CANDU ENERGY EXPERIENCE IN CONDITION ASSESSMENT OF NUCLEAR SAFETY RELATED CONCRETE STRUCTURES

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ABSTRACT

A nuclear research facility went into operation in the mid-1950s. While the nuclear facility doesn’t produce electricity, it serves as a materials and fuel testing facility and supports and advances the CANDU® design technology. It produces neutrons used to investigate and non-destructively study all types of industrial and biological materials. It is also produces medical isotopes used in both the diagnosis and treatment of life-threatening diseases.

It is important to confirm the integrity of the safety-related concrete structures to continue successful operation of the facility. 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. Upgrades of systems and structures took place over the years to support the changes in research activities and to increase safety and reliability of the facility.

The objective of the Condition Assessment (CA) is to evaluate the current condition of the structure and to provide a health prognosis. 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, and operational requirements. The health prognosis for extended life is then based on both this current condition and a systematic identification and assessment of Ageing Related Degradation Mechanisms (ARDMs) and their impact on the functional requirements of concrete structures.

The condition of the safety-related concrete structures of the facility was assessed. This paper presents the methodology used to perform the Condition Assessment. The overall performance of safety-related concrete structures after more than 50 years exposure to radiation, elevated temperatures, and other aggressive environmental parameters is described. The knowledge gained during this assessment is unique considering the age of the facility.

1. INTRODUCTION

A nuclear research facility that started operation in the mid-1950s serves as materials and fuel testing facility and supports and advances the CANDU design technology. It produces neutrons used to investigate and non-destructively study all types of industrial and biological materials. It is also used to produce medical isotopes used in both the diagnosis and treatment of life-threatening diseases.

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 of the facility, continuous integrity of the safety-related concrete structures shall be ensured by controlling and mitigating ageing related degradation. A key

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element of ageing management is the systematic and rigorous assessment of structures. Ageing assessments generally involve a review of facility data to assess the effect of age related degradation on safety-related structures, establish their current condition, and provide predictions of future performance.

2. CONDITION ASSESSMENT PURPOSE

The Condition Assessment is a form of ageing assessment that is typically applied to structures or groups of structural components with similar characteristics. CA involves a general review of design, manufacturing, construction, commissioning, operations, inspections and maintenance at a component level.

Typically, a CA has the following major purposes:

(1) To establish structure baseline conditions to which results of the future periodic inspections, testing, and monitoring can be compared;

(2) To identify Ageing Related Degradation Mechanisms (ARDM) that may cause degradation and also identify structural components / areas most susceptible to degradation; and

(3) To provide a health prognosis for the structure.

The Ageing Management Program (AMP) can then be optimized to concentrate efforts on critical areas and use inspection and monitoring techniques that are appropriate for the suspected degradation. CA results enable schedule optimization for periodic inspections by prioritizing structures and components in terms of safety significance, environmental exposure and anticipated degradation tolerance.

As stated in Safety Guide NS-G-2.12 [1], an ageing management review is an integral part of a CA. Thus, in addition to current condition and future health predictions, CAs are performed to identify changes necessary to address issues related to ageing effects, and may include economic improvement opportunities. As a result of CAs, recommendations are provided to ensure a structure’s integrity and capability to satisfy design requirements until the end of its design life, which includes any planned life extensions and requirements during decommissioning.

CAs can be performed periodically, in conjunction with periodic safety reviews (PSRs) [2]. Defining and updating knowledge of the actual condition of Systems Structures and Components (SSCs) is necessary to satisfy PSR objectives. Candu Energy has performed a number of CAs for CANDU plants in preparation for life extensions. A CA is required to be completed as part of the ageing review for long-term operation beyond the assumed design life of the plant. As defined in Canadian regulatory document RD-334 [3], the CA also forms part of the integrated AMP framework.

3. CONDITION ASSESSMENT METHODOLOGY

Figure 1 provides an overall generic schematic of the CA process. A methodology developed and specifically tailored to civil structures includes the following:

- Gather and review design, manufacturing, construction, commissioning, operation, inspection, and maintenance history, and any other relevant documentation;
- Define the design basis and identify any changes made to the structure during construction and operation;
- Establish the structure's physical and functional boundaries and associated components;
Undertake an ageing assessment of structures or components remaining after screening. This includes an assessment of ARDMs, ageing evaluation, and establishing the structure’s health prognosis; and

Provide recommendations for each structure in terms of repair and monitoring, as well as maintenance activities to ensure plant safety and production goals over the plant life.

The depth and quality of the CA is highly dependent upon the qualifications and experience of personnel performing it, and on the quality of gathered information. Besides a review of documents and drawings, interviews with site personnel, suppliers, constructors, etc. typically help to identify information that was not formally documented. Walkdowns and photographs are essential as they help in identifying locations of distress and possible deterioration of a structure.

Based on a review of available information, design and operational exposure conditions of a structure are also compared. Engineering judgement is used to document all potential ageing mechanisms that might influence performance of the structure being assessed. Evaluation process shown in Figure 2 is used to assess and prioritize ARDMs. An ARDM matrix is then created to record evaluation results, an example of which is shown in Table 1.

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 programmes or has no impact on achieving target life.

ARDMs not included in the table, or those having no marks against them in the table, 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 ageing 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 programmes are provided to ensure continuing structure health.

4. **DISCUSSION OF RESULTS**

Given the ages of concrete structures of the nuclear research facility and the duration of their exposure to nuclear operating environments, the experience gained assessing the condition of these structures is invaluable. Although the nuclear research facility does not produce electricity, the structures within the facility are exposed to elevated temperatures and temperature fluctuations, radiation and moisture. The effects of these on the performance of the structures are discussed below.

4.1 **Exposure to Radiation**

The following sources of radiation contribute to the absorbed dose in the reactor concrete structure: core fission neutrons, prompt gamma radiation, neutron-capture gamma radiation, decay gammas from fuel and decay gammas from activated core components. Fast and thermal neutrons may cause expansion of aggregates, decomposition of water and heating of concrete. Gamma radiation affects
the cement paste, producing heat and causing water migration. Continuous exposure of a structure to radiation may cause a decrease in the tensile and compressive strength and modulus of elasticity of concrete.

Due to the difficulties with obtaining quantifying exposure and testing the irradiated concrete samples, there is not a lot of data available on effects of radiation on concrete properties. As the energy of absorbed radiation is converted to heat, it is difficult to separate the effects of irradiation from the effects of temperature exposure. As noted in Reference [4], heat generated by the radiation is quite insignificant in comparison to the temperature generated by a reactor vessel as a whole.

Based on reviewed experimental data, approximate threshold levels necessary to create measurable damage in concrete cited in References [5], [6] and [7] are $1 \times 10^{19}$ neutrons/cm$^2$ for neutron fluence and $1 \times 10^{10}$ rads of dose for gamma radiation. Higher threshold levels of $10^{19}$ neutrons/cm$^2$ for fast neutrons and $10^{12}$ rads for gamma radiation were cited in a study described in Reference [8]. It is possible that in addition to the concrete composition and variations in testing conditions, the combination of the levels of neutrons, gamma radiation and temperature exposure could be important in quantifying the adverse effects on concrete properties. A study cited in Reference [4], reported that exposure to the neutron fluxes of $10^9$, gamma dose of $10^{11}$ rad and temperature of 130°C had minimal effects on concrete.

Concrete is an effective shield against neutron and gamma radiation as demonstrated by the rapidly decreasing dose rate as a function of distance through the shield [5]. Thus, as noted in References [5] and [8], only the concrete closest to the inner surface could be subjected to higher levels of radiation; at a distance of greater than 50 cm, nuclear radiation is attenuated sufficiently so that it is of no significance to the mechanical properties of concrete. It is also acknowledged in References [5] and [8] that the design of the structures exposed to the levels of radiation around the thresholds cited above is typically governed by shielding requirements and therefore some deterioration of the concrete strength characteristics can be tolerated particularly since the shielding effectiveness of the concrete seems to be unaffected by radiation. Furthermore, as stated in Reference [7], irradiation has little effect on shielding properties of concrete beyond the effect of moisture loss due to increased temperature.

The massive reactor concrete structure of the research facility is exposed to a benign indoor environment, in which concrete strength is typically increases with age. Adverse effects of radiation on shielding properties and the load carrying capacity of the structure are considered negligible as the neutron radiation that the reactor concrete structure is exposed to on the inside and the temperature in the concrete due to the cooling are below the threshold levels cited in the literature. It should be noted however, that there is a lack of available data to understand the effects of radiation on properties of concrete beyond 60 years of exposure and studies have recently been initiated on this subject by research organizations in the United States [9] and Japan [10].

4.2 Exposure to Temperature and Temperature Fluctuations

Safety-related concrete structures of the nuclear research facility are not routinely exposed to temperatures above those that may significantly affect concrete properties. The long term exposure temperature is typically below 65°C as per Canadian nuclear codes. Locally, however, concrete surfaces have been exposed to higher temperatures for periods of time.

Temperature gradients and temperature fluctuations can cause thermal strain and cracking, especially in massive restrained structures such as those used in the research facility since the heat is unevenly dissipated from the concrete mass.

Cracks were observed in the walls of the structures used for experiments in the nuclear research facility. Over the years, the use of the structure changed to suite the experimental requirements. Concerns with possible overloading of the structures were raised and a finite element analysis (FEA) was performed. While addressing concerns with overloading, the importance of maintaining the
temperature inside the structures such that the temperature gradient is within the values that were used in the analysis was noted.

Cracks’ propagation as well as the temperatures are measured periodically to evaluate if cracks dimensions change with time specifically in relation to temperature changes due to reactor start up and shut down and those associated with the changes in operating conditions (Figure 3). One hundred and fifty mm long DEMEC Mechanical Strain Gauge with the accuracy in the order of 0.001 mm is used for strain measurements.

4.3 Exposure to Water

As water tends to facilitate a variety of degradation mechanisms, exposure of concrete structures to water leads to progressive degradation and typically requires the most attention as experience with many condition assessments performed shows. Often remedial measures including repairs and monitoring are required to preserve integrity of the structure.

The structures of nuclear research facility due to the age of the facility experienced a long term exposure to action of standing, flowing or spraying water.

Flowing water causes loss of material from the concrete surface with time due to abrasion, erosion or cavitation. Demineralised or acidic water causes deterioration of calcium hydroxide in concrete resulting in gradual disintegration of concrete. Concrete exposed to water experiences leaching which, causes an increase in porosity and permeability of concrete lowering its strength and making the concrete more vulnerable to an aggressive environment. Also, leaching causes local reduction in alkalinity of concrete leading to corrosion of reinforcement. Corrosion result in a reduction of cross-section area of the reinforcement, which reduces the load carrying capacity of the structure. Rust, formed because of corrosion, occupies up to seven times the volume of steel, thus inducing splitting forces that cause cracking and spalling of concrete. Expansion and spalling of concrete due to reinforcement corrosion might adversely affect the integrity of the mechanisms supported off the concrete structures and cause interferences for the operation.

Areas of concrete at the air/water interface that are exposed to alternate wetting and drying tend to deteriorate more than those exposed to the steady water. Figure 4 shows a picture of a water retaining structure at nuclear research facility showing cracking. Signs of leakage are visible on the other side of the wall of this structure.

5. SUMMARY AND RECOMMENDATIONS

Considering the age of the nuclear research facility, the condition of concrete structures assessed was mostly satisfactory. Concerns associated with overloading and temperature exposure were addressed and recommendations for operations and ageing management to ensure the long term integrity of the structures were provided. Cracks propagation and the temperatures are measured periodically to ensure that existing cracks are passive (i.e. not growing or changing dimensions) and do not adversely affect performance of structures. Structures exposed to the action of water appear to sustain the most damage and in some cases require repair.

A Condition Assessment for nuclear safety-related structures could be 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. It is an effective tool in assessing ageing of the structures, evaluating their current condition, providing a health prognosis, recommending remedial measures and identifying opportunities for improvements including design, operation and ageing management.

The importance of ensuring that operating conditions including environment and loading, etc. remain within the parameters that were accounted for in the design cannot be overemphasized. 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 ageing of the structure. Specifically for concrete structures, samples should be obtained if possible and tested to determine actual properties that account for ageing. Concrete, unless subjected to degradation (such as leaching for example) 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.

6. REFERENCES

Table 1 Example of Ageing Related Degradation Mechanism Matrix

<table>
<thead>
<tr>
<th>ARDM</th>
<th>Concrete</th>
<th>Reinforcing Steel</th>
<th>Steel Components</th>
<th>Sealing Compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Attack</td>
<td>Low</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fatigue / Vibration</td>
<td>-</td>
<td>-</td>
<td>Low</td>
<td>-</td>
</tr>
<tr>
<td>Thermal Exposure / Cycling</td>
<td>Medium</td>
<td>-</td>
<td>-</td>
<td>Medium</td>
</tr>
<tr>
<td>Irradiation</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Corrosion</td>
<td>-</td>
<td>Medium</td>
<td>Medium</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 1 Schematic Condition Assessment Process
Figure 2 Assessment of ARDMs
Figure 3 Measurements of Crack Propagation

Figure 4 Deterioration of Water Retaining Structure: Cracks, Signs of Leaching