch engagement and disengagement to increase the life of clutch and reduction in breakdowns of the mills.

Over five decades of operation, the fuel production operations in NFC, Hyderabad have been modernized through adoption of state-of-the-art control and instrumentation system for enhancing the safety of the production operations. Instruments with highway addressable remote transducer (HART) protocol communication for measurement of process parameters like level, pressure, temperature etc. coupled with remote operable valves have resulted in the development and implementation of process and safety interlocks in the production operations.

I–9. CASE STUDY OF LEAKAGE IN THE SS LINER IN THE ISSF CONNECTING CHANNEL IN BATAN, INDONESIA

Interim storage facility of spent fuel (ISSF), located in Serpong, has been in operation since 1998. The ISSF was designed to store the spent nuclear fuel in a water pool (wet storage). Currently, the spent fuel at the ISSF comes from the RSG-GAS in Serpong entirely, while the spent fuel from the Yogyakarta and Bandung research reactors is stored in a pond near each reactor.

In the current practice, the fresh spent nuclear fuel from the RSG-GAS research reactor will be stored temporarily in a reactor cooling pond, near the reactor for 100 days or more. Afterwards, the spent nuclear fuel is transferred to the ISSF through the transfer channel containing water and stored in a rack at the bottom of an ISSF pool. The transfer channel is also used to transfer the irradiated targets from the reactor to Radioisotope Installation (RI) facility and to transfer the spent fuel from reactor to the Radio Metallurgy Installation (RMI) and from RMI facility to the ISSF, as shown in Fig. I–22. The ISSF pool has a 14 m length, 5 m wide and 7.6 m depth. It was designed with a multi-barrier construction (SS–304 liner, walls, mild steel, and concrete). The transfer channel and storage pond are built with reinforced concrete having thickness of 29.5 cm, density 3.0 –3.5 g/cm3 and equipped with a liner made of stainless steel having a thickness of 3 mm on inside which functions as a confinement of demineralized water. This concrete tank is surrounded by a steel tank which is a secondary support. The steel tanks are supported by concrete and tankage and are structurally located.

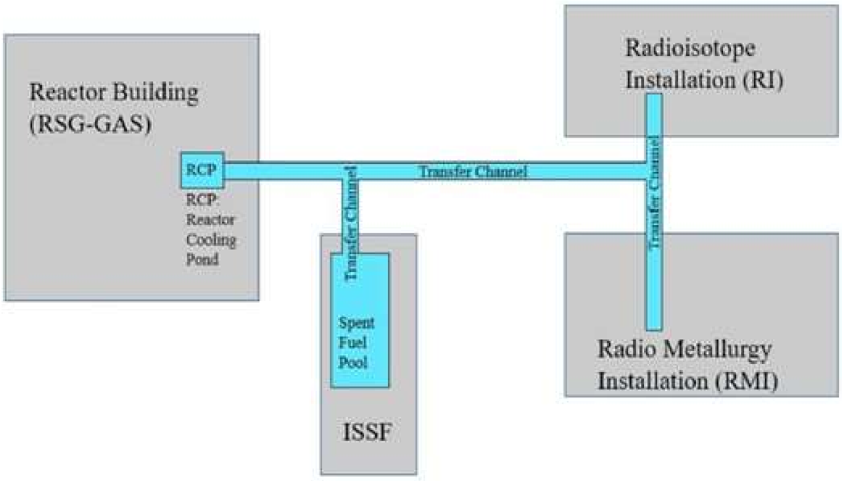


FIG. 1–22. Connections between the ISSF and the Serpong research reactor, RI and RMI facilities (curtesy of BRIN, Indonesia)

During the start of operation of the installation in 2007, several leak points were found in the connecting channel of the spent fuel storage installation. Storage ponds and connecting channel had been filled with demineralized water but had not been used for the storage of spent nuclear fuel. Before starting the detection of liner leaks in the connecting channel, the water in the pond and canal was drained out first. After the draining of water, the activity of detecting leaks in ponds and channel was started by using a dye penetrant test as shown in Fig. I–23. The visible dye penetrant is a non-destructive test with red dye test mark which aims to identify defects that occur on the surface of the test object as depicted in Fig. I–24 and I–25. This penetrant testing method uses the principle of capillary where this color dye will show the locations of discontinuities. From this test, 109 leak points on the channel walls and 236 leakage points on the channel floor were detected. The defect diameters varied between 2–10 mm especially at the welded joints. All welding defects in the liner were repaired using TIG welding and tested again with dye penetrant test.

This case study gives important feedback for fuel storage facility project managers and operators that quality assurance during welding of SS liners need to be very strictly adhered. The online leak detection system also provides the operator to take appropriate repair action before situation becomes un-manageable.

FIG. 1–23. Detection using Dye Penetrant test (curtesy of BRIN, Indonesia)

FIG. 1–24. Counting of leakage points in transfer channel (curtesy of BRIN, Indonesia)

FIG.I–25. Leak points marking

I–10. DATA DRIVEN ASSET MANAGEMENT AT SWEDEN FUEL OPERATIONS IN A FUEL MANUFACTURING FACILITY IN SWEDEN

I–10.1. Introduction

At Westinghouse Electric Sweden Fuel Operations (SFO), long term operation (LTO) of the nuclear fuel manufacturing facility is managed by the overall asset management process. The process includes several important programmes such as maintenance programme, Ageing management programme (AMP), design & construction process, project management process, Spare part process etc. The Asset management process makes it possible for all separate departments, units, and individuals to work towards a common goal where all contributions is pointed in a similar direction.

The facility is affected by customer and market variations as well as ageing equipment, new technology together with efficiency and quality requirements. To be able to adapt to short term variations without losing our long term goals, they are working with an asset management process based on data driven input and structured cross functional reviews. The very heart of asset management work is documented in 5–year plans equipment summaries named as workshop visions. These plans exist both as separate communication material for each of the areas of responsibility as well as an overview for the whole fuel factory. Information in these summaries support their long term target by increasing organizational awareness of current focus areas as well as preparations for the next few years (see Fig. I–26).

FIG. I–26. Overall process flow diagram (courtesy of Westinghouse, Sweden)

I–10.2. Cyclic and iterative process

To be able to work with our Asset Management process in a structured way, we use a yearly cycle with input and continuous actions from different parts of the organization. An advantage of this is that we also get an iterative process simplifying continuous improvements. The process is also implemented in our management system. We set the overall direction by our strategy work. This would be based on market and company strategy as well as regulatory and customer input (plant strategy). Also, major initiatives lasting for several years need to be accounted for. An example of this is efficiency improvement programmes or digitalization and automation initiatives. strategy work is carried out both globally, locally and for separate departments, units, and special areas. Locally they have a well-established process sharing and deciding of the upcoming years team missions and **K**ey **P**erformance **I**ndicators (KPI) and key focus areas including expected success factors. During the year there are several actions supporting asset management process, mainly these are data driven with input from our systems but also from our personnel in cross functional improvement teams. KPIs are available through business intelligence software connected to the systems.

For yearly asset management process (see Fig. I–27), there is a specific process called key business risk (KBR), which is reviewed every autumn. This gives an important input for next year's strategy work. In KBR, they look at major safety risks and potential impacts to the possibility to deliver according to plan and quality requirements. One example is lack of redundancy or risk for major shut down if certain equipment or system would breakdown.

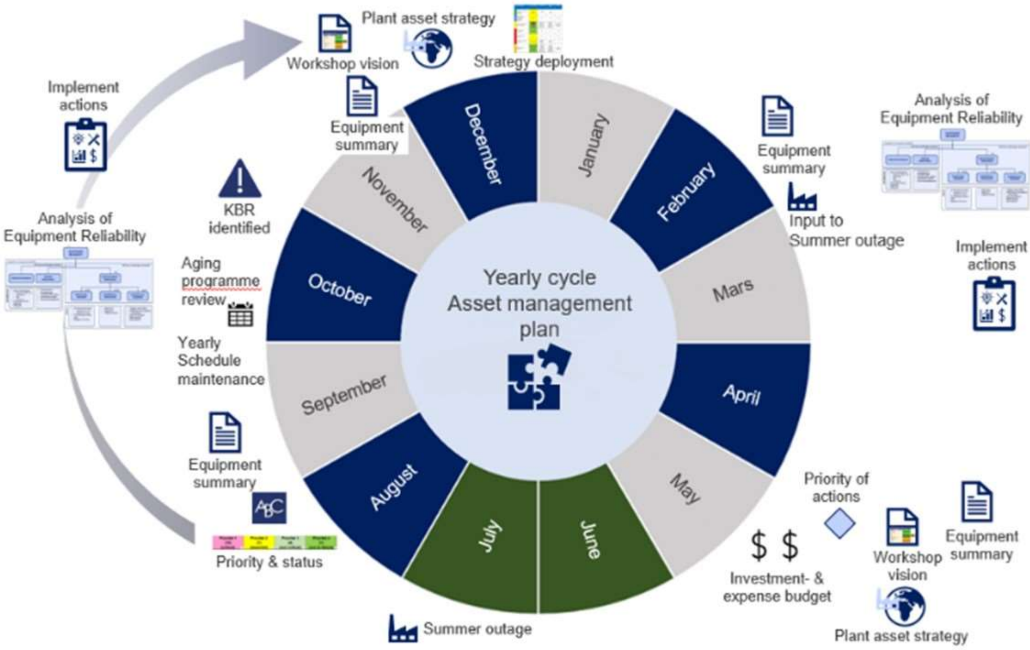


FIG. I–27. Yearly asset management process cycle (courtesy of Westinghouse, Sweden)

I–10.3. Data driven Asset Management process

Most of the data is collected directly from work order system, but for visualization purposes business intelligence software normally is used to simplify analysing and prioritizing activities. This gives a live update with the benefit that all personnel can share the current status view. One example of data driven input is that all systems and equipment have been categorized as A, B or C equipment based on status and requirement indicating what level of focus that is necessary from the organization. The base for this categorization is work order system data combined with cross functional structured reviews (Table I–10). The priority is given 1 for critical systems, 2 for essential systems, 3 for non-critical systems and 4 for non-critical and non-essential systems which can be run to failure.

TABLE I–10 PRIORITIZATION AND STATUS MATRIX COURTESY OF WESTINGHOUSE, SWEDEN

Priority criteria	**Status criteria**	**Prerequisites**
Capacity utilization Safety/environment Quality Nuclear waste Operation Bottlenecks/production flow Redundancy Remaining service life Essential “essential” (service system) Replacement of the system Reliability in performance	Trends in performance Preventive maintenance Relation planned and unplanned maintenance Corrective maintenance action time Preventive maintenance action time Spare parts Suppliers Education/skills Service tools/measuring equipment Service contract	Technical performance Operational performance - Functional reliability - Availability - Maintainability

To be able to implement the data driven asset management process, a major effort has been carried out in the field of data validation. Initially it was of great importance to explain the importance of correct data to the whole organization. It was also crucial that operators and technicians understood that their contribution in the work order system was important and actually was being used. An architecture of the dashboard of data driven asset management system is shown in Fig. I–28.

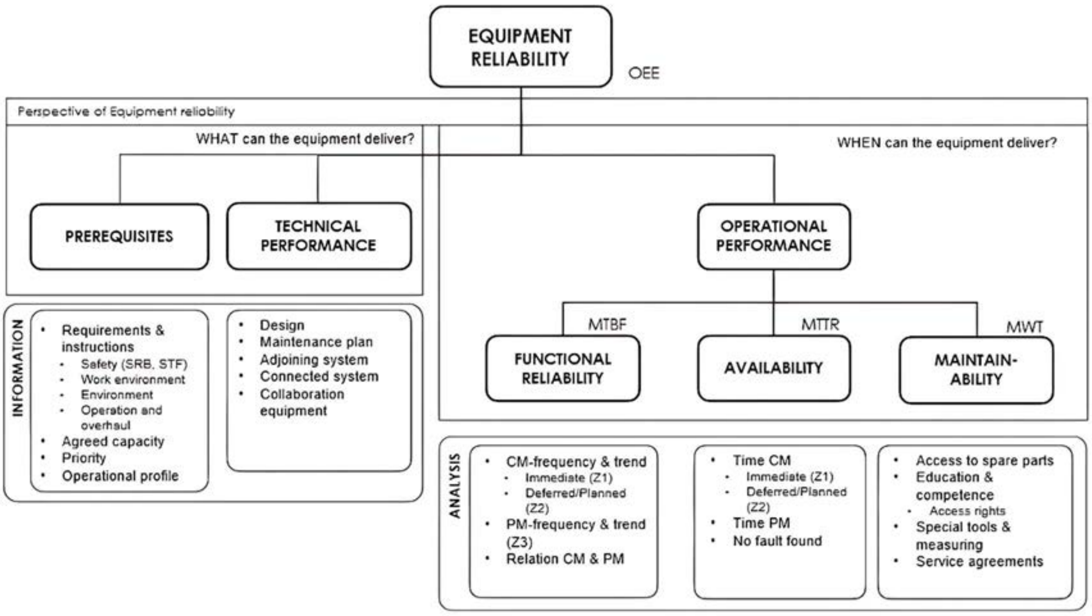


FIG.I–28. An architecture of dashboard (courtesy of Westinghouse, Sweden)

I–10.4. Communication and employee commitment

To summarize all data into status overview of the equipment we use extensive data compilations which is difficult to interpret even if you are a skilled engineer. These are called machine lists and consist of data regarding internal and external competence, spare parts, breakdowns, safety remarks, capacity requirements etc. To be able to share this status in a more populistic version we use a presentation file called workshop vision (Table I–11) based on RAG coding (**R**ed, **A**mber, **G**reen) including short comments and explanations. This is basically an overview of the workshop's status and asset management plan for the next five years. It includes both hardware improvements and identified need of focus in other more general areas such as safety, competence, resources, waste etc. These workshops visions exist for all workshops, special areas of responsibility and as an overview for the whole fuel factory. These workshop visions are intended to share information to all employees strengthening our journey towards our shared goal including increasing employee commitment before, during and after implementation of our projects and initiatives. The template of the workshop visions includes around 15 slides, but for every new version it seems to be a need for additional dat. Below there is a few examples from our workshop vision template.

TABLE I–11 WORKSHOP VISION TEMPLATE (COURTESY OF WESTINGHOUSE, SWEDEN)

Equipment	What characterizes the equipment in your area? Old, new, complex, automated, manual, standardized, unique…
Capacity	Describe current capacity and shift pattern. Are there any barriers present to deliver required capacity for production? What are these obstacles and what are their characteristics?
Plan forward	What investments and/or improvements will be made in your area in the coming years? What is the expected result from this? Will it increase capacity, increase reliability, increase automation, improve quality, improve work environment, improve safety…?
Previous year	What major events occurred in the area of operations in the previous year? Capital investments, major improvements, trend…?

I–10.5. Funding process

An important part of asset management plan and the yearly cycle is the funding process. Based on asset management plan and overall and local strategy a CAPEX (Capital Expenditure) plan is compiled. There details are compiled at least 5 years ahead and the accuracy and level of details are increasing around execution periods. The asset management process is the key for compilation and updating of the funding plans.

ANNEX II.
CASE STUDIES ON MODIFICATIONS, MODERNIZATION AND REFURBISHING FOR LONG TERM OPERATION

II–1. TECHNOLOGY UPGRADING OF NUCLEAR FUEL ASSEMBLY MANUFACTURING AT CNNFC, CHINA

This introduces development and upgrading of China North Nuclear Fuel Co., Ltd (CNNFC)'s nuclear fuel assembly production lines for four types of reactors, which include heavy water reactor CANDU–6, pressurized water reactor (AFA3G), AP1000 and high temperature gas cooled reactor.

II–1.1. CANDU–6 fuel

The annual production capacity of fuel is 200 tons of uranium. It would provide fuels for Qinshan heavy water reactor. The production line (Fig. II–1) began to be upgraded in November 2020 and completed in June 2021. The new fuel assembly is called 37M.

The advanced technology includes powder preparation using natural U_3O_8 powder as raw material, ADU wet process without denitration treatment, high activity UO_2 powder, the pellet preparation is done by optimized granulation process, equipment for integrating prepressing and granulation, automatic green billet loading and automatic grinding of pellets. For the fuel bundle assembly, a special equipment for end plug processing and graphite solidification has been developed to realize the efficient assembly of fuel bundles. The chemical production line and the assembly production line, use a newly developed automatic transfer system for material transfer which reduced the welding time in the rod bundle production process from 20 min to 11 min and the fuel element production efficiency was increased by 45%.

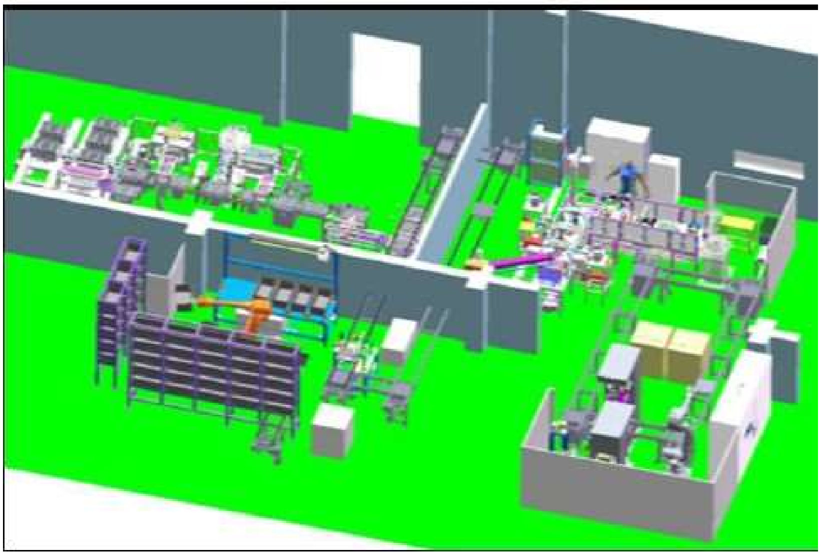


FIG. II–1. CANDU fuel assembly line (courtesy of CNNFC, China)

II–1.2. AFA3G Fuel fabrication facility

The construction started in July 2006 and began to operate in August 2009. The annual fuel production capacity is 200 tons of uranium. Since 2020, it has the production capacity of tube holders, grids, and gadolinium rods. It provides fuels for Qinshan, Fangjiashan, Tianwan, Fuqing reactors.

The technology advances include ADU wet process, UF_6 conversion, return material production, waste water treatment and independent IDR dry process, short production process, and high level of automation. A high efficiency mixing equipment of large capacity is used for uniform mixing of uranium and gadolinium. It uses ultrasonic welding process which produces no air holes, no inflation, no tungsten inclusion, and gives high production efficiency. The system has passive on-line detection of pellet enrichment having detection speed from 1.1m/min to 6.6m/min; uses a miniature probe with high signal-to-noise ratio, better linear correlation, higher sensitivity and system repeatability.

II–1.3. AP1000 Fuel fabrication

The construction started in March 2012 and began to operate in June 2017. The annual fuel production capacity is 400 tons of uranium with reserve capacity of 400 tons uranium expansion interface. It provides fuels for Sanmen, Haiyang reactors. The technology advancements include:

- High performance zirconium alloy ZIRLO™;
- Oxide film on cladding surface: improve corrosion resistance;
- IFBA pellet: UO_2 coated with ZrB2, 10B enrichment, Regulate reactor reactivity;
- Precision casting of socket: improve material utilization and reduce processing time;
- Expansion joint technology: no corrosion, simplified inspection process.

II–1.4. HTGR Fuel

The construction started in March 2013 and began to operate in August 2016.The annual fuel production capacity is 300 thousand Spherical fuel element. It provides fuels for Shidaowan reactors. The development was aimed at the transformation from experimental line to industrial production line (Fig. II–2). It has following characteristics:

- Spherical fuel: good fluidity, non-shutdown refuelling;
- Graphite matrix: high temperature resistant, large heat capacity, no core melting accident;
- UO_2 core: sol-gel process;
- TRISO particles: CVD, high temperature resistance, retain fission product release.

FIG. II–2. Automation in TRISO fuel production (courtesy of CNNFC, China)

II–1.5. Advanced Fuels

The development of high performance CF_4 fuel assembly for CAP 1400 is a breakthrough and key technology of manufacturing. The pilot assembly and PWR annular fuel pilot assembly are under commercial reactor irradiation test. The developments for accident tolerant fuel (ATF) for finalization of silicon carbide composite cladding and coated particle dispersion fuel, is under irradiation tests in commercial reactors. The development of spherical fuel element, for various types of fuel cores (UC, UCO, MOX, etc.) with high fuel consumption and high stability, and develop high performance spherical fuel element manufacturing technology is in progress.

II–1.6. Large Grain UO_2 Pellet

Experiments of adding U_3O_8, Al_2O_3 and aluminium di stearate were carried out. At present, the grain size can be increased to 8.5μm~10μm. It basically meets the engineering conditions, but it needs to be approved by all concerned before it can be industrialized and popularized.

II–1.7. Application of digital twins

In order to improve the accuracy of parts processing and assembly, and improve the mechanical performance of fuel assemblies, a digital twin integration method for equipment parts fault warning has been proposed. By using the digital twin technology in the processing process, the visualization of the processing process and the dynamic optimization of the processing technology are realized, and the processing efficiency is improved. Taking AFA3G lower tube socket as an example, the processing time can be shortened by 30% through digital twin technology.

II–2. MANAGEMENT OF LONG TERM OPERATION OF MOX FUEL FABRICATION FACILITY IN FRANCE

II–2.1. Introduction

The management of the life of a MOX Fuel fabrication Facility is managed at three different levels:

II–2.1.1. Investment level

The design needs to consider redundancy of lines and or equipment and the capability to have internal storages. It will allow to perform maintenance on each part of the plant without creating problems to the production. During the design a greater attention has to be given to remote control and automation of most activities.

II–2.1.2. Learn from experience (LFEs)

Either internal or external experience feedback management is an essential part, considering the events that have occurred in the installation but also in the uranium fuel plants or equipment suppliers. This process will help define the best practices.

II–2.1.3. Innovation and new techniques

A process is based mainly on new ideas or technologies and ensuring the modernizations of certain systems or parts of the installation. It will be supported by research and development aimed, for example, at finding new ways for cleaning up glove boxes.

II–2.2. MOX Fuel Fabrication Facility ageing process

Due to the toxicity and radiological behaviour of plutonium, all operations are to be conducted in gloves boxes (GBs) to confine the nuclear material away from the environment and personnel.

The technical issues concerned with ageing of MOX Facility are the following:

— Difficulties of access to equipment; doses are increasing and render maintenance difficult;
— Development of specific means of control (telescopic means, robots, specific non-destructive techniques and analysis);
— Ageing is mainly due to GBs dusting and material retention that will damage equipment, sensors, and all internal material;
— Leaks and powder dissemination;
— Equipment design needs to consider modularity and small parts concepts.

The ageing process is described in the following Fig. II–3:

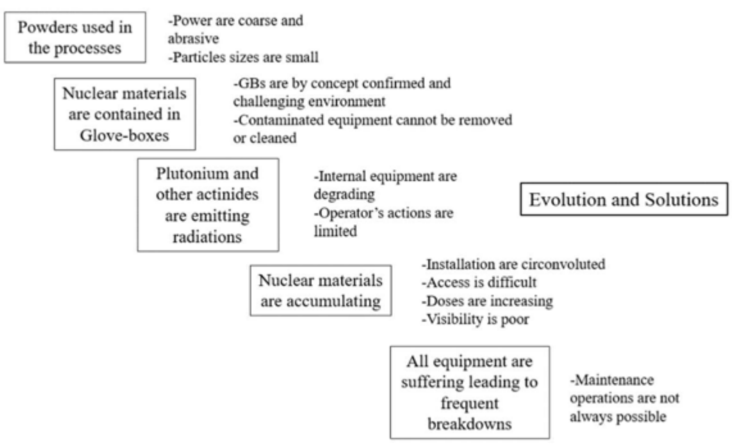


FIG. II–3. Ageing process flow diagram (courtesy of ORANO, France)

This ageing process need to be managed at the source by limiting the source of powder leaks and optimizing the design to facilitate operation and maintenance inside GBs. A cleaning device based on venturi vacuum system is shown in Fig. II–4 below.

FIG. II–4. Venturi vacuum system to clean GBs without mechanical parts or engine inside (courtesy of ORANO, France)

II–2.3. Lifetime extension project

After thirty years of operation, a new project, (GOMOX project), with independent funding, a multi-disciplinary staff and a mid-term agenda has been launched in order to define and implement what is needed to increase the production levels and extend the life of the plant strictly following safety and environmental protection rules and regulations. The project has a taskforce dedicated to innovative solutions for the medium and long term.

The project will work to increase redundancy and remove bottlenecks and thus improve maintainability by:

- Adding a new final dosing work-station;
- Adding a new homogenization work-station;
- Adding a new work-station for recycled material;
- Adding a new pelletizing press.

All the new workstations will include improvements and LFEs based on years of cumulated operation and maintenance. The project will also work to limit the powder leakage inside GBs by:

- Better confinement of powders inside vessels;
- Better joints and bellows;
- Dynamic confinement;
- Better lids and caps;
- Better detection techniques.

The project will also work to limit the radiation doses for the operators by:

- Use of modern robots inside and outside GBs;
- Increase the level of remote control and automation;
- Better decontamination and cleaning techniques fir the surfaces and material inside the glove-boxes.

II–3. MODIFICATIONS AND INNOVATIONS IN A FUEL FABRICATION FACILITY IN INDIA

II–3.1. Introduction

Nuclear Fuel Complex (NFC), Hyderabad, India started its fuel production operations in 1972 using technologies developed in Bhabha Atomic Research Centre, Mumbai. Over the years of operations, the fuel production operations have continuously evolved towards improving quality, productivity, and safety. Notable developments in powder production include development of oxidative dissolution, in-house development of slurry units, implementation of vapour ammonia precipitation, process intensification of solvent extraction, and implementation of direct reduction of ADU, etc.

In pellet fabrication, the adoption of high performance tooling, adoption of organic admixed lubricant for compaction of uranium oxide powder, individual machine level automation and line-based automation systems like automatic stacking and loading system have been implemented for improving the quality, productivity, and consistency in production processes.

Automation has played a key role in the assembly fabrication process. Over the years, state of art automation systems like automated appendage welding units, automated end cap welding unit, robotic end plate welding systems etc. have helped in achieving high productivity and consistent quality. On par with production activities, automation in quality assurance activities is also contributing towards achievement of ‘zero defect’ target. State of art automations like automatic pellet density measurement system, automatic UT of fuel elements and fully automated bundle inspection system have been deployed in the production line. Automation helped in reducing manual operations leading to increased safety, reduction of radiation exposure to the personnel.

II–3.2. Innovations in Testing Methods

The fuel bundles produced are subjected to 100% helium backfilling, helium leak testing, dimension measurement and visual inspection prior to their dispatch to reactor sites (Fig. II–5). These operations were being carried out manually which is strenuous and manpower intensive as the fuel assemblies weigh around 23 Kg each. In order to overcome these problems, a robot aided fuel bundle handling and inspection system (Fig. II–6) was introduced in place of manual system.

FIG. II–5. Tubular Helium back filling chambers (courtesy of NFC, India)

The new system has provided following benefits:

— Enhanced the inspection throughput by 500 % when compared to manual testing;
— Introduction of helium recirculation has brought down helium consumption rate by 900%;
— Elimination of the human based judgment errors;
— Database software has eliminated manual record keeping and provides faster report generation;
— Reduced human strain and monotony.

FIG. II–6. Robot aided Fuel Bundle handling and inspection system for 700 MWe PHWR fuel (courtesy of NFC, India)

II–3.2.1. Ultra-sonic end cap weld scanning unit

At NFC every year, over 3 million end cap welds are evaluated for weld integrity. Manual ultrasonic testing (UT) of these welds requires large skilled manpower and is also time consuming. The reliability of the results is highly dependent on the operator skill in precisely indexing the probe, rotating element, and evaluation of the UT signal.

An automated high speed end cap weld ultrasonic testing (UT) was developed in-house and put into use. A PCI based ultrasonic card was used for ultrasonic testing purpose. Defect detection software was developed by considering defect echo amplitude and time of flight (TOF) measurements. A customized graphic user interface (GUI) was developed for database and report generation. The entire operation is controlled by a PLC based system (Fig. II–7).

Advantages over manual ultrasonic Testing are:

— Increased reliability.
  - Precise probe movement in defined steps will ensure coverage of entire circumference of end cap weld region;
  - Automatic signal capturing ensures capturing of all defects crossing the threshold region.

These two features completely eliminate manual errors thereby assuring the quality of outgoing product.

— Increased productivity;
  - The total cycle time for completing one element inspection (both ends) in auto UT system is 16 sec. as compared to 60 sec. (for checking both sides) in manual UT system there by increasing the productivity.

— Operator independency;
  - Test results are independent of UT operator's skill & experience.
  - Repeatability; test results are repeatable within ± 5 % total FSH.

— Result recording & report generation. (Record of signal data for individual elements can be saved and reported).

FIG. II–7. Ultra-sonic end cap weld scanning unit (courtesy of NFC, India)

The introduction of automated testing procedure in place of manual testing helped to avoid human error, enhanced productivity besides minimizing the effects of ageing. These include automated ultrasonic testing (UT) system (refer Fig. II–8) for pressurized heavy water reactor (PHWR) fuel elements, automated bundle inspection system, automated clad & Zr component inspection system (Fig. II–9) and automated pressure tube inspection system.

FIG. II–8. Automated UT system (courtesy of NFC, India)

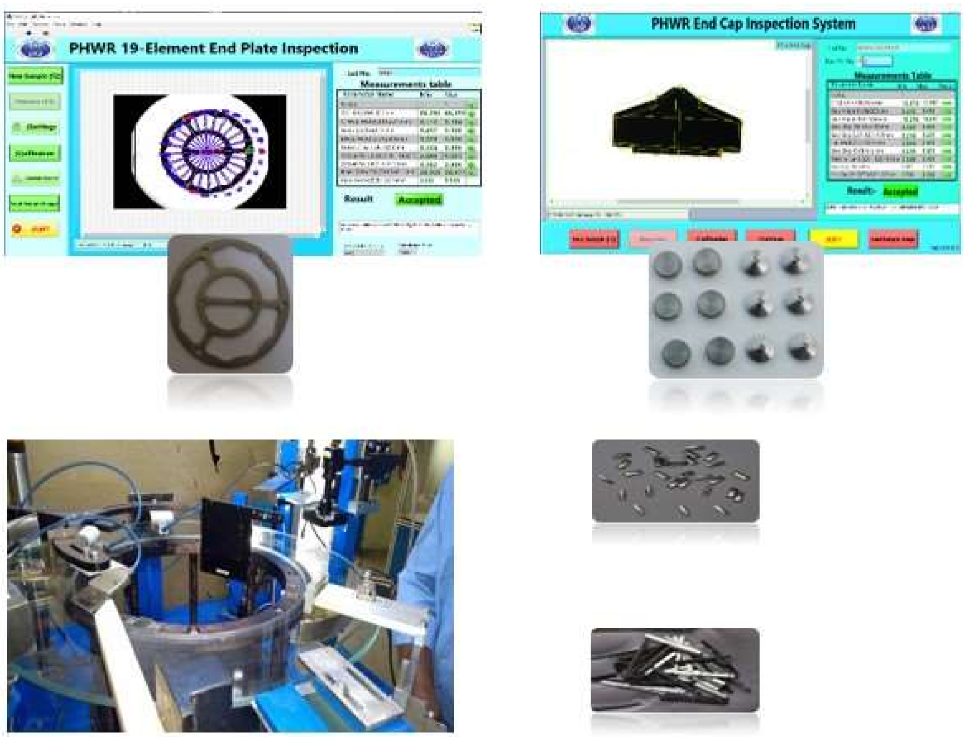


FIG. II–9. Automated machine vision system for end plates, bearing and spacer pad (clockwise) (courtesy of NFC, India)

II–3.2.2. Automation in fuel production

The need for automation in industrial scale fuel production operations towards attaining zero failure target with stringent and rigorous quality checks is well acknowledged. Automation in the day-to-day operations helps in minimization of ageing effects. Automation have been adopted in fuel production operations in NFC to improve productivity, quality, process and radiological safety. Many of the operations in the areas of material transfer methodologies, material inspection methods and production processes that have been implemented at NFC and are described in following paragraphs.

PLC SCADA based automation system has been adopted for conversion of uranium raw material to sinterable grade UO_2. Machine level automations have been adopted in pellet and assembly fabrication operations. Bundle manufacturing and inspection operations are fully automated and are carried out using multi-axis robots. Several material handling operations have been automated using advanced systems like automatic guided vehicles (AGVs) (see Fig. II–10) for reducing the radiation exposure of operating personnel. AGVs offer greater flexibility and less obstruction on the shopfloor.

FIG. II–10. Automated Boat Transfer using AGV (courtesy of NFC, India)

The sintered pellets need to be grounded to meet specification for diameter because of having an hourglass type of effect after sintering, caused by the poor compressibility of the UO_2 powder. Grinding of the sintered uranium dioxide pellets is accomplished by using centreless grinding (CG) machine. The manual operation of feeding of sintered uranium dioxide has been replaced with automated pellet feeding and this has resulted in the operational ease along with improved productivity.

Introduction of automated welding operations of pre-welding, end cap feeding, end cap welding and element machining operations (Fig. II–11 (a) to (d)) in an integrated mode in the place of manual handling have resulted in significant enhanced productivity.

(a) Tube machining

(b) End cap feeding

(c) End Cap Welding

(d) Element Machining

FIG. II–11. Automation in machining (courtesy of NFC, India)

II–4. TECHNICAL CHALLENGES AND MODERNIZATION IN THE FABRICATION OF LWR FUELS AT TVEL, RUSSIAN FEDERATION

Fuel manufacturing facilities in Russian Federation produce nuclear fuel and fuel components for power and research reactors and feed more than 70 power reactors and 30 research reactors in thirteen countries. The chain of engineering, supply and service of the nuclear fuel have been developed in the long term which include a number of the leading Russian and foreign companies, and an international business infrastructure, which ensures secure, uninterrupted support for the operation of nuclear reactors.

Security of supply is provided by reservation of capacities. TVEL has four enrichment facilities and two fuel fabrication facilities. TVEL also practices technology transfer wherever feasible. For example, VVER fuel is also fabricated to TVEL designs in China for their local NPPs.

Continuous development and improvement of nuclear fuel designs and processes has been achieved by building long term relationships with several leading design companies in Russia that have a high international profile, including, where appropriate, elements of competition. This reasonable balance of integration and diversification of value chains provides a broader and more comprehensive asset management, covering a whole range of production areas and engineering solutions. This allows for the concentration of resources and ensures a broad exchange of the best practices resulting in an enhancement of the corporate knowledge base.

The pellet design has been based on larger grain size within the standard UO_2 specification reducing the fission gas release during reactor operation at high burnup. These characteristics have been proven by decades of successful in-core performance in reactors of various fuel designs.

Nuclear fuel manufacturing is done under the system of regulations ranging from inter-governmental agreements and basic national legislation to contracts and process documents as shown in Table II–1. The system is covering the whole life cycle of production facilities.

TABLE II–1. BASIC DOCUMENTS CHART FOR THE LIFE CYCLE OF THE FABRICATION EQUIPMENT

<table>
<tr><th>Functional area</th><th>Design and procurement</th><th>Manufacturing, delivery, installation and commissioning</th><th>Operation</th><th>Maintenance</th><th>Decommissioning</th></tr>
<tr><td rowspan="2">Documents of the subsidiaries</td><td colspan="5">Contracts, process documents, etc</td></tr>
<tr><td colspan="5">Regulations of subsidiaries</td></tr>
<tr><td rowspan="2">Fuel division regulations</td><td colspan="2">Process engineering, Procurement, supply chain management</td><td>Manufacturing</td><td colspan="2">Maintenance and repair, outsourcing</td></tr>
<tr><td colspan="5">Technical policy, Quality manual</td></tr>
<tr><td rowspan="3">Organisation regulations</td><td>Requirements Management policy</td><td colspan="3">Cost management</td><td>Guidelines for decommissioning of nuclear installations</td></tr>
<tr><td colspan="5">Standards for procurement</td></tr>
<tr><td colspan="5">Regulations for quality management system, non–conformance management policy</td></tr>
<tr><td rowspan="2">International and National standards</td><td>GOST2(design documentation),
GOST15,
GOST R 15
(development and production set up)</td><td colspan="2">GOST 3 (Process documentation)</td><td colspan="2">GOST 18322–2016
(Maintenance)
GOST 27.002–2015
(dependability in techniques)</td></tr>
<tr><td colspan="5">Standards of GOST and ISO series for quality and labour protection</td></tr>
<tr><td rowspan="3">Russian Federal legislation, International legislations</td><td colspan="5">Technical regulations of the Russian Federation and EACU</td></tr>
<tr><td colspan="5">Nuclear and radiation safety requirements
НП–016–05, НП–063–05 (safety of NFC sites);
НП–090–11 (quality assurance for objects using nuclear energy);
НП–091–14 (safety at decommissioning of nuclear installations);
НП–071–18 (conformity assessment);
НП–057–17 (safety at decommissioning of NFCFs);
НП–038–16 (safety of radioactive sources);
НП–058–14 (safety engineering at radioactive waste management); etc</td></tr>
<tr><td colspan="5">Convention on Nuclear Safety, 1994;
Federal Law on the Use of Atomic Energy, 21.11.1995 No. 170–Ф 3;
Federal Law on the Radiation Safety of the Population, 09.01.1996 No. 3–Ф 3; etc.</td></tr>
</table>

All operations are done under ISO and NQA–1 quality system. In general, the integrated management system allows for flexible customization of the product and supporting processes to meet the particular needs.

The technical policy towards the life cycle of fabrication equipment is based on the following principles:

- Comprehensive management of condition and advancement of the technical systems;
- Minimization of total cost of ownership;
- Continuous rhythmic and coordinated advancement of processes;

— Refreshment and modernization of fixed assets in accordance with the Russian and global best practices;
— Unification of processes and technical solutions, unification of the new equipment with the operable;
— Application of modern methods of maintenance and repair of equipment;
— Absolute priority of stable quality and safety of manufacturing.

There are two fuel fabrication facilities; MSZ (Elektrostal) plant, which was founded in 1917, and NCCP (Novosibirsk) plant founded in 1948. During their lifetime, they underwent a number of significant rearrangement and upgrades. The latest upgrade of fabrication facility in Elektrostal had been carried out in 2019. The plant in Novosibirsk has completed refurbishment in 2021 including commissioning of series production of TVSK fuel for PWRs. The completed projects resulted in the reduction in production areas and optimization of a number of operations, which led to significant savings in inventories. The automation of some operations led to a decrease in the influence of the human factor on production.

Automation of pellet inspection is aimed at eliminating inspection by operator using glove boxes (Fig. II–12 and 13). A result was a significant improvement in performance at this production area and elimination of the inspection quality dependence on the operators.

FIG. II–12. Automated circumference inspection (courtesy of TVEL, RF)

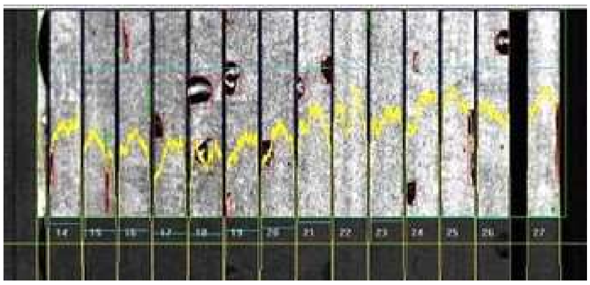


FIG. II–13. Examples of defects on circumference (courtesy of TVEL, RF)

Inspection is carried out using video cameras that perform high speed shooting of the pellet at circumference and at end faces.

The modernization of the pellet loading in container area was aimed at reducing the risk of pellet damage during movement to the fuel rod production area and at reducing the amount of work in progress (see Fig. II–14 (a) to (c) below).

(a)

(b) (c)

FIG. II–14. Automated loading on pallets into containers (courtesy of TVEL, RF)

The renewal of the fuel rod production lines was aimed at reducing the number of movements of the components and finished products. As a result, compact high performance automated fuel rod production lines have been built at both facilities. Fuel rods for VVER–440, VVER–1000 and VVER–1200 reactors, as well as PWR 12 ft and 14 ft can be manufactured at these lines (see Fig. II–15).

FIG. II–15. Fuel rod production line (courtesy of TVEL, RF)

Automated fuel rod production lines include the state-of-the-art production and inspection systems that ensure fuel rod fabrication from feeding the fuel rod cladding to the line to packing the finished fuel rods into a transport container.

Quality control is carried out at each stage of fabrication enables making sure of the required quality of a fuel rod, in compliance with the specification requirements.

Assembly components that are part of the fuel assembly are produced at special benches. Fuel assemblies (FAs) are assembled at the assembly lines, where, along with the special benches, automated systems are used to ensure the accurate mutual arrangement of the components during assembly (Fig. II–16). When organizing workplaces for the manufacture of skeletons, assembly, inspection and packaging of the fuel assemblies, the principle of a single process flow (sequence) with the pellet loading line is implemented.

FIG. II–16. Combined manufacturing line for fuel rods and fuel assemblies (courtesy of TVEL, RF)

The upgrade programmes were aimed at feeding the rapidly growing global VVER fleet and increasing demand in the PWR market. The next stage is introduction of ATF solutions, production of higher efficiency fuel (providing for longer cycles, up to 24 months) and establishment of remote fabrication for U-Pu fuel.

Management of the equipment life cycle is based on the following principles:

- Use of reliable and high performance equipment from domestic and international OEMs;
- Exchange on experience and best practices with peers in global nuclear industry and other industries;
- Introduction of TPM (Total Productive Maintenance) methods for maintenance and repair of equipment;
- Increase of equipment dependability and period between overhauls

The equipment reliability is increased by selection of efficient materials and parts, advancement of processes, monitoring of equipment condition in operation, performance, time in service and predictive maintenance.

II–5. LONG TERM OPERATION EXPERIENCE AT A SNF REPROCESSING PLANT IN RUSSIAN FEDERATION

II–5.1. Introduction

Plant RT–1 is located in Ozyorsk, Chelyabinsk region. SNF reprocessing was commissioned on March 29, 1977. Till the present the plant has been operational for 45 years. With the commission of RT–1, implementation of closed fuel cycle has started in Russia. The plant design reprocessing capacity is 400 t heavy metal (HM) per year. Till now, more than 6600 t HM of SNF has been reprocessed and more than 1200 transportations of SNF and nuclear materials have been made safely.

The main feature of RT–1 is a wide range of SNF types that can be reprocessed, and RT–1 is reprocessing fuels from:

- Nuclear power plants (NPPs);
- Research reactors (RRs);
- Small modular reactors (SMRs).

The main production line in RT–1 comprises units for spent fuel receipt and storage, removing end-pieces, grinding and dissolution, filtration, chemical separation of the fission products by PUREX–process, with further uranium and plutonium extraction, vitrification of high-level radioactive waste. There are three universal technological lines at RT–1, which also allow to combine reprocessing of different types of SNF. The RT–1 end product are:

- Low to middle enriched uranium;
- Plutonium dioxide;
- Radioisotopes.

Reprocessed uranium is sent for nuclear fuel production. Plutonium is partially used for fabrication of MOX fuel for BN–800 reactor. In the course of doing so, RT–1 is continuously developing technologies, improving hardware design, technological schemes, production and process organization. A chronology of developments at RT–1 has been shown in Fig. II–17. The main areas of developments at RT–1 are:

- Improving the reprocessing stability;
- Safety operation, reduction of radiation exposure of plant staff and environment;
- Increasing the reprocessing capacity;
- Cost reduction.
- Minimization of volumes and improving efficiency in radioactive wastes management.

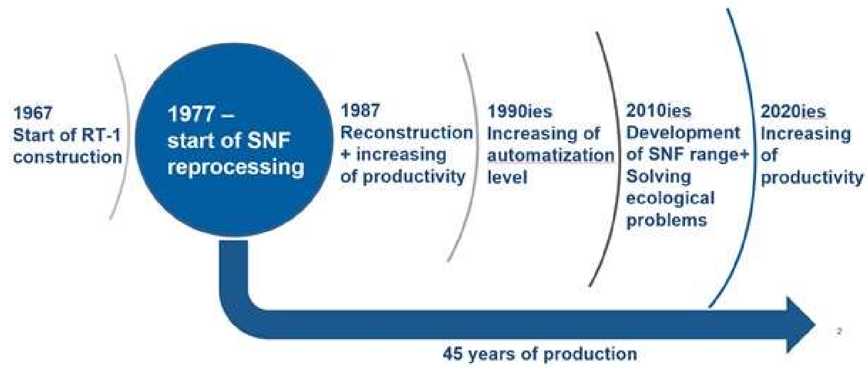


FIG. II–17. Milestones of RT–1 (courtesy of ROSATOM, RF)

II–5.2. Modifications

The most revolutionary modifications in plant technology were made during 1986–1988. At that time significant renovation of the plant was done. The commissioning of the third technological line improved the reprocessing capacity to 400 t TM per year. This line was specialized in NPPs SNF reprocessing and at the same time modernization of extraction unit was done. The commissioning of vitrification unit was done in 1988. At the same time, third technological line had reached the design capacity.

During development of the third technological line, all the shortcomings identified during operation of first and second lines, have been rectified. It has much improved layout for larger volumes handling and improved transport and technological systems, and significantly changed design of equipment.

At the same time the first and second technological lines have undergone a major refurbishing in the late 1980’s. Design of many equipment were changed for similar equipment of the third technological line. The main changes were made in head end and extraction units of the reprocessing plant. The modernization features were the following:

- Implementation of new technologies, aimed at increasing the sealing degree of systems;
- Improving the stability of equipment operation;
- Simplification of complex equipment, with no loss in quality and safety;
- Demolition of unused equipment, for simplification of maintenance.

For example, a procedure for insoluble spent fuel assemblies’ residues, which goes to dissolution tank after grinding, was changed. Before 1987, it used to be transferred to special canisters for which it required constant attention to technological process and high level of staff qualification, to avoid hulls scattering. In that case staff had to remove it in short time to provide an acceptable level of radiation exposure. During the plant refurbishing, new sealed system was developed, installed, and commissioned. It allowed to remove shells from dissolution tank to special storage by sealed tube system. In the following years this process was fully automated. Today an operator only starts and monitors the process. This made it possible to unload staff, reduce staff’s radiation exposure, and improve the reprocessing stability. It also improved the unit and the plant reprocessing capacity.

Automation has been developing steadily and in 1990’s, the rate of automation has significantly increased. Today main part of technological processes at plant are fully automated. This made it possible to reduce manpower, improve technological process control and therefore improve the reprocessing stability, increase resistance to external influence. Some of the examples of automation are shown in Fig. II–18 (a) and (b).

FIG. II–18. (a) Canisters for spent fuel (b) Sealed system (courtesy of ROSATOM, RF)

The safety monitoring was significantly automated for grinding, nuclear materials accumulation in dissolver and technological tanks, movement of nuclear materials in extraction systems, and formation of third phase in extractors.

The nuclear safety in production has always been the most important and a priority. Accuracy of calculations has been improved and neutron absorbers (gadolinium, boron, cadmium) were implemented. Important role in safety has always been given to fire and explosion safety. A number of safety rules have been developed for methods of handling sorbents accumulating radioactive substances. Safety of working with organic materials, which have a radiation decomposition, was increased. Safety criteria and parameters of storage of SNF and radioactive waste solutions were determined.

Due to this implementation, the radiation exposure of staff was reduced, as well as the reduction in number of plant personnel. Average effective dose is several times less than the normal (Fig. II–19).

At the same time, the reliability of equipment has increased. For example, the reliability of the grinding machine has increased two times and similarly for auxiliary productions (supporting systems). For an optimal design, it takes from 3 to 4 generations of equipment for developmental changes.

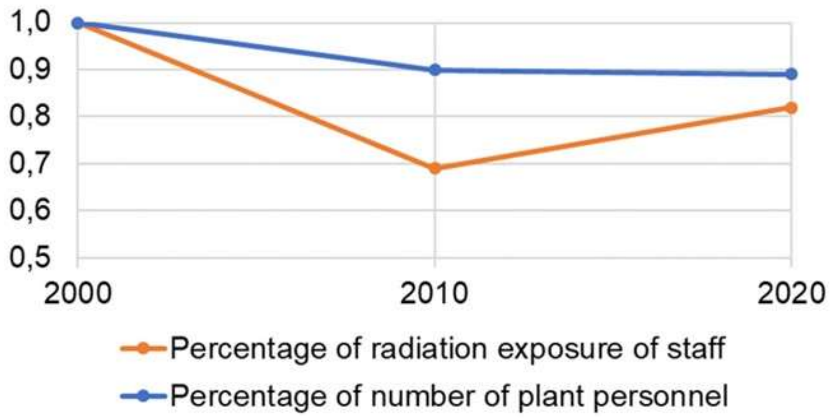


FIG. II–19. Percentage of radiation exposure and number of plant personnel (courtesy of ROSATOM, RF)

Most of the equipment at first zone (hot cells) have been working for decades. The equipment like pipelines, valves, and tanks use corrosive and non-corrosive chemicals. Most of the pipelines and valves did not require replacement since commissioning. All these equipment have undergone regular examinations and tests in accordance with the requirements of regulatory documents.

For the plant lifetime period, a certain frequency of replacement of filter elements of gas cleaning equipment have been developed. It is based on the data from equipment control devices and control of atmospheric releases. It allowed to organize the plant production plan and unify repair period for the whole plant, and the units during which the staff can organize inspection and repair of all major equipment without loss of performance. Today RT–1 is a modern plant, and it plans to increase the reprocessing capacity, to develop partitioning of HL RAW.

II–6. ADVANCED FUEL MANUFACTURING READINESS LEVEL AT THE SOUTH AFRICAN NUCLEAR ENERGY CORPORATION

II–6.1. Introduction

In 1978, the United States took the lead in initiating a programme, Reduced Enrichment in Research and Test Reactors (RERTR), to help provide the capability for research and test (non-power) nuclear reactors to convert from the use of high enriched uranium (HEU) to low enriched uranium (LEU) fuels . It is important to note that world's operating non-power reactors could have all successfully made the conversion with fuel types that were technically feasible at that time. However, higher powered and higher performance reactors were never designed for possible LEU usage. Therefore, a fuels review and development programme was initiated to provide the capability for more of these reactors to convert without serious detriment to their research projects. Under that programme, established at the Argonne National Laboratory (ANL), a dispersion type fuel containing uranium silicide in aluminium were developed and tested. The fuel provides a total uranium concentration significantly higher than that previously available in the plate geometry. The fuel has proven capability of maintaining a concentration of ^{235}U that is sufficient for operational use in non-power reactors at a ^{235}U enrichment that is as low as 20 percent.

II–6.2. Technology Development

Before a process can be developed, the desired product needs to be understood. The outcome of the qualification process is the information needed to convince regulatory bodies and reactor operating organizations that the new fuel can safely be used in a specific research reactor. The current fuel design is dispersed silicide fuel (U_3Si_2) in plate forms that have been assembled using aluminium cladding and machined material (see Fig, II–20 below).

U_3Si_2 fuel, was developed following the 9 levels of technology readiness levels (refer Table II–2) until it was demonstrated that the fuel can safely be used through an irradiation programme. This is then followed by manufacturing readiness level where the fuel manufacturer demonstrates that the fuel can be manufactured routinely in the right quantity and with right quality.

Technology readiness levels (TRLs) are a method for understanding the technical maturity of a technology during its acquisition phase. TRLs allow engineers to have a consistent datum of reference for understanding technology evolution, regardless of their technical background.

FIG. II–20. Dummy fuel assembly (courtesy of NECSA, SA)

TABLE II–2 TECHNOLOGY READINESS LEVELS

Technology readiness level	**Action**
TRL–1	Basic principles observed and reported
TRL–2	Concept and/or application formulated
TRL–3	Concept demonstrated by analysis and/or experiment
TRL–4	Key elements demonstrated in laboratory environment
TRL–5	Key elements demonstrated in relevant environment
TRL–6	Representative deliverables demonstrated in relevant environment
TRL–7	Final development demonstrated in production environment
TRL–8	Product qualified for test and/or demonstration
TRL–9	Product manufacture is routine and quality level is repeatable

II–6.3. Roadmap to HALEU

SAFARI–1 was converted to the use of HALEU in 2011 after successful irradiation of four lead test assemblies (LTA). The HEU elimination in research reactors started in 1978 and first U_3Si_2 fuel was delivered to Oak Ridge Research Reactor (ORR) in 1983. After those tests, a safety evaluation report by ANL (NUREG–1313)[1] was submitted in 1988. In 2006, the lead test assemblies were supplied for SAFARI–1.

II–6.4. Key fuel properties

Fuel properties were defined based on the study in reference [1]. The defined properties are paramount to the establishment of the required fuel specifications. The specifications requirement as given below led to a qualification programme which was agreed with the manufacturer of the LTAs:

- Fuel core porosity;
- Heat capacity;
- Thermal conductivity;
- Compatibility of U_3Si_2 and aluminum;
- Corrosion behavior;
- Irradiation behavior;
- Swelling;
- Blister resistance;
- Fission product release.

II–6.5. Important technical issues

The issues which were considered during the specification agreement process with the manufacturer of the LTAs are the amount of U increase by 10 to 15% to overcome the additional neutron absorption of the greatly increased ^{238}U content in LEU fuel and the effects of a harder neutron spectrum. The additional ^{235}U and ^{238}U can be accommodated by increasing the uranium density of the fuel and/or by redesigning the fuel element to increase the volume fraction of fuel in the reactor core (not an easy step due to licensing risks and manufacturability regime).

II–6.6. Design qualification

NESCA adopted as per IAEA recommendations [2] of the qualification process of both fuel and target plates (excluding other regulatory organisation) as shown in Fig. II–21.

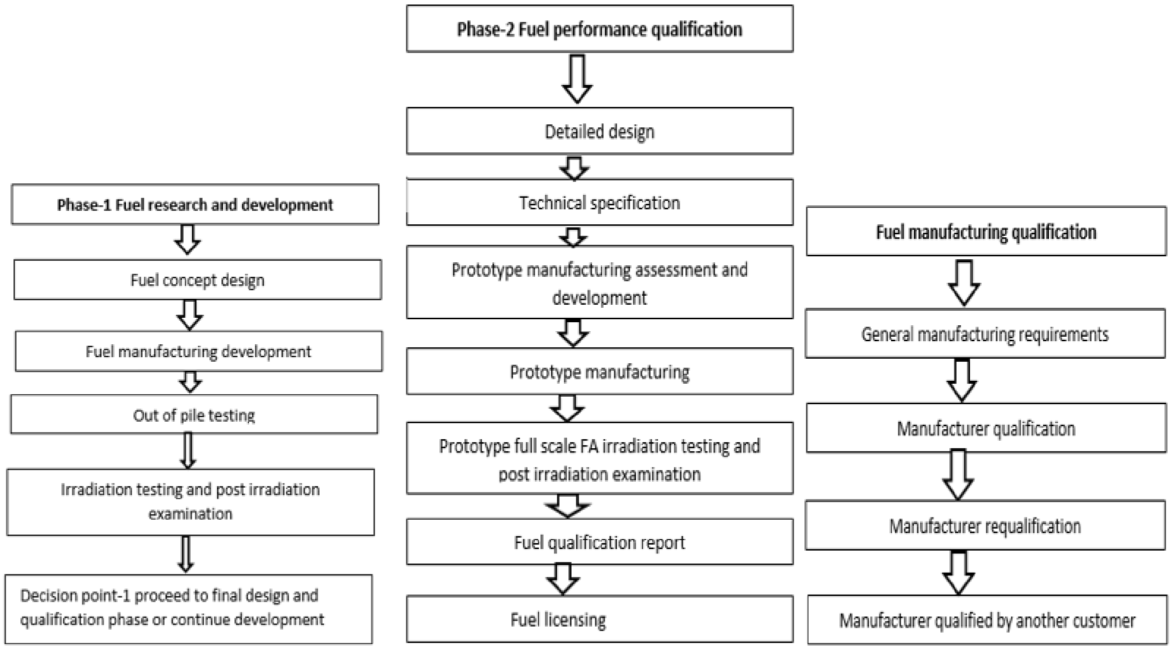
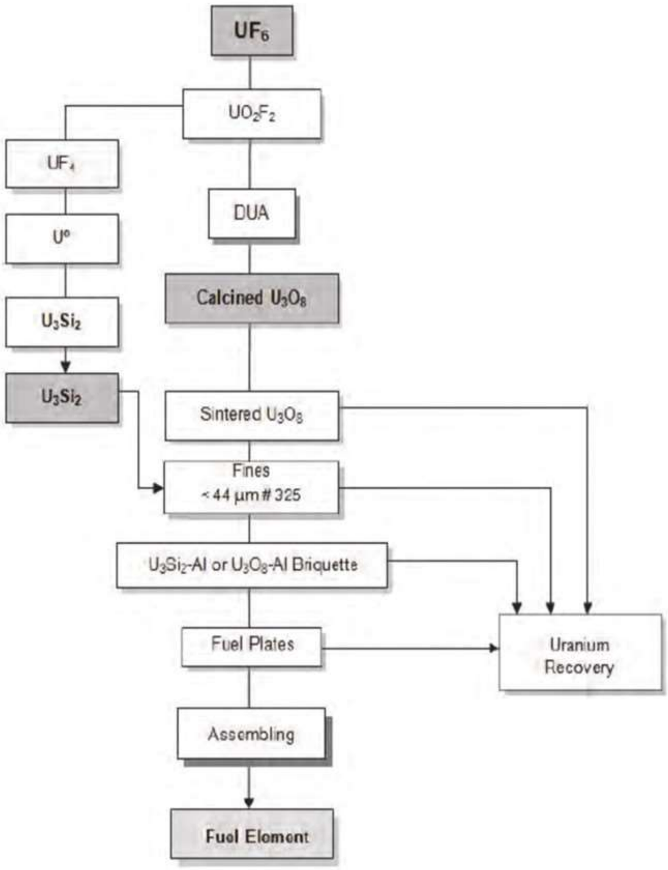
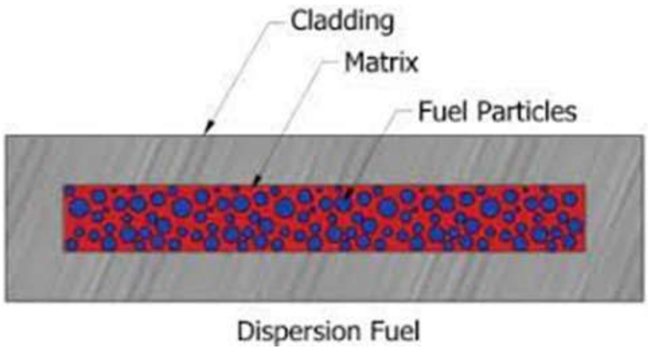


FIG. II–21. High Density Fuel Qualification Process (courtesy of NECSA, SA)

The uranium-silicide fuel is produced by melting stoichiometric amounts of uranium and silicon, followed by comminution to produce a powder. The fuel powder is mixed with aluminum powder and formed under pressure into a powder metallurgical compact. The compact is placed in an aluminum picture frame and aluminum cover plates followed by hot and cold rolling process to produce the fuel plate (refer Fig. II–22 below).



(a)



(b)

FIG. II–22. (a)U3Si2 Fuel Element Production Process and (b) Fuel Cladding and Core Matrix (courtesy of NECSA, SA)

It is important to ensure the U_3Si_2 still contains some USi, and U_3 Si. The deviations from stoichiometry on the silicon rich side produce some USi, while deviations on the uranium-rich side produce a solid solution of silicon in uranium [U(Si)].

II–6.7. Manufacturing readiness levels (MRLs) for HALEU fuel

MRLs are designed to manage manufacturing risk in conjunction with the development of new technologies. MRLs ranges from the manufacturing feasibility assessment to the repeatable quality production on a routine basis. The qualification process that is independent of the supplier origin involves listing of product and supply scoping requirements, specifications, classifications, technical requirements, user quality requirements quality assurance system, assessment of supplier's technical capabilities, safeguards implementation, country bilateral agreements during supplier selection. This process will be applicable to both local and international suppliers.

II–6.8. Manufacturing integrated management system (IMS)

NECSA has adopted international standard on which its management system is built on.
The IMS architecture and processes are designed based on the following main elements:

- Specification of international standards applicable to its business.
- Verification and validation process for all requirements.
- Capturing of all international good practice (IGP) and translate them into requirements.
- Segregate requirements as per applicable IMS element and assigning the appropriate management tools/management arrangement to support all processes that will satisfy all identified, verified and validated requirements.
- Required procedures, plans, templates and forms requirements for the applicable processes.
- Risk management.

Figure II–23 below provides the main components of the NESCA's IMS to ensure that the environmental factors are well aligned to the requirement for a fabrication facility using HALEU.

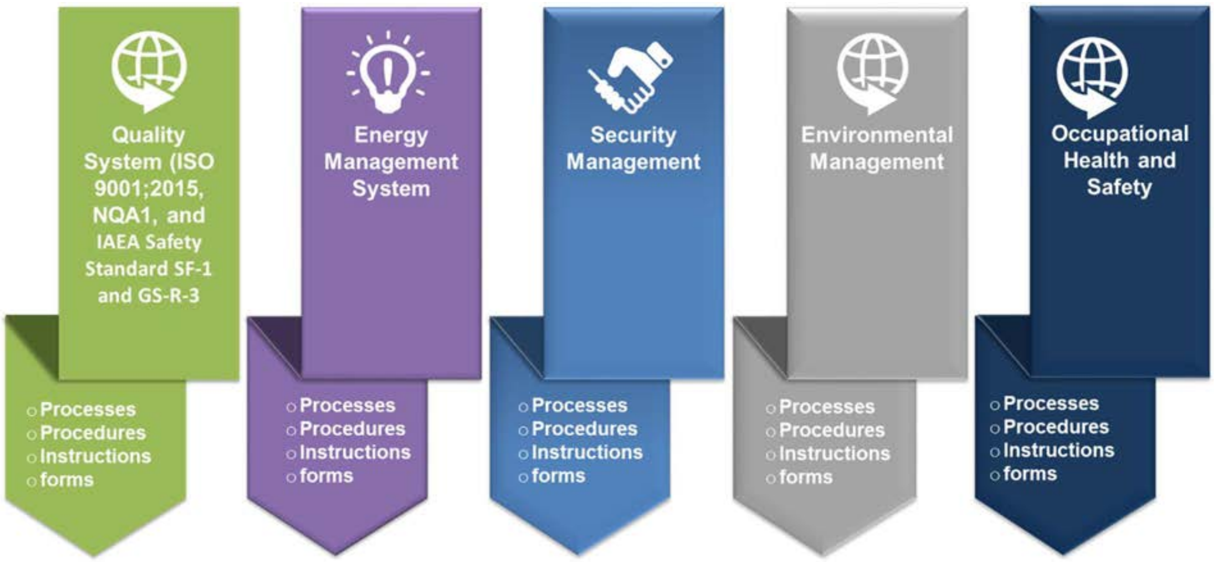


FIG. II–23. IMS main components (courtesy of NECSA, SA)

II–6.9. Fuel Manufacturing plan

NECSA currently has a Research Reactor Fuel Fabrication Facility that has been in operation for the past 30 years. An ageing management programme process was initiated in 2018 to maintain a healthy and safe operation of all systems, structures, and components (SSCs). This also include the fabrication of UAlx fuel made until SAFARI–1 is converted. In addition, NECSA can effectively recover uranium from uranium bearing material and produce uranium metal.

II–6.10. Current development activities

The current plan is based on research performed using local cladding material as part of the local manufacturing feasibility study. The study will allow NECSA to decide what the next course of action will be. It is important to note that cladding material is a vital component of the reactor safety and business case. While safety case parameter are investigated to ensure reactor safe operation, the business case parameters are important to ensure availability and affordability of raw materials.

The key current activities performed include testing of new cladding material for target plate (UAlx) to ensure adequate bonding of the alloys and any impact on SAFARI–1 and NTP's dissolution and purification processes, Production of full-size dummy plates (U free plates) production. The tests results are positive for the material selected. Aluminum bonding tests were also positive. This is an important development in demonstrating availability of local material and minimize security of supply. With the conversion of SAFARI–1 to LEU target plates, study on how to increase the uranium density of the target, while keeping the same geometry due to regulatory constraints is under progress. Various technologies are being assessed, including spheroidization and 3D printing. The next step would be to request acceptance from the National Regulator to modify the facility and produce on a lab scale, UAlx plates using HALEU and complete the feasibility study for the establishment of new fuel fabrication plant for power and non-power reactors.

II–6.11 References

[1] Office of Nuclear Reactor Regulation, US Nuclear Regulatory Commission, NUREG–1313, July 1988.

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Energy Series, NF–T–5.2, Good practices for qualification of high density low enriched uranium research reactor fuels, Vienna, 2007.

II–7. EVALUATION INDEX FOR TECHNICAL CONDITION FOR LONG TERM OPERATION IN RUSSIAN FEDERATION

One of the tools that can support strategy and decision taking on the LTO of complex equipment may be introduction of indices of the equipment's technical condition. Such tool was developed and introduced in the Russian electric power industry.

The assessment is done by comparison of the actual values of technical condition parameters with the maximum permissible values. As a result of comparison each parameter is assigned one of 5 possible states is given in Table II–3:

TABLE II–3 POINT TABLE FOR DEVIATION FROM PERMISSIBLE VALUES FOR INDEX EVALUATION

4	No deviations from the permissible values
3	Still in the permissible range, but negative trends noticed
2	Still in the permissible range, but there is a threat of failure
1	Permissible limits reached, the equipment performance decreased
0	Beyond the permissible limits

The evaluations are weighed and grouped to characterize the condition of a component, assembly, equipment and group of equipment.

The resulting index characterizes type of the technical condition and corresponding strategy towards the unit of equipment. A range of index with condition and action to be taken is given in Table II–4:

TABLE II–4. RANGE OF INDEX WITH TECHNICAL CONDITION AND ACTION REQUIRED

Technical condition index	**Type of technical condition**	**Technical action required**
≤25	Critical	Decommissioning, refurbishment
25<i≤50	Non-satisfactory	Additional maintenance and repair, reinforced inspections, refurbishment
50<i≤70	Satisfactory	Reinforced inspections, capital repair, refurbishment
70<i≤85	Good	According to the planned monitoring results
85<i≤100	Very good	Monitoring as planned

II–8. WASTE MINIMISATION INITIATIVES AT SWEDEN FUEL OPERATIONS

II–8.1. Introduction

The last few years there has been an increased focus at Sweden fuel operations regarding waste management. For some material it has been challenging to find an efficient way of treatment. Without a robust process to deal with both historic and new waste of all types, a situation with potential production disturbances and regulatory concerns is faced.

To reduce new waste, different steps are being worked out in construction and design phase as well as sustainability awareness in operations and maintenance. One fundamental part is the waste hierarchy, which more or less is using common sense and have the right mindset. A graded approach towards waste minimisation with prevention, minimisation, reuse, recycling, energy recovery as favoured option and disposal as least favoured option, is followed.

II–8.2. Burnable waste reduction

The investigations on how to reduce burnable waste from controlled areas are in process. One such example is to reduce paper used for cleaning and drying. This is mostly used by operators and maintenance technicians. Instead of industrial type of cleaning paper, reusable clothes/towels can be used, which can be cleaned in our existing laundry and cleaning station, which is connected to the sites water cleaning system, and recover possible uranium residues.

Another example in the same area is to use hand drying stations (blowers) instead of paper towels. Both these examples have the possibility to reduce our burnable nuclear waste as paper. This also has an advantage in leaching process, since silicon content in paper makes it more difficult to extract the uranium.

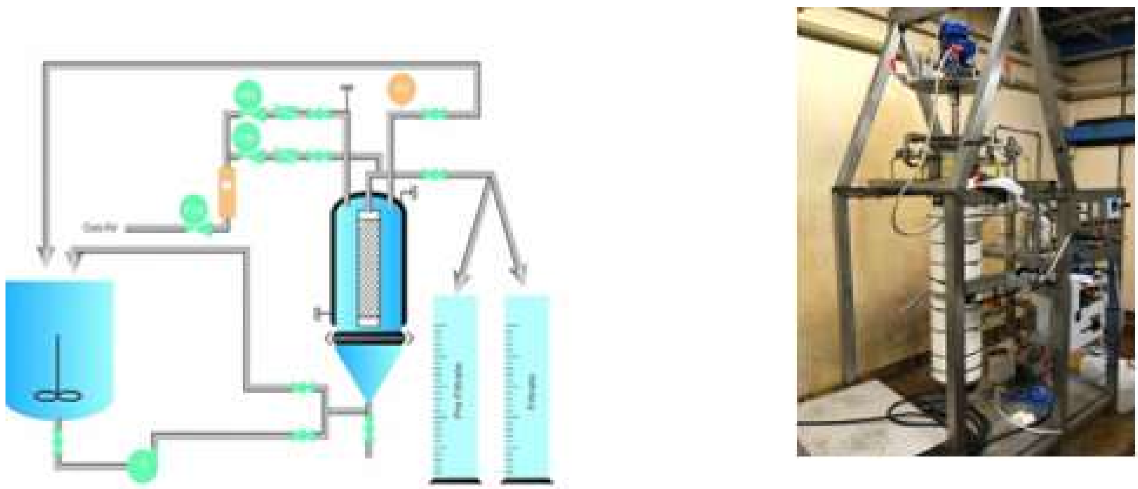
II–8.3. Sustainable design

When the need of substitution, upgrade or replacement of systems or components occur, think in a sustainable way with elements of circular economy. First of all, it is important to understand the full life cycle cost including the cost for waste management in a project. This can impact decisions resulting in increasing level of refurbishments or upgrades instead of complete replacements. As for example, refurbishment of a number of safety valves is done internally or by having specialists doing this on site.

A strategic approach is to use standard components, when possible, to simplify competence and training as well reduce spare part storage (cost and storage room). This means that during a replacement for component's beginning to be obsolete we can increase the internal spare part storage with the used components. This helps to extend the usable lifetime of systems.

II–8.4. Leaching of HEPA-filter

Use of new technology to improve waste management is also implemented. For example, working with improvements on taking care of HEPA-filters from controlled area which can contain uranium. Different solutions have been tested to improve current manual intensive dismantling. Besides initial vibration in a confined space leaching of the HEPA-filters in hot acid is tested in a pilot installation. The pilot study indicates uranium recovery in the range of 99,99% in 3 runs and final residue meeting strict requirement for landfill (<10 Bq/g in average). To reduce the number of HEPA-filters that needs to be recovered the preferred solution is to redesign parts of the ventilation system and to have a smaller leaching system to take care of historic and future filters (see Fig. II–24 (a) and (b)).



(a) *(b)*

FIG. II–24. Pilot installation of leaching equipment (courtesy of Westinghouse, Sweden)

II–8.5. Plasma gasification

Another example is plasma gasification of burnable waste, which has the potential of providing significant volume reduction of organic material down to 1–2%. A pilot study is currently in progress. The installation is expected to be installed in containers suitable for Nordic climate and will have 0,5 ton/day capacity.

ANNEX III.
SUMMARY OF IAEA TECHNICAL MEETINGS

III.1.THE TECHNICAL MEETING ON AGEING MANAGEMENT AND LIFE EXTENSION OF NFCFS

The meeting was conducted during the period December 6–10, 2021. The meeting was conducted by virtual means. The purpose of the meeting was to provide Member States with a forum to discuss and exchange experience on the operation and good practices for ageing management and long–term operation of their NFCFs as well as on new technologies implementation for waste minimization during all stages of NFCFs lives. The other purpose was also to update the NFCFs Database (NFCFDB) with MSs' inputs.

The meeting was attended by 51 participants from 21 Member States and two International Organizations (NEA and WNA). The participants included representatives from operating organizations, research facilities, regulatory bodies, and government organizations.

The meeting was organised in 4 technical sessions and there were total 28 presentations including from NEA and IAEA.

Session–I: Ageing Management of NFCFs: Programme and Experiences

Session–II: National Regulatory Practices on Ageing Management

Session– III: NFCF Database

Session–IV: WG Exercise– breakout session for:

- review of safety report series on ageing management and
- identification of technical issues in life extension.

Session–I Ageing Management of NFCFs: Programme and Experiences

III–1. I Operating Experience and Safe Management of Fuel Cycle Facility at Nuclear Fuel Complex (NFC), (Dr Dinesh Srivastava, India)

Nuclear Fuel Complex, Hyderabad, India gave a talk on "Operating Experience and Safe Management of Fuel Cycle Facility" which described the operating experience during fabrication of fuel for PHWRs/BWRs, Zr-tube manufacturing and programmes for ageing management at the facility undertaken to extend the life of equipment and the facility. It also provided a number of practical examples on innovative technologies, refurbishing, modernization and replacements since last 50 years.

III–1.2 Obsolescence in Control & Instrumentation systems: Assessment of risk impact analysis, mitigation and migration strategies (Jeetendra Bhavrani, India)

NFC (India) gave an account on Assessment of risk impact analysis, mitigation and migration strategies for Obsolescence in I&C systems at Fuel fabrication facilities. He provided an evaluation method for risk analysis due to ageing. Factors driving obsolescence including those in control and instrumentation systems, technological advancement. His presentation looked at different aspects of risk assessment of parts with an emphasis on determining the risk factor, strategy of selection of approach to handle the risk i.e. reactive approach or proactive mitigation, where reassessment is needed on regular basis. A case study was presented that illustrated the risk assessment and strategy selection.

III–1.3 Ageing management at La-Hague: an enhanced approach (Olivier D, France)

ORANO, France talked about an enhanced approach for Ageing Management at La-Hague Facilities (UP 3 and UP 2–800). The presentation focussed on issues with ageing of stainless steel resulting in long term outages of La-Hague plants. Details of so called "sustainability method/process" was presented. Examples of monitoring and supervision of processes were provided, such as the assessment of minimum operating duration of equipment subjected for corrosion. It can be estimated from the thickness available for corrosion and corrosion rate. Based on this assessment three evaporators at the La Hague site have to be replaced. There are 400 on–going investment projects at La Hague, 40% of them related to ageing management (sustainability). Innovative technologies are introduced for ageing equipment control, such as walking drones, telescopic arms etc. mainly for use in hot cells.

III–1.4 Methodology for implementing ageing management at NFCFs (Ms Daniela Yllañez, Argentina)

CNEA, Argentina provided on methodology for implementing ageing management at Spent fuel storage facilities. In Argentina the implemented methodology for ageing management (AM) consists of scope setting, grouping of SSCs with similar construction, function, materials and operating conditions, identification and assignment of ageing related degradation mechanisms (corrosion, leakage, concrete cracking, etc), development and implementation of AM programme (AMP), and reporting of results of the activities carried out and periodic reviewing.

III–1.5 Operating and Ageing Management for NFCFs (Andrew M, Canada)

CNSC, Canada provides a Canadian perspective on Operation and Ageing Management for NFCFs. The Canadian perspective (to ageing management is based on so called "fitness for service programme". It includes the scope and frequency for periodic testing, calibration and maintenance of facility SSCs and is a part of service programme. Regulatory body assess "fitness for service programmes" and conducts inspections to verify compliance of the maintenance, testing and control activities with the programme.

III–1.6 Ageing Management of dry SF Storage systems in the Czech Republic (Peter Lietava, Czech Republic)

The presentation briefed on AM on dry spent fuel storage systems in Czech Rep. It provided details of approaches and regulatory framework on ageing management in Czech Republic. The frequency of re-licensing of dry storage systems has been fixed at 10 years.

III–1.7 Designing Ageing Management System for safety related SSCs in hypothetical nuclear fuel cycle facility (Mohamed Abdelaziz Salem, EAEA, Egypt)

The presentation provided details of ageing management and preventive maintenance of safety related SSCs at Fuel Manufacturing Pilot Plant (FMPP) in Egypt. It also provided details of case study done at FMPP for various SSCs from 2011 to 2020 with few examples of technical and non-technical ageing like, process degradation in pipes and mechanical components due to corrosion, stress fatigue and erosion, knowledge management, training leadership and organisation.

III–1.8 Issues from Ageing Management Programme (AMP) at nuclear facilities in Norway (Ms. Brit Farstad, and Ms. Liv Gjønnes Norway)

The presentation gave details on issues from ageing management programme (AMP) at nuclear facilities in Norway. Norway is dealing with research reactors; some are closed and are going to be decommissioned what is expected to take several decades. AM was not taken into account during design, therefore there where some challenges when trying to assess the SSCs and they were hard to inspect. An overall AMP was designed based on IAEA Safety Standards Guide–SSG–10. Interesting examples of visual inspections and ultrasonic inspections that were carried out at reactor vessel were described. The AMP was established from operation to permanent shut down and preparation. Future work will be carried out next on fuel storage facilities.

III–1.9 Ageing Management Programme of NFCFs in Indonesia (Ms Dyah Sulistyani Rahayu, Indonesia)

An overview of NFCFs in Indonesia was presented along with details and status of fuel cycle facilities in Indonesia and strategies adopted for ageing management. The presentation briefed on systematic ageing management process outline (plan-do-check-act), creation of a database, surveillance, carry out maintenance. It also informed on corrosion coupon study on pool liners and observations and importance on knowledge management.

III–1.10 Ageing management programme for NFCFs (Mr Muhammad Jalil Haydir, Pakistan)

A presentation from PAEA was given on reviewing the relevance of ageing management for the safety of the people and the environment. Important concepts of AM were exposed, as well key degradation mechanisms that can affect NFC facilities, like corrosion, radiation damage, fatigue or obsolescence. A systematic approach adopted to manage ageing was described that includes a continued improvement perspective with plan-do-check-act structure to assure effectiveness. Some practical examples of good ageing management practices at Pakistan were given, this included examples of important structures and components, ageing mechanisms that could affect them, and how, and techniques to monitor and mitigate the ageing effects. Examples included process equipment and civil structures.

III–1.11 NEA working groups activities in ageing management and fuel cycle safety: (Diego Escrig Forango, OECD-NEA)

The NEA presentation gave details on working groups activities in ageing management and fuel cycle safety: Working Group on Integrity and Ageing of Components and Structures (WGIAGE) and Working Group on Fuel Cycle Safety (WGFCS). WGIAGE – main group and three subgroups, started in 1977, activities on LTO research with three subgroups; Concrete subgroup, Seismic subgroup and Metal subgroup which cooperates with other groups (e.g., IAEA IGALL, other NEA, CSNI, WGs). CODAP (component operational experience, degradation and ageing programme) – builds on two recent NEA projects – example of a database provided a list of topical reports. The WG on fuel cycle safety has programme of work and collaborative specific discussions (e.g., FINAS database) and reports published. The areas identified for research of technical obsolescence of C & I and electrical components and change from analogue to digital system.

Session–II: National Regulatory Practices on Ageing Management

Brazil, France, Germany, India and Netherland gave an overview on regulatory practices on Ageing management in their respective countries. Mr Christian and Mr Westermeier gave an example of ageing effects at a reactor vessel in a fuel fabrication plant. The Indian presentation was focussed on ageing management of related chemical industries through in service inspection. The licencing approach for NFCF was introduced. And have specific guidelines for covering AM and periodic safety assessment, which are publicly available. They establish monitoring concepts, inspection and testing techniques and required documentation.

A practical example of a chemical reactor vessel was shared, from a facility from the late 70s, that manufactures fuel rod and fuel assemblies. Several cracks were found in nozzles of different vessels from different production lines. The component was studied, its operating conditions, and characteristics. The crack was found during routine testing and further investigated with different NDE techniques. Fatigue was identified in the component probably due to vibrations. Affected nozzles were repaired and remaining nozzles where inspected.

Several technical issues covering ageing management, life extension, interface with other areas of NFCFs lifecycle, and non-technological areas were discussed with practical examples from different existent facilities. The draft list of the technical and non-technical issues has been compiled. With respect to time limited ageing analysis (TLAA), only UK follows this practice similar to NPPs for periodic safety review after every 10 years, compared with for example Canada, where a service analysis is carried out only for re-licensing or PSR review.

The presentation from the regulatory body of Netherlands, authority for nuclear safety and radioprotection, dealt with their view on ageing management (AM), focused mainly on NPPs but since the past year, it has begun paying attention to NFCFs. The country has an enrichment facility and a waste treatment, conditioning and SF storage facility. At the enrichment site a review including AM was carried out based on SSG–10, and an AM plan (AMP) was recently developed. It includes many of the activities also discussed and carried out by other members, like scoping, understanding of ageing, and detecting, minimizing, mitigating techniques. A similar review of the ageing management of a SF storage facility is done through PSR, and the development of an AMP is still in progress.

The presentation from India’s regulatory body AERB discussed on the importance of ISI inspections to assess ageing and prevent failures. The main aspects that ISI is required to consider (frequency of inspection, technique, QA aspect) and also some criteria to establish and carry out Inservice inspections was described. The role of the regulatory body regarding in service inspections were also summarised.

Session– III: NFCF Database

A brief overview of NFCFs in their country was covered by most of the presentations and specially from Brazil, Czech Rep, Indonesia, and Uzbekistan. The questionnaire for updated information was responded by 25 MSs. An appeal was made to appoint NC for IAEA–NFCFDB from those countries who have to designate a coordinator for 2021–24. Some important suggestions were:

— To push notifications for National Coordinators annually for timely updating of information
— To harmonise and minimise duplication of information among other databases in IAEA.

Session–IV: WG Exercise– Breakout session – Review of Draft document on AM of NFCFs

The participants were divided in 3 working groups and 3 facilitators from the Agency aided in their discussions on two tasks. The task –1 was on observations on draft SRS titled "Ageing Management of NFCFs" (jointly co-authored by Division of Nuclear Safety and Nuclear Installation (NSNI) & Nuclear Fuel Cycle and Waste Technology (NEFW) Divisions, IAEA). The participants provided feedback on the draft document through working group exercise. The second task was for identifying technical issues and challenges in life extension of fuel cycle facilities. This list will be useful in preparing TECDOC on long term operation of NFCFs.

III.2. THE TECHNICAL MEETING ON THE LIFE MANAGEMENT AND MODERNIZATION OF FUEL FABRICATION AND FUEL REPROCESSING FACILITIES

The meeting on the Life Management and Modernization of Fuel Fabrication and Fuel Reprocessing Facilities was conducted during the period 22–25 August 2022.The purpose of the event was to exchange technical information on lessons learned and best practices related to the life management and modernization of fuel fabrication and fuel reprocessing facilities.

The meeting was attended by 43 participants from 11 Member States. The participants included representatives from operating organizations, regulatory bodies, and technical support organizations for fuel cycle facilities.

Mr Jean Michel Marin from ORANO, France volunteered to chair the meeting and Mr Andrew McAllister (Canada), Ms Daniele de Azevedo Baêta (Brazil), and Mr Sanjay Jaiswal (India) volunteered as a rapporteur for the meeting.

The meeting was organised in 4 Technical Sessions and there was a total of 27 presentations (19 from 11 MSs, and 8 from the IAEA). Session 1 was focused on "Life Management of Fuel Fabrication Facilities: Programme and Experiences". In Session 2, the aspects of "Life Management of Fuel Reprocessing Facilities: Programme and Experiences" were covered. Session 3 was dedicated to National Regulatory Practices on Life Management of Fuel Cycle Facilities. Session IV was meant for the IAEA's Integrated Nuclear Fuel Cycle Information Systems databases for NFCFs.

Technical Sessions

The presentations from the IAEA described the elements of a systematic programme for the long term operation and modernization of NFCFs based on the IAEA safety standards and highlighted the safety aspects and operating experience related to life management and modernization of NPPs, management of life extensions of research reactors and their relevance to NFCFs. The presentations also discussed the outcome of various coordinated research projects (CRPs), IAEA safety missions and expert advisory services on ageing management, long term operations of NFCFs and various databases being maintained by the IAEA for the benefit of MSs.

Session 1: Life Management of Fuel Fabrication Facilities: Programme and Experiences

The presentation from ORANO, France covered the enhanced approach for extending the life of a MOX fuel fabrication facility (Melox), which is operational since 1995, by detecting and monitoring ageing. The ageing process is peculiar due to handling of plutonium powders. In 2014, they put the ageing management plan into action, which is based on lessons learned, understanding of ageing processes, and improvements needed with innovative solutions such as modular and redundancy features, partial replacements and treating the problem at its source.

The presentations from Nuclear Fuel Complex, India described the operating experience during fabrication of fuel for PHWRs/BWRs, modernization and automation in PHWR fuel manufacturing at various steps of manufacturing blending and compaction, pellet loading/unloading, pellet stacking, boat transfer and automation of appendage welding of thin walled tubes to increase the productivity, minimise radio-active waste and improve quality of fuel bundles. They also provided a number of practical examples on innovative technologies, refurbishing, modernization and replacements since last 50 years. These improvements have resulted in material recovery (powder to pellet) drastically by 15–20% and reduction in dose to operators by 20–30%.

The presentation from TVEL, RF described the technical challenges and advances in the fabrication of LWR/VVER fuels. It provided a brief detail on documentation during the life cycle of the fabrication equipment and technical policy of TVEL towards the life cycle of fabrication equipment with absolute priority to stable quality and safety in manufacturing. Key changes in manufacturing steps taken for automation and optimisation of pellet handling, inspection, laser marking and packing in pallets and containers were also highlighted.

Sweden’s presentations were based on implementation of methods of data driven asset management and innovative methods for waste management in fuel manufacturing such as leaching uranium recovery, plasma gasification and nitrogenous water recycling.

The South Africa’s presentation covered the SAFARI–I, which was built in 1978 and was equipped for fabrication of HALEU fuel in 2011. The key information includes the establishment of an ageing management programme and current plant development activities.

The other presentations from MSs i.e., Brazil, China, Egypt, and Indonesia in this session mainly addressed the operating experiences and practical examples related to advances in fuel manufacturing, life management, ageing management and refurbishments, modernization and replacements supporting the long term operation of NFCFs. The experiences and practical examples included the following aspects:

- Life management programmes for fuel fabrication facilities for long term operation;
- Monitoring and assessment of ageing for determination of safe operating period for SSCs;
- Challenges in advanced fuel manufacturing;
- Advancements and modernization in fuel manufacturing;
- Waste minimization in fuel manufacturing.

Session II: Life Management of Fuel Reprocessing Facilities: Programme and Experiences

The presentations in the session 2 mainly covered the programme and practices on life management of fuel reprocessing facilities. The presenters described life management practices, role of periodic review, experience feedback and a case study of modernization of the ventilation system at ORANO fuel reprocessing facilities (UP2–800 and UP3) in France, extension of service life of SSCs at Fuel reprocessing facilities in India and long term operation and modernization experience in RF (RT–1) with practical examples of equipment generation changes, modernization, automation and life extension programmes since 1987 such as addition of a new stream for increasing productivity, increase in automation level, minimization of radio-active waste generation, expanding the range of spent nuclear fuel and addition of a vitrification unit. These steps resulted in reduction radiation exposure to plant personnel by about 20%.

Session III: National Regulatory Practices on Life Management of FCFs

The presentations detailed the regulatory approaches and framework for long term operation of NFCFs in respective MSs. The aspects related to interface of ageing management with periodic safety review and relicensing of the NFCFs were also highlighted in these presentations.

Session IV: Integrated nuclear fuel cycle information systems (iNFCIS) databases

In Session– IV, discussions on the INFCIS databases were held and the response to survey questionnaire sent prior to the meeting was discussed. An appeal was made to appoint national coordinators (NC) for the IAEA–NFCFDB from those countries who have yet to designate a coordinator for 2022–24.

The Session–IV was also dedicated to providing feedback on the draft IAEA publication (TECDOC) titled “Long Term Operation of NFCFs”. The participants expressed that the TECDOC is a good initiative from the Agency and that the draft is a comprehensive document covering all aspects related to long term operation of NFCFs.

Conclusions of the meeting

The main conclusions of the meeting are:

1. Effective programmes for ascertaining actual conditions of SSCs, ageing management, maintenance, periodic testing, and inspection of SSCs, can enhance the operable lifetime of the facility;
2. For a long term operation of NFCFs the essential area is a proactive ageing management strategy developing for all stages of facilities’ life cycle, from the design, construction and commissioning stage, start–up, operation, and shutdown, keeping in mind asset criticality assessment and failure mode analysis, and the monitoring for critical equipment as well as the monitoring of degradation mechanisms, including structural and construction infrastructure and equipment.
3. Feedback from the operator's staff can provide valuable insights for planning the refurbishment and modernization of the facility.
4. It is necessary to focus on ageing management and modernization of the facility considering changing safety requirements, the need for advanced fuel cycles

implementation (with new fuels such as ATF, GEN-IV and SMR fuels, HALEU fuels), to improve product quality, diversify the feed material, reduce waste or by-product flows and to reduce the radiation doses.

5. Knowledge management is an important element for planning modernization and life management of NFCFs. Programmes for ensuring proper knowledge transfer from the operators leaving the organization are helpful in ensuring smooth operation of the facility during the extended life.
6. The IAEA databases such as the NFCFDB are very useful tools for dissemination of information on fuel cycle facilities and the Agency strives for regularly updating this database.
7. An ageing database for NFCFs similar to IGALL for NPPs may be developed by the IAEA or arrangements may be made to extend this database to NFCFs. For this, MSs' cooperation is also needed for sharing their data.

The draft IAEA document on "Long Term Operation of NFCFs" is a comprehensive document covering all aspects related to establishment of a systematic life management programme of NFCFs with practical examples.

LIST OF ABBREVIATIONS

ADU	ammonium di-uranate
AGV	automated guided vehicle
AI	artificial intelligence
AM	ageing management
AMP	ageing management programme
AMR	ageing management review
ARDM	ageing related degradation mechanisms
ASME	American society of mechanical engineers
ASTM	American society for testing materials
BARC	Bhabha Atomic Research Centre
BRIN	National Research and Innovation Agency
BWR	boiling water reactor
CCTV	close circuit television
CG	centreless grinding
CNSC	Canadian Nuclear Safety Commission
CNEN	National Nuclear Energy Commission
CNNFC	China North Nuclear Fuel Co., Ltd
CS	carbon steel
CSNI	Committee on the Safety of Nuclear Installations
CVD	chemical vapour deposition
DBP	di-butyl phosphate
DCSF	dry storage facility
ECT	eddy current testing
EE&I	electrical, electronics and instrumentation
EMC	electromagnetic compatibility
EMI	electromagnetic interference

EOT	electric overhead travelling
FEM	finite element method
FINAS	fuel incident notification and analysis system
FPGA	field programable gate arrays
FSP	fuel storage pool
GBs	glove boxes
HALEU	high assay low enriched uranium
HART	highway addressable remote transducer
HEPA	high efficiency particulate air
HEU	high enriched uranium
HM	heavy metal
HMI	human machine interface
HRC	high rupturing capacity
HTGR	high temperature gas reactor
IAEA	International Atomic Energy Agency
I & C	instrumentation and control
IGALL	international generic ageing lessons learned
IGSCC	inter granular stress corrosion cracking
IMS	integrated management system
IOT	internet of things
ISI	in service inspection
ISSF	interim storage of spent fuel
IT	information technology
JAEA	Japan Atomic Energy Agency
KBR	key business risk
KPI	key performance indicators
LEU	low enriched uranium

LPT	liquid penetrant testing
LTA	lead test assembly
MBP	mono-butyl phosphate
MOD	minimum operating duration
MOX	mixed oxide
MPT	magnetic particle testing
MSs	Member States
MTBF	mean time between failures
MTRR	mean time to repair
NEA	National Energy Agency
NEFW	Nuclear Fuel Cycle and Waste Technology
NDT	non-destructive testing
NDE	non-destructive evaluation
NECSA	South African Nuclear Energy Corporation
NFC	Nuclear Fuel Complex
NFCF	nuclear fuel cycle facility
NFCFDB	NFCFs database
NPPs	nuclear power plants
NSNI	Nuclear Safety and Nuclear Installation
ODS	oxide dispersion strengthened
OEF	operating experience feedback
OEM	original equipment manufacturer
OLM	on–line monitoring
O&M	operation and maintenance
PAUT	phased array ultrasonic testing
PC	personal computer
PCI	pellet-clad interactions

PHWR	pressurised heavy water reactor
PLC	programable logic controller
POMS	pro–active obsolescence management system
PSR	periodic safety review
PU	polyurethane
PUREX	plutonium uranium extraction
PVDF	polyvinylidene fluoride
PWR	pressurised water reactor
RCC	reinforced cement concrete
QA	quality assurance
RFID	radio frequency identification
RLA	residual life assessment
RRs	research reactors
RSW	radiation shielding window
SAT	systematic approach to training
SCADA	supervisory control and data acquisition
SNF	spent nuclear fuel
SNFSF	spent nuclear fuel storage facility
SS	stainless steel
SSCs	systems, structures and components
SSG	safety standard guide
SSR	safety standards series
SUJB	State Office for Nuclear Safety
TBP	tri-n-butyl phosphate
TECDOC	technical document
TLAA	time limited ageing analysis
TLD	thermos-luminescent dosimeter

TOF	time of flight
TOFD	time of flight diffraction
TRL	technology readiness level
TVEL	heat releasing element
VAR	vacuum arc melting
VVER	water-water energy reactor
UT	ultrasonic testing
WGs	working groups
WNA	World Nuclear Association

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Technical Meetings

Vienna, 6–10 December 2021
Vienna, 22–25 August 2022

Consultancy Meetings

Vienna, 30 March–1 April 2021
Vienna, 16–18 May 2022
Vienna, 15–17 March 2023

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