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Effective Aging Management of NPP Concrete Structures

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Abstract

Nuclear concrete structures are typically passive under normal operating conditions. They are, however, play a key role in mitigating impacts of extreme/abnormal operating and environmental events. As structures age, changes in material properties arise from continuing microstructural changes and environmental influences. Changes in environmental conditions anticipated during the original design can sometimes lead to unpredicted effects, which may jeopardize the integrity of the structures.

In order to continue successful operation, continuous integrity of the safety-related concrete structures shall be ensured by controlling and mitigating aging related degradation. A key element of aging management is the systematic and rigorous assessment of structures most commonly referred to as Condition Assessment (CA). Over the years, SNC-Lavalin personnel have assessed containment structures and safety related structures of Nuclear Power Plants (NPPs), research reactor and waste storage facilities.

This paper discusses requirements and approach to aging management for existing as well as new NPP concrete structures, and presents the methodology used to perform the CA.

1. Introduction

Nuclear concrete structures have history of reliable performances. Structures are subject to time-dependent changes that may impact their ability to withstand various demands from operation and the environment thereby reducing design margins. In accident conditions, excessive degradation can lead to failure that often affects serviceability of concrete structure. Some components of nuclear concrete structures may be difficult to inspect and repair. Typically concrete structures are not replaceable except for some of their components (e.g. joint sealants). As concrete structures age, assurances need to be provided that the capability of the safety-related systems to mitigate extreme events has not deteriorated unacceptably.

A key element of aging management is the systematic and rigorous assessment of structures most commonly referred to as Condition Assessment (CA). CA generally involves a review of facility data to assess the effect of age related degradation on safety-related structures, establish their current condition, and provide prognosis of future performance. The assessment of the current condition of the concrete structures is based on the history of operation and maintenance assessed against the design basis and the functional, safety, as well as operational requirements. The health prognosis for extended life is then based on both this current condition and a systematic identification and assessment of Aging Related Degradation Mechanisms (ARDMs) and their impact on the functional requirements of concrete structures.

Many assessments were performed by SNC Lavalin personnel over the years that included concrete, prestressing system, non-metallic liner system and joint sealant material. Assessed structures were of different age. The oldest one being assessed after more than 50 years of service is a nuclear research facility that went into operation in the mid-1950s.

2. Requirements and guidelines for aging management

In 2014 Canadian Nuclear Safety Commission (CNSC) has published the document for fitness for service and aging management (CNSC 2014) that provides requirements for managing aging of Structures, Systems and Components (SSC) of a power reactor facility. It provides guidance on how these requirements are to be met and is intended as a framework within which codes and standards are to be applied. The document references CSA N287.7 (2013a) Standard and N291 (2013b) Standard that provide requirements for in-service examination of concrete containment structures and safety related structures respectively. It also references CSA N287.1 (1993) that provides general requirements for concrete containment structures. It should be noted that new revisions of CSA N291 and N287.1 have been issued recently.

Furthermore, the new standard on aging management of concrete containment structures has been developed as described in Tcherner (2015a). The CSA N287.8

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Standard (2015) was issued in 2015. The standard provides aging management requirements to ensure that concrete containment structures satisfy their functional and performance requirements in all different phases of their life-cycle including design, construction, commissioning, operation, and decommissioning. Moreover, the requirements provided in this standard are intended to ensure that for new concrete containment structures, aging is addressed during design and construction phases.

The International Generic Aging Lessons Learned (IGALL) project was initiated by IAEA a few years ago in order to provide detailed information on specific programs to manage aging and degradation of SSCs. This initiative followed the United States Nuclear Regulatory Commission (USNRC) Generic Aging Lessons Learned (GALL) activity (USNRC 2010) but was extended to summarize international practices for aging management of mechanical, electrical and civil SSCs of NPPs.

Phase 2 of the project completed in 2015 provides collection of proven aging management programs and Time Limited Aging Analysis (TLAAs). Phase 3 of the project is currently underway. The aging management programs for concrete structures refer to IAEA TECDOC 1025 (1998) issued in 1998 to address assessment and aging management of concrete containment structures. The TECDOC was revised recently as discussed in Moore et al. (2015) to include state of the art information regarding aging management of concrete structures. The document was also expanded to address other NPP concrete structures besides containment. The revised document (IAEA 2016) was issued in 2016.

3. Effective aging management of existing structures

The documents listed in Section 2 require a systematic approach to aging management to be implemented as illustrated in Fig. 1. As can be seen from this figure, understanding aging lies in the heart of the effective aging management.

Other components of effective aging management include development of the Aging Management (AM) plan, operating to minimize expected degradation, performing inspections and monitoring activities to check for degradation, and implementing mitigative measures.

![Fig. 1 Systematic Approach to Managing Aging of a Structure or Component (IAEA 2016)](image-url)
The lessons learned in implementation of AM plan along with the applicable Operating Experience (OPEX) and Research and Development (R&D) activities should be considered for optimisation of the AM plan. The major components of effective aging management as it pertains to existing nuclear concrete structures are discussed in this Section.

3.1 Understanding aging and planning aging management plan

Prior to the development of an AM plan, evaluation for aging management and condition assessment shall be performed in order to ensure understanding of aging and to establish base line condition of the structure. Requirements for condition assessment and evaluation for aging management are defined by CSA N287.8 (CSA 2015).

3.1.1 Methodology for evaluation for aging management and condition assessment

As stated in IAEA Safety Guide NS-G-2.12 (IAEA 2009), an aging management review (or an evaluation for aging management) forms an integral part of a CA. Thus, the condition assessment and evaluation for aging management are typically performed in combination and constitute Life Assessment (although, more commonly the process is referred to as Condition Assessment). Figure 2 illustrates schematics of the process.

The methodology was specifically tailored to civil structures and includes the following:

- Gathering and reviewing of design, manufacturing, construction, commissioning, operation, inspection, and maintenance history, and any other relevant documentation;
- Defining the design basis and identifying any changes made to the structure during construction and operation;
- Establishing the structure's physical and functional boundaries and associated components;
- Undertaking an aging assessment of structures or components remaining after screening. This includes an assessment of ARDMs, aging evaluation, and establishing the structure’s health prognosis; and
- Providing recommendations for a structure in terms of inspections, monitoring, repair, and maintenance activities to ensure plant safety and production goals over the plant life.

In addition to current condition and future health predictions, changes necessary to address issues related to aging effects are identified as a result of CA; economic improvement opportunities might also be included.

![Fig. 2 Schematic Condition Assessment Process (Tcherner and Aziz 2013)](image)

1 The term Condition Assessment, as more commonly used, refers to Life Assessment as well.
The comprehensive data is required to ensure the depth and quality of the CA. Since the results of CA are largely based on the engineering judgement, qualified and experienced personnel shall be performing the CAs. Engineering judgment comprises of the knowledge of the design and functional requirements of the structure being assessed as well as the understanding of how the stressors can influence the onset and development of degradation mechanisms and how these mechanisms may affect ability of the structure to meet its functional requirements. While there are standards and guidelines documents available to evaluate influence of various parameters on performance of structures e.g. (CSA 2015; IAEA 2016), the value of experience should not be underestimated.

Interviews with the station staff and contractors involved in design, construction, commissioning and operation of the structure as well as the walkdowns are required in order to identify information not formally documented and locations of deterioration of the structure.

Based on a review of available information, design and operational exposure conditions of a structure are also compared and engineering judgement is used to document all potential aging mechanisms that might influence performance of the structure being assessed. Evaluation process shown in Fig. 3 is used to assess and prioritize ARDMs. An ARDM matrix is then created to record evaluation results. A structure’s susceptibility to each ARDM is evaluated as high, medium, or low, based on the following criteria:

- **High** means the degradation mechanism is occurring or has occurred, either in this structure or in a similar structure under similar conditions, and that steps have not been taken, or it is unclear if any such steps are adequate to mitigate degradation for the target life or to prevent forced outages, etc.;
- **Medium** means the degradation mechanism is known for this structure or component, either at this facility or a similar one, and is being managed or mitigated; and
- **Low** means the mechanism is possible for the structure, but is easily managed with the current programs or has no impact on achieving target life.

ARDMs not included in the matrix, or those having no marks against them, are considered unlikely for the structure given the environmental conditions or materials or a combination thereof and are not considered further.

Conclusions and health prognoses are provided based on a thorough review of available information with particular attention to aging related degradation. Where sufficient information to provide a health prognosis is not available, activities to support the CA results are recommended. Additionally, recommendations related to existing plant programs are provided to ensure continuing structure health.

AM plan can then be developed based on the understanding of the design, construction, material properties, operating conditions, aging mechanisms and stressors, consequences of degradation, inspection, operation and maintenance history and taking into consideration recommendations for inspection, monitoring and mitigative activates. Refer to CSA N287.8 (2015) for contents of an effective AM plan.

### 3.1.2 Implementation example

Table 1 contains example of ARDM matrix created for a safety related reinforced concrete structure with a non-metallic liner containing demineralised water and exposed to elevated temperatures and radiation. Based on materials and environment of exposure for the structure,
the following ARDMs were considered potentially relevant:

- For concrete:
  - leaching/efflorescence,
  - Alkali Aggregate Reaction (AAR),
  - elevated temperatures/thermal cycling,
  - shrinkage;

- For reinforcing steel:
  - corrosion.

Fig. 3: Assessment of ARDMs (Tcherner and Aziz 2013).
• For embedded parts – corrosion;
• For joint sealant – elevated temperature/thermal cycling, irradiation, weathering, and wear.
• For non-metallic liner - elevated temperature/thermal cycling, irradiation, weathering, and wear.

Each ARDM listed above was systematically evaluated following the process illustrated in Fig. 3. For example, evidences of efflorescence and leaching were observed on the outside (dry) surface of the structure. There was no program in place to detect and manage leaching. Leaching increases porosity and the permeability of concrete, thus lowering its strength and making concrete more vulnerable to aggressive environments. However, since there were no evidences of a widespread degradation, this was considered a local phenomenon that was not likely to affect facility target life. Therefore, medium ranking was given. It should be noted however that as part of the life assessment, recommendations are provided including those related to enhancements to the facility’s aging management program. Thus, although it is stated that the mechanism is not expected to affect facility’s target life, this may change in the long term as local phenomenon may become a widespread phenomenon if aging management is not implemented.

As far as corrosion of reinforcement and embedded parts is concerned, there were no evidences of corrosion damage observed during inspection of the structure. It is however considered possible given the material and environment of exposure including exposure of concrete to demineralised water (discontinuities in the liner were evidenced by observed efflorescence) and elevated temperatures. Leaching may cause local reduction in alkalinity of concrete that might lead to corrosion of reinforcement and embedded parts. Furthermore, elevated temperature tends to accelerate the rate of corrosion reaction. Corrosion has a potential to impact facility’s target life, therefore medium ranking is given.

3.2 Minimizing expected degradation
In order to minimize expected degradation, the operators should understand the importance of aging management and be involved in the implementation of AM plan. Operating conditions that affect aging assumptions should be monitored and trended to ensure that the assumptions made during design are valid. Any excursions or events causing the change in operating conditions should be evaluated and their effects on aging of concrete structures should be assessed.

Aging must be considered when implementing any change in operations or modifications to the structure or its components.

3.3 Checking the degradation
Periodic visual inspections are typically used to ensure adequate performance of the structures. However, nuclear concrete structures often have limited accessibility for visual inspection. In addition, the internal degradation may not necessarily be manifesting itself on the surface of the structure. Therefore, monitoring instrumentation is often relied upon to provide assurance with the integrity of the structure and to confirm its predicted response to the applied loading (e.g. during containment leakage rate test).

Monitoring of environmental and operating condition enables assessing and trending the degradation stressors. While it is imperative for inaccessible structures to ensure that design assumptions are valid, it has also proven to be useful to monitor environment of exposure of accessible structures particularly in between periodic inspections. The change in exposure environment might facilitate existing degradation mechanisms and may cause origination of the new ones, i.e. the aging management activities may need to be refocused on other mechanisms than those identified as per the original condition assessment. Depending on the structure, its location, geometry, function and possible degradation mechanisms, monitoring of the following parameters has proven to be simple (as far as monitoring instrumentation involved) and informative: ambient and operation temperature and humidity, chemistry of the ground water and soil, elevation of the ground water table and its fluctuations, monitoring chemistry, temperature, level of the liquid inside the structure (for liquid retaining structures) and the amount of a make-up water.

As aging is a dynamic process, it is important to trend performance of the structure in order to establish the rate of degradation. Experience shows that in order to track performance of the structure, condition indicators – a characteristic of the structure that may infer or directly indicate the current and future ability of the structure to function within acceptance criteria. Examples of condition indicators include cracks, spills, delaminations, deflections, ingress of harmful substances (e.g. chlorides), depth of carbonation, leak rate, prestressing force.

Furthermore, environmental and operating conditions (e.g. temperature, humidity, radiation, chemistry of the water and soil that the structure is exposed to) should be trended and any excursions from the parameters considered in the design should be noted to establish the relationship between degradation and associated stressors. Predictions for future performance of the structure may then be made based on the analysis of past performance, the rate of degradation and the changes in associated stressors. Knowledge of the rate of degradation and influencing parameters will also allow selecting appropriate mitigative measures if necessary.

3.4 Mitigating degradation
Maintenance activities may be required to mitigate degradation. These might include preventative maintenance, corrective maintenance, spare parts management, and replacement. Typically, corrective maintenance is used for nuclear concrete structures.

OPEX shows that majority of the issues with concrete structures are either directly caused by or facilitated by
Inadequate repairs may facilitate degradation of the structure and are often impractical to mitigate. Therefore in order to ensure satisfactory and long-lasting repair, the importance should be placed on the pre-qualification tests as opposed to the verification tests. Materials qualified by tests and satisfactory field performance in similar application and environment should be specified. The pre-qualification tests should be performed to ensure proper application of the specified material in the anticipated conditions. Mock-up tests should be considered for first-of-a-kind repair activities. Additional information related to waterproofing of nuclear concrete structures is provided (Tcherner 2015b).

### 3.5 Optimising aging management

As illustrated in Fig. 6, the inputs for optimisation of the AM plan include the lessons learned from implementation of the AM Plan including operating, inspection and mitigation activities.

Repeating evaluation for aging management and condition assessment would determine if there are any changes in the condition of the structure that may necessitate changes to operation, inspection/monitoring and maintenance activities. It would also help ensuring that operating and environmental conditions that were accounted for in design have not changed. As aging is a dynamic process, the benefits of trending the stressors as well as the performance of the structures to improve understanding of aging as discussed in Section 3.3 cannot be overemphasised. This information needs to be addressed when optimising AM plan.

Furthermore, it is important to consider applicable OPEX and R&D activities thus help addressing any “surprises” that tend to manifest themselves more often.
as the knowledge and experience in NPP operation and nuclear concrete structures’ performance grows.

Thus, optimising includes improvements/revisions to AM Plan addressing the following:

- Evaluation of changes in performance of the structure via monitoring and trending of condition indicators;
- Evaluation of changes in the environmental and operating conditions via monitoring and trending of the stressors and comparing them to those considered in the design;
- Evaluation for aging management and condition assessment (i.e. life assessment);
- Relevant OPEX including OPEX with implementation of AM Plan as well as OPEX with performance of other structures subjected to similar environmental and operating conditions; and
- Relevant R&D.

4. Conclusions

OPEX indicates that concrete structures have a history of reliability and durability, but there have been occurrences of degradation. As OPEX increases, more “surprises” are to be expected. Degree of degradation depends on quality of the structure as constructed and the aggressiveness of environment. Analysis and design assumptions should be confirmed during the life of the structure to account for changes in operating environment and material properties. If changes are identified (such as higher operating temperatures, greater loading), their effect should be evaluated and analyses need to be updated so that the structures can perform their functions safely. Material properties used for analysis should consider aging of the structure. Specifically for concrete structures, samples should be obtained if possible and tested to determine actual properties that account for aging. Concrete, unless subjected to degradation is known to gain strength with age. This should be confirmed by physical testing and should be accounted for when analysis of mature structures are performed.

An evaluation for aging management and condition assessment for nuclear safety-related structures performed as part of periodic safety review, in preparation of life extensions, to establish a baseline condition for periodic inspection, prior to modification of the structure, or for other purposes provide an effective tool in assessing aging of the structures, evaluating their current condition, providing a health prognosis, recommending remedial measures and identifying opportunities for improvements including design, operation and aging management.

It is important to consider instrumentation as well as ability to inspect and monitor the structures during design and construction. Concrete containment structures particularly those with grouted post-tensioning system should be monitored to ensure that they will continue meeting their functional requirements and have adequate margins available during the life of the plant (including life extensions). Monitoring of the stressors (environmental and operating conditions) and perform-
anc of the structure is paramount.

In spite of recently issued documents providing requirements and guidance for aging management of nuclear concrete structures, the decisions are largely based on engineering judgement necessitating involvement of knowledgeable and experienced personnel.

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