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NRG EXPERIENCE IN SUPPORT OF AGEING MANAGEMENT AND SAFE LONG TERM OPERATION OF NUCLEAR POWER PLANTS AND RESEARCH REACTORS

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ABSTRACT

This paper provides results of analysis of current status and perspectives of operating nuclear power plants (NPPs) regarding to their preparedness for safe long term operation (LTO) based on IAEA SALTO (Safety Aspects of LTO) mission results in section 2.

In section 3, it provides general description of NRG TULIP ageing management and LTO approach which has been used to support NPPs and research reactors in several countries in preparation for safe LTO.

Section 4 provides detailed examples of successful LTO projects which were supported by NRG and led to extension of NPPs license/ operating permission beyond originally intended time frame. It describes all key activities which were performed and supported by NRG.

NRG has decided to build its TULIP ageing management and LTO approach on IAEA safety standards and on IAEA safety reports. IAEA safety standards represent consensus of all countries operating nuclear facilities on what represents systematic approach to ageing management and preparation for safe LTO. They are being regularly revised and updated. IAEA safety reports provide the most up-to-date information on best practices in implementation of IAEA safety standards.

NRG TULIP is recognized as a proven approach to ageing management and LTO preparation in line with IAEA Safety Standards and led to successful LTO projects in several countries.

INTRODUCTION

As of November 2021, 295 out of 442 nuclear power plants (NPPs) worldwide have been in operation for more than 30 years and 120 for more than 40 years (see figure 1). In view of these facts, many countries are giving a high priority to continuing the operation of NPPs beyond the time frame originally anticipated (e.g. 30 or 40 years).

Even though the design life of a nuclear power plant is typically 30–40 years, it is quite feasible for many NPPs to operate beyond their original design lives, provided that nuclear specialists demonstrate by analysis, testing and ageing management safe operation for intended period of long term operation (LTO). Safety upgrades of the plants also provide increased assurance that the plant will operate safely. In the operation of NPPs, safety should always be the prime consideration. Plant operators and regulators must always ensure that plant safety is maintained and, where possible, enhanced during its operating lifetime.

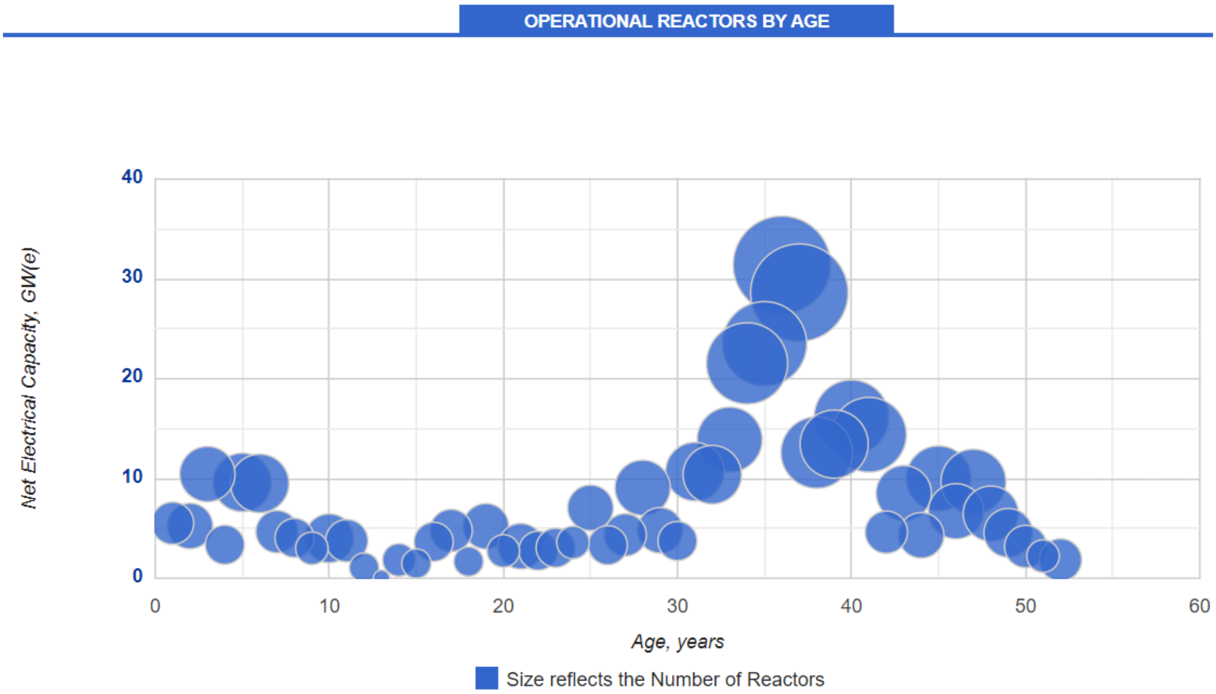

Figure1. Operating reactors by age (https://www.iaea.org/pris)

LTO of a nuclear power plant may be defined as operation beyond an established time frame set forth by, for example, license term, design, standards, license and/or regulations, which has been justified by safety assessment, with consideration given to life limiting processes and characteristics of systems, structures and components (SSCs). Proper and safe LTO is based on the experience and practices in areas such as ageing management programmes (AMPs), other plant programmes relevant for LTO, time limited ageing analyses (TLAAs) and plant license renewal. Other activities, including periodic safety review, current licensing basis and plant modifications, are also relevant to LTO. Effective AMPs are key elements in the safe and reliable operation of NPPs during the time frame originally planned for operation and for the period of LTO. LTO is justified by a safety assessment that considers life limiting processes and characteristics of structures, systems and components.

In order to assist Member States in effectively managing the effects of ageing and preparation for safe LTO, the IAEA has developed related safety standards and guidance publications such as Safety Guide SSG-48 on *'Ageing Management and Development of a Programme for Long Term Operation of Nuclear Power Plants'* [1], Safety Report No.82 (Rev.1) on *'Ageing Management for Nuclear Power Plants: International Generic Ageing Lessons Learned (IGALL)'* [2] and associated IGALL database. IAEA Safety Guide SSG-25 on *'Periodic Safety Review for Nuclear Power Plants'* [3] can be also in support of ageing management and LTO.

The IAEA Safety Aspects of Long Term Operation (SALTO) Peer Review Service was introduced in 2005 to support Member States in their activities for safe LTO. Updated version of IAEA SALTO Guidelines [4] was published in 2021 and covers also research reactors and review of ageing management of NPPs in early phase of operation and during LTO period.

CURRENT STATUS AND PERSPECTIVES OF OPERATING NUCLEAR POWER PLANTS

Historically, the major drive of NPPs for improvement of ageing management and related activities was demonstration of preparedness for safe LTO. The IAEA SALTO Peer Review service was since its introduction in 2005 also focused primarily on preparation of NPPs for safe LTO. NPPs preparedness for safe LTO has significantly improved worldwide since then but there are still some persisting issues which can be clearly seen from results of the IAEA SALTO peer review service.

The IAEA performs periodical analysis of SALTO mission results to identify typical NPPs strengths and weaknesses. This is presented in SALTO Highlights 2005-2015 and SALTO Highlights 2015-2018 posted on IAEA web site and also published in [5-6]. SALTO Highlights 2015-2018 identified following issues as the most common (23 missions performed in analyzed period):

- Existing organization is not adequate for supporting LTO (7/23)
- The content of the LTO implementation programme is not complete (6/23)
- Periodic Safety Review is not comprehensive (9/23)
- Insufficient evaluation of effectiveness of existing plant programmes (7/23)
- Incomplete scope of SSCs for ageing management and LTO assessment (7/23)
- Ageing management review (AMR) of mechanical structures and components (SCs) for LTO is not adequately performed (12/23)
- Revalidation of TLAAs for mechanical SCs is not complete or adequate (7/23)
- AMPs for mechanical SCs are not adequately developed or implemented (6/23)
- EQ programme not comprehensive (9/23)
- A proactive programme for managing technological obsolescence is not developed/ fully established (7/23)
- AMR for civil SCs for LTO is not adequately performed (13/23)
- AMPs for civil SCs are not adequately developed or implemented (10/23)

The most important deficiencies connected with physical ageing of safety SSCs and demonstration that SSCs will perform their safety function during intended period of LTO can be divided into five categories (see [7] for more details):

1. Insufficient input data for demonstration of preparedness for safe LTO;
2. Insufficient demonstration that safety SSCs will perform their safety function during the intended period of LTO;
3. Incomplete or missing ageing management programmes (AMPs) and other plant programmes to manage physical ageing of safety SSCs;
4. Incomplete or missing equipment qualification (EQ) programme;
5. Time limited ageing analyses (TLAAs) not demonstrating safe LTO.

The IAEA Specific Safety Guide SSG-48 [1] states that 'ageing management is most effective when it is properly carried out at all stages of the lifetime of a nuclear power plant'. There is an important number of countries embarking on nuclear energy, commissioning first units and many new builds in countries already operating NPPs. That predetermines a need of more focus on NPPs in early phase of operation.

Large portion of NPPs is already operating in LTO but heading towards further operation extension beyond 50 or 60 years (see figure from IAEA PRIS database above) which will trigger need for addressing new challenges.

NRG TULIP AGEING MANAGEMENT AND LTO APPROACH

There is a need for a generally accepted approach for ageing management and LTO assessment of NPPs. The IAEA has developed safety standards and other guidance to provide a sound basis for such approach. Specific Safety Requirements SSR-2/2 (Rev. 1) on *'Safety of Nuclear Power Plants: Commissioning and Operation'* [8] provide requirements on ageing management and LTO that must be met to ensure the protection of people and the environment. Specific Safety Guide SSG-48 [1] provides recommendations and guidance on how to comply with the requirements. As a part of IAEA safety standards, they represent a mutual consensus of all IAEA member states (which means all countries operating NPPs) on what means an effective ageing management and appropriate preparation for safe LTO. Safety Guide SSG-25 [3] also provides recommendations on some aspects of physical ageing of SSCs but focuses more on non-physical ageing of SSCs. SSG-25 also stresses the need to seek safety improvements and implement those improvements that are practicable if the plant is to continue to operate beyond the time frame originally anticipated for its operation.

For research reactors (including radioisotope production facilities and experimental devices), IAEA Safety Standards provide similar guidance in Specific Safety Requirements SSR-3 on *'Safety of Research Reactors'* [9] and the associated recommendations in Specific Safety Guide SSG-10 on *'Ageing Management for Research Reactors'* [10].

Recently published Safety Guide SSG-69 on *'Equipment Qualification of Nuclear Installations'* [11] is primarily focused on environmental qualification and applies to electrical equipment, instrumentation and control and active mechanical equipment, as well as components associated with this equipment (e.g. seals, gaskets, lubricants, cables, connections, mounting and anchoring structures) of NPPs and research reactors.

IAEA reports on safety in nuclear activities are issued as Safety Reports, which provide practical examples and detailed methods that can be used in support of the safety standards. IGALL Safety Report [2] provides a technical basis and practical guidance based on proven practices on managing ageing of mechanical, electrical and instrumentation and control (I&C) components and civil structures of NPPs. This publication encompasses generic sample of AMR tables, a collection of proven AMPs, a collection of typical TLAAs and technological obsolescence programme.

Safety Report on *Ageing Management and Long Term Operation of Nuclear Power Plants: Data Management, Scope Setting, Review of Plant Programmes, Documentation* [12] provides supplementary information to support the implementation of the recommendations and guidance provided in SSG-48 [1] relating to ageing management and preparation for safe LTO of NPPs such as data collection and record keeping for ageing management and LTO assessment, scope setting of SSCs for ageing management and LTO assessment, review and improvement of plant programmes relevant to ageing management and LTO, including corrective action programmes and documentation of ageing management and LTO.

The NRG 'TULIP' brand name and approach to ageing management and LTO builds on above mentioned IAEA safety standards and IGALL Safety Report. TULIP comprises of:

- Ageing management and LTO project management/ overall support
- Methodologies development
- Scope setting
- Ageing management reviews
- Development, implementation and improvement of AMPs
- Identification and revalidation of TLAAs
- PSR preparation and conduct
- Data management

Since 2006, NRG supports operators and regulators of NPPs and research reactors in capacity building in ageing management, LTO and PSR, provides technical support, calculations, analyses, project management support, helps in preparation of facilities personnel for review missions such as IAEA SALTO missions and supports in resolution of missions findings.

EXAMPLES OF NRG SUCCESSFUL LTO PROJECTS

As one of the Europe's largest independent ageing management and LTO consultants for NPPs and research reactors, NRG has been working on challenging ageing management and LTO projects:

- Ageing management improvement and LTO preparation of Borssele NPP
- Ageing management improvement and LTO preparation of Ringhals NPP
- Ageing management improvement and LTO preparation of Oskarshamn NPP
- Ageing management improvement and LTO preparation of Atucha NPP
- Ageing management establishment for permit preparation of Olkiluoto NPP
- Ageing management improvement and continuous operation preparation of HFR research reactor

Two examples will be given of ageing management and LTO assessment projects which used relevant IAEA guidelines and 'TULIP' approach [13]. The experience gained in the Borssele project in the Netherlands in 2006 to 2014 was used for the set-up of the ageing management and LTO assessment project for Ringhals NPPs in Sweden in 2014 to 2017.

The Borssele NPP planned for operation until 2034 (60 years). On 16 June 2006, a covenant between the owners and the government was signed in which operation until 31 December 2033 was agreed upon. 40 years of operation was assumed in the original safety analysis report (SAR). A formal license change application process had to be completed based on a comprehensive LTO assessment project to revalidate the SAR for 60 years of operation.

In the Netherlands, the nuclear regulatory requirements are contained in the Nuclear Energy Act. Within the Nuclear Energy Act, the so called Nuclear Safety Rules (NVRs = Nucleaire Veiligheids Regels) provide the basis for a system of more detailed safety regulations for NPPs. This set of rules is based on the IAEA Safety Standard Standards. The IAEA Safety Guide NS-G-2.12 and Safety Report No. 57 (later incorporated into and superseded by IAEA Safety Guide SSG-48 [1]) were therefore used as a basis for their LTO assessment project.

The scope setting was performed as an initial step of the LTO assessment. All SSCs in scope of LTO assessment were identified on a system level based on the criteria from IAEA Safety Report No.57. In the subsequent process further detailing of the scope on component or commodity group level was performed.

AMR involved detailed technical evaluation of in-scope passive long-lived components (e.g. main coolant piping) as well as passive subcomponents of active long-lived SCs (e.g. main coolant pump casing) to demonstrate that the ageing effects are adequately managed in a way that the intended function(s) will remain consistent with the plant licensing basis during LTO.

During the AMR process, different methodologies were used to evaluate different SCs and commodity groups. Mechanical A SCs form part of the fission product barrier, i.e. the barrier for radioactive release. Mechanical B SCs consist of the remaining safety related in-scope mechanical systems. Commodity groups were developed separately for mechanical A SCs, mechanical B SCs, electrical SCs and structural/civil SCs. A total of 17 AMR reports were prepared for Borssele NPP in the framework of LTO in the three disciplines. A catalog of relevant degradation mechanisms was also prepared for each of the 3 disciplines, to guide the performance of each AMR. As applicable, recommendations were made to improve Borssele NPP programmes and/or practices to align the NPP with current nuclear industry. With the fulfillment of the AMR recommendations the effects of ageing on in-scope SCs is adequately managed (i.e. the intended function(s) will be maintained consistent with the Borssele NPP licensing basis during LTO). All reports were reviewed by the Dutch nuclear regulatory authority.

The IAEA Safety Report No.57 was largely based on US NRC rules, which assume that any plant implementing LTO also applies the Maintenance Rule [14]. The Maintenance Rule ensures proper ageing management of active components, however, the Maintenance Rule is not mandatory in NPPs that do not fall under the regulations of the US NRC. Therefore, evaluation of active components was included in the LTO project in line with the methodology of the Maintenance Rule. The active components are classified into three groups: mechanical, structural/civil and electrical. (Note: Currently valid IAEA Safety Guide SSG-48 [1] already clearly recommends to manage ageing of both passive and active SSCs.)

AMPs and existing plant programmes (e.g. maintenance, in-service inspection, surveillance and monitoring, equipment qualification, water chemistry) were reviewed against nine attributes of effective AMP [1] and identified deficiencies were dispositioned. AMR identified gaps which were basis for development or improvement of AMPs and existing plant programmes.

TLAAs were identified according to criteria from IAEA Safety Report No.57 (consistent with currently valid IAEA Safety Guide SSG-48 [1]). Identified TLAAs at Borssele NPP were TLAAs for reactor pressure vessel (RPV), fatigue, leak before break and equipment qualification for design basis accidents.

A safety assessment of the RPV, including the assessment of neutron embrittlement of the Borssele RPV, was carried out. The structural integrity of the RPV with respect to operation and design accidents, including pressurized thermal shock was assessed using fluence calculations validated by shadow calculations and scraping samples from the RPV. Finally, the RPV safety was evaluated in terms of the up-to-datedness of the assessment methods used (including Master Curve) and by a general benchmark of the Borssele results with RPV safety assessment data worldwide. It could be proven that the safe operation of the Borssele RPV is guaranteed by comprehensive state-of-the-art methods for all load cases with large safety margins.

To be able to revalidate the fatigue analyses for LTO including the incorporation of possible environmental influence, best estimate calculations of the fatigue life were needed including realistic assumptions of the thermal loads. The FAMOS system was implemented for this reason during the yearly outage in 2010. It abled to precisely monitor thermal loads including stratification. A systematic review of fatigue assessment was performed for all component locations in the scope. A cumulative usage factor for expected number of transients by the end of operation in 2034 (CUF2034) was calculated for every in-scope component location. Detailed assessment was performed for the locations where CUF2034<1 could not be demonstrated for LTO period to prove that adequate safety margins against crack initiation by fatigue are in place. Calculations and additional measures provide a sound basis for the prevention of crack initiation by fatigue for the period of LTO.

Leak before break (LBB) is part of the break preclusion concept at Borssele NPP. Primary piping, main steam lines and feed-water lines within the secondary containment are in the scope for break preclusion. In particular, the LBB argumentation contains time dependent assumptions regarding the growth of defects. The goal of the review was to demonstrate that the break preclusion concept, as implemented in 1997, remains valid for LTO until 2034. Two steps of LBB include time dependency, time for growth of surface defect to through-wall defect (the number of reactor lives from this step has to allow for 60 years of operation) and time for growth of through wall defect to critical through-wall defect (only when through wall defect occurs). Since no through-wall defect has been detected, this time dependency always occurs after the step mentioned above and is therefore not relevant for life time extension to 2034. The relevance of time dependency in break preclusion of Borssele NPP for operation until 2034 is concentrated on the first step. The assessment concluded that the time-dependent assumptions in TLAA on LBB are not restricting operation for 60 years.

After the Harrisburg accident, it was realized in the mid-1980s that the electrical and I&C components did not have a qualification for harsh environment conditions. Subsequently, a list of equipment needed to manage the design accidents was developed based on design basis accident scenarios and required safety functions. The selected hardware was qualified in conformity with the German KTA standards. TLAA on equipment qualification was assessed by the implementation of a method to establish the qualified life of each component with a harsh environment qualification for LTO. The equipment qualification project led to the qualification of design basis accident resistant equipment, where for components with insufficient data requalification and replacement programmes was carried out.

NRG used the experience of the Borssele NPP LTO assessment project to set up the LTO assessment project of Ringhals NPP. After development and agreement upon the LTO approach, Ringhals NPP and NRG had set-up a more detailed LTO methodology for Ringhals units. During multiple workshops, NRG consultants trained Ringhals NPP staff to understand related IAEA guidance and suitable way how to implement it. Based on these workshops and with support of NRG consultants, Ringhals staff defined their LTO methodology. The IAEA IGALL TLAAs were used as a basis for identification and revalidation of Ringhals NPP TLAAs.

The IAEA guidelines provide a generally and globally accepted methodology for ageing management and LTO assessment. Two examples of LTO projects which used these guidelines were presented. Borssele NPP in the Netherlands used IAEA guidance as a basis for their LTO assessment project. The outcome of the LTO assessment project was submitted to the Dutch regulator for an extension of operational license for LTO until 2034. In 2013, the extended license was approved by the Dutch regulator. The experience gained in the Borssele LTO assessment project was used for the set-up of the LTO assessment project for Ringhals NPP in Sweden. Ringhals NPP also adopted the IAEA guidance for the general structure of their LTO project which have led to successful approval of Ringhals LTO.

CONCLUSIONS

NRG has decided to build its TULIP ageing management and LTO approach on IAEA safety standards, particularly on safety guides such as SSG-48 [1], SSG-10 [10], SSG-25 [3], SSG-69 [11]; and on IAEA safety reports [2, 12]. IAEA safety standards represent consensus of all countries operating nuclear facilities on what represents systematic approach to ageing management and preparation for safe LTO. They are being regularly revised and updated. IAEA safety reports provide the most up-to-date information on best practices in implementation of IAEA safety standards.

Most of the regulatory authorities worldwide use the same IAEA safety standards and safety reports as a basis to develop there national regulations, which are usually published with some delay after IAEA publications. In many countries, the regulatory authorities require licensees to fully comply with IAEA safety standards and also demonstrate compliance in LTO license application reports or PSR reports.

NRG TULIP is recognized as a proven approach to ageing management and LTO preparation in line with IAEA Safety Standards and led to successful LTO projects in several countries.

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