An Approach Regarding Aging Management Program for Concrete Containment Structure at the Gentilly-2 Nuclear Power Plant

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Abstract

The current paper presents the approach used by the Gentilly-2 Nuclear Power Plant, Hydro-Quebec, in elaborating a specific Aging Management Program (AMP) for its concrete containment structure. It is developed as a part of preparation activities for the plant refurbishment project. The specificity of the AMP consists in addressing Alkali-Aggregate Reaction (AAR) degradation mechanism which is not well known in the nuclear power industry. HQ developed a numerical model based on finite elements for assessing the concrete containment structure behaviour under the impact of AAR and other relevant degradation mechanisms. Such predictions enable a better targeting of corrective and mitigating actions during the second cycle of the G-2 operation while required.

Key words: Aging Management Program, Alkali-aggregate reaction, Concrete containment structure.

1. Introduction

The design life of existing nuclear power plants was often chosen to be 30-40 years. This original 40-year term for reactor licenses was based mainly on economic considerations – not on limitations of nuclear technology [Naus, D.J., 2008]. Due to this selected period, some structures and components may have been designed on the basis of an expected 30-40-year service life. Given than numerous NPPs are at the end of this projected life span, and plan to continue operation for another 25-40 years, it is essential to elaborate adequate aging management programs.

It is essential that the effects of age-related degradation of plant structures, as well as systems and components, be assessed and managed during both the current operation and subsequent extension life cycle period for ensuring the safe operation of nuclear power plants in the extended life cycle.

The nuclear power plant Gentilly-2, Hydro-Quebec, is approaching the end of its initially designed life cycle of 30 years. The plant is poised for a major refurbishment project to extend its life cycle for another 25-30 years. Such an enterprise also involves elaborating satisfactory aging management programs (AMP) of systems structures and components (SSC) critical for both safety and generation, including its concrete containment structure. It is important to emphasize that the concrete structures at G-2 are also under impact of a particular degradation mechanisms known as Alkali-Aggregate Reaction (AAR), which is not necessarily observed as a nuclear industry-wide phenomenon. So, the G-2 AMP also has to adequately address this particular issue in its AMP.

The paper presents a G-2 approach in developing a systematic AMP for its concrete containment structure.

2. Relevant Degradation Mechanisms

In general, the degradation mechanisms affecting concrete structures are extensively studied and relatively well known. It is also true for the concrete containment structures in the nuclear power industry where those degradation mechanisms are subdivided in the following subgroups as a function of the main influence factors: temperature, chemical, mechanical or radiation [HQ Technical Documentation; EPRI, 2010; COG, 2009].

However, not all the degradation mechanisms presented in the technical and scientific literature are applicable to the G-2. Extensive research works at G-2 [HQ Technical Documentation] have identified a number of dominant degradation mechanisms, which have to be monitored and controlled:

- Cracking occurred during concrete construction (due to constraints related to thermal hydration),
- Freeze-Thaw,
- Concrete creep and loss of post-tension,
- Impact of seism,
- Periodic integrated leakage-rate testing (high pressure air tightness safety testing) at 124 kPa(g) (each 3 years),
- Alkali-Aggregate Reaction (AAR)

Other known concrete degradation mechanisms [IAEA, 1998; EPRI, 2010] have been analyzed as well but no immediate particular activity is needed in the AMP for their control. However, the designed aging management program (AMP process) has capabilities of capturing any new issues/concerns (observed at G-2, through new knowledge or industry-wide operating experience - OPEX) for taking them into account more closely, and elaborating the disposition in an adequate manner.

Alkali-aggregate reaction (AAR)

AAR is a chemical processes that involves the reaction of alkali ions in cement with silica mineral aggregates, and can cause degradation in concrete [EPRI, 2010]. The reaction forms an alkali-silica gel that expands when it comes into contact with water, generating hydrostatic pressure. A similar reaction involves carbonate aggregates and alkalis. Incipient-stage damage of this sort typically manifests itself as small surface cracks in an irregular pattern. Extensive damage due to alkali-aggregate reactions consists of crack propagation in the direction of least impedance (for example, normal to a compressive stress direction).

3. Technical Basis of the Aging Management Program

3.1 General Approach

Basic requirements and safety functions for containment structures include [Naus, D.J., 2008]:

- Provide an "essentially" leak-tight barrier against the uncontrolled release of radioactivity to the environment for all postulated design basis accident conditions;
- Accommodate the calculated pressure and temperature conditions resulting from a loss-of-coolant accident and other postulated accidents;
- Withstand periodic integrated leakage-rate testing at the peak calculated accident pressure that maybe at levels up to and including the containment design pressure; and
- Permit appropriate periodic inspection of all important components and surfaces and the periodic testing of the leak tightness of containment penetrations.

The Aging Management Program of the concrete containment structures is a set of engineering, operation and maintenance actions to control its aging degradation within acceptable limits. These actions include inspections, detection and assessment of defects, maintenance, component replacement or refurbishment, and modification of operations [COG, 2009].

The technical basis of the aging management program for the concrete containment structure at G-2 is based on the regulatory requirements and philosophy described in RD-334, CSA N287.7-08, and CSA N285.5-08. The program's intent is to comply with these regulatory documents.

This AMP primarily aims at elaborating an adequate inspection and monitoring program for controlling aging degradation mechanisms, and proposing, in a structured way, corrective/mitigating actions if required, which will ensure an acceptable fulfilling of its safety function for the second life cycle after the refurbishment (another 25-30 years). The AMP has to be a living program and should also be integrated without major changes into existing plant-wide Quality Assurance program.

The program also defines the following specific objectives:

- Assure the regulatory compliance to relevant standards and CNSC regulatory documents
- Monitor and control AAR
- Optimize the frequency of the integrated leakage-rate test.

Apart its own technical and research works within Hydro-Quebec (HQ), the program takes into account relevant internal and external operating experience, industry-wide research works, and the best practices in this area [IAEA, 1998, 1999; 2000; 2001; 2006, 2009a; 2009b; EPRI, 2003; 2005; 2006; 2007; 2008; 2010; NRC, 2000, 2003a, 2003b, 2004, 2006a, 2006b, 2010; 2011, COG, 2006, 2008, 2009, 2010, 2011; HQ Technical Documentation; Gocevski, 2010; NEA/CSNI/R, 2009].

3.2 AAR issue

Addressing the issue related to the impact of AAR on the G-2 concrete containment structure requires more elaborated approach. This matter was also extensively discussed with CNSC who requires that Hydro-Quebec develops an adequate approach in tackling this problem. The AAR may potentially affect the concrete structural integrity, and the air tightness of the concrete containment envelope due to a development of micro and macro cracking [HQ Technical Documentation; EPRI, 2010]. The existing nuclear industry-wide experience and practice do not provide sufficient technical basis to deal adequately with this AAR concern, and HQ has had to develop its own methods in this regard.

The G-2 NPP as a part of Hydro-Québec has chosen to develop a numerical model based on finite elements, which has capabilities of accurately modeling the impact of relevant degradation mechanisms including AAR. It is based on the significant experience of other HQ's hydro dams and structures which have been affected by the AAR. HQ structural experts have developed an elaborated approach using numerical simulations based on finite elements for predicting the structural behaviour of those structures under the impact of AAR. The accurate prediction of their behaviour is of a great value in defining corrective and mitigating actions. Thus, the G-2 NPP made a decision of developing an extensive collaboration with HQ's structural experts in this field for tackling the AAR issue. A numerical model of the reactor building has been developed. It includes all the relevant degradation mechanisms including AAR for temporal definition of its behaviour. The numerical model has been validated against CSA N286.7 Standard. This orientation is in general consistent with the newest industry developments [NRC, 2006b, 2010].

The fact that this model is able to predict the behaviour of the concrete containment structure over time helps the decision-making process in defining and targeting corrective and mitigating actions if required. It is integrated in the whole AMP as its constitutive part. There is little experience in the nuclear power industry of systematically integrating numerical model tools into an integral AMP of concrete containment structures. Therefore, its adequate integration into the program represents an engineering and organisational challenge. The technical and mathematical basis of the numerical model is discussed below.

4. Structure of the aging management program

In accordance with regulatory requirements, and best industry practices, the constitution of the AMP of the concrete containment structures at G-2 understands several activities and tasks. The G-2 program takes into consideration high level approaches proposed by [IAEA, 1998, 2000; 2001; 2006, 2009a; 2009b; COG, 2009; CNSC, 2011; HQ Technical Documentation]:

- Periodic inspection of the containment SSC for the identification and assessment of defects,
- Monitoring and/or mitigation of defects by existing, modified or new maintenance activities,
- Repair defects

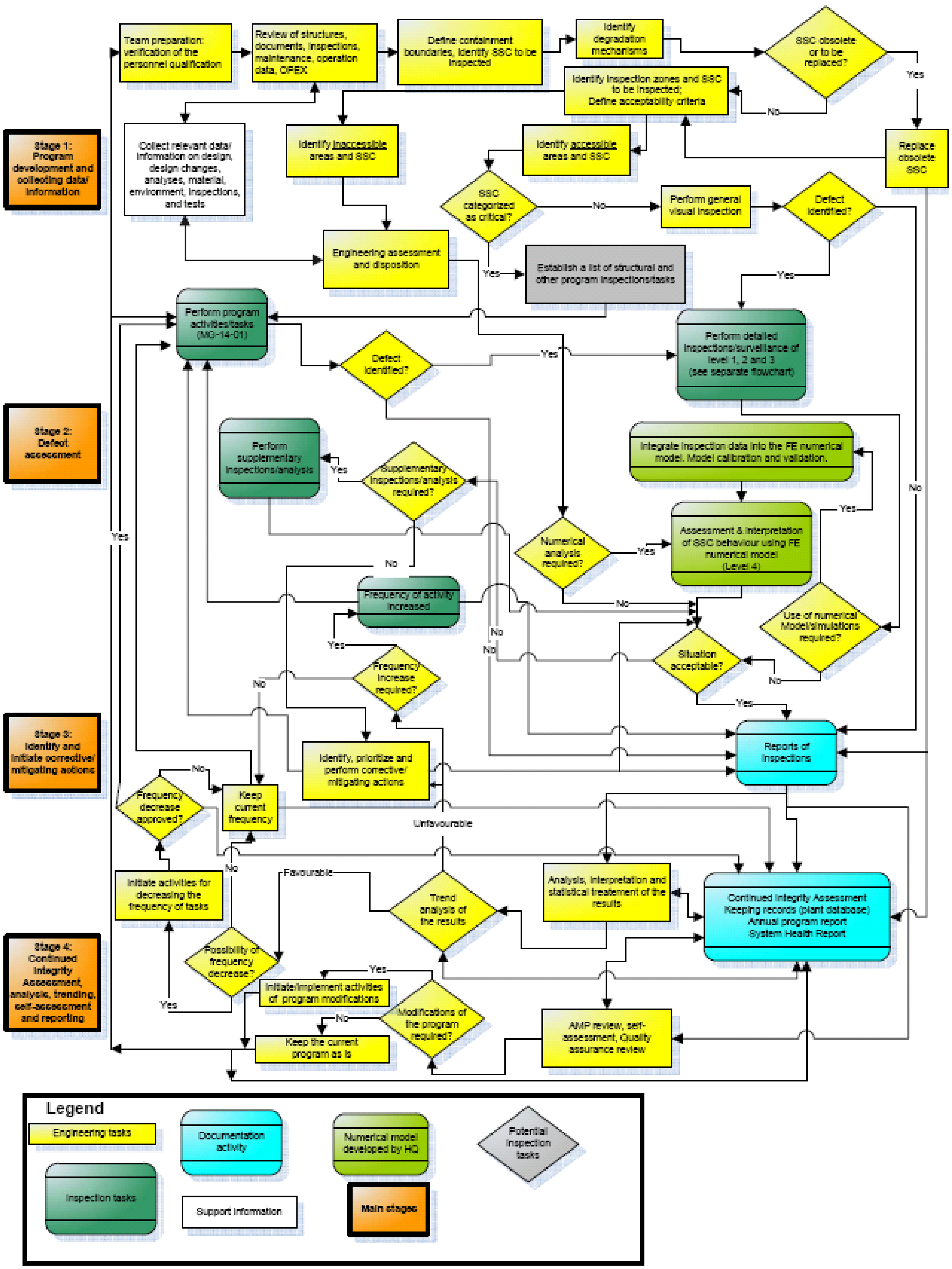


Figure 1: High level flowchart of the concrete containment aging management program at the G-2 NPP

- Record keeping
- Continued integrity assessment
- Trend assessment.

The AMP flowchart is depicted in Figure 1. It also shows the integration of the numerical model into the program which is a novel approach in the nuclear power industry in Canada. The proposed process relies to a similar four stage approach depicted in [COG, 2009]. Meanwhile, it has been significantly modified in order to take into account G-2 specific needs. The AMP shown in Figure 1 is designed as a living process.

The program developed an approach where it uses four levels of inspection, monitoring and assessment regarding the concrete containment structure as a part of the entire AMP depicted in Figure 1:

1. Visual inspections
2. Instrumentation and non destructive evaluation (NDE)
3. Sampling and destructive evaluation
4. Structural integrity evaluation and use of the numerical model based on finite elements.

Detailed flowchart regarding four levels of inspections is shown in Figure 2.

In general, the first three levels of inspection are widely applied in the nuclear power industry managing concrete aging issues with frequent and well known degradation mechanisms. The fourth level proposed in the G-2 AMP is a novel approach. It is aiming at particularly addressing AAR issue through an accurate prediction of behaviour of structures under the impact of AAR. Such information is of a great value in defining corrective and mitigating measures. In our opinion, numerical simulations are not necessarily required for concrete containment structures in the absence of AAR although it may be valuable as a decision-supporting tool.

Data collected in the first three levels of inspection and monitoring serve as input into numerical model for its calibrations. Thus, it will integrate latest inspection data enabling more accurate predictions of the reactor building (RB) behaviour (potential displacements and crack network propagation which could affect RB air tightness) through a decrease of modelling uncertainty (epistemic and aleatory).

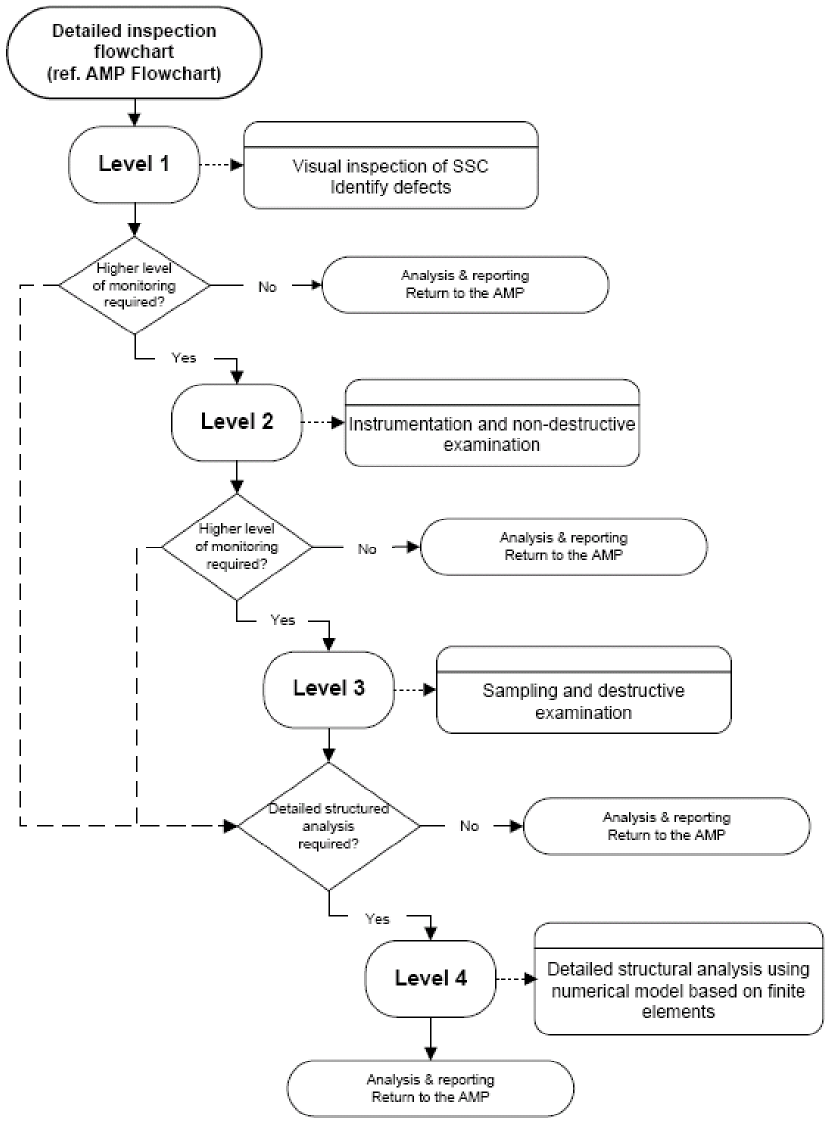


Figure 2: Four level detailed inspection and monitoring program activities

The development and implementation of the AMP at G-2 is designed in three phases:

1. Aging Management Program design
2. Implementation and inaugural inspection
3. Integration of AMP into plant organisational structure and program application and maintenance

The relevant governing documents, tools and procedures have been elaborated. Certain works are in preparation or ongoing (procedure/tools development, procurement and installation of instrumentation for NDE, personnel training etc).

The criticality of the containment SSC is basically determined using approaches defined in INPO/WANO AP-913 Equipment Reliability Process and [INPO, 2007].

The AMP organisational structure takes into consideration the G-2 organisation with defined roles and responsibilities. Figure 3 depicts a general organisational scheme.

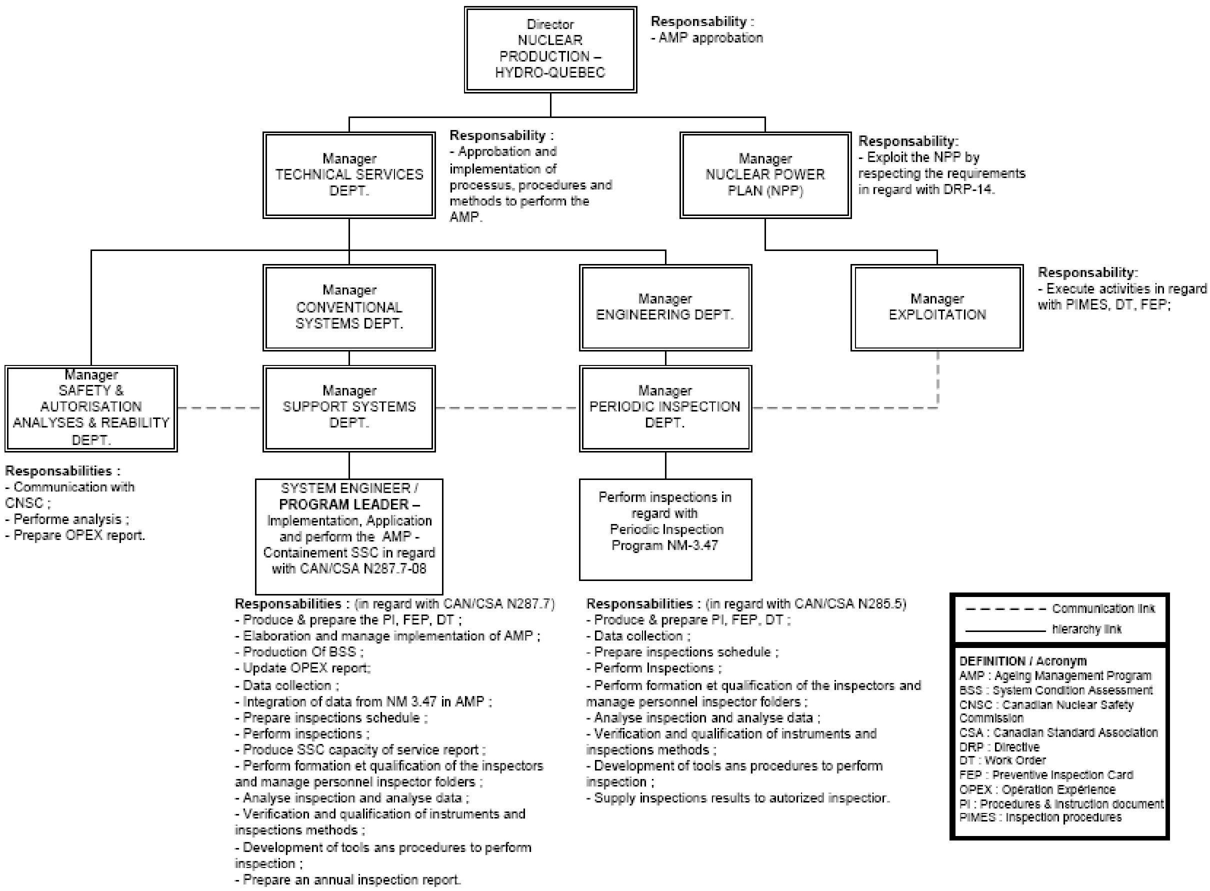


Figure 3: Organisational structure of the G-2 concrete containment AMP

5. Technical Basis of the Numerical Model Integrating AAR Impact at G-2 NPP

5.1 General Characteristics and Technical Basis

This section describes both the technical and mathematical basis of the concrete containment numerical model based on finite elements introduced above, which is an integral part of the G-2 concrete containment AMP (see Figures 1 and 2).

The material properties of the containment structures at the G-2 NPP evolve with the age of the plant due to environmental influences as well as various chemical processes.

The main source of chemically triggered degradation at G2 concrete and reinforced concrete structures is the alkali-aggregate reaction (AAR). The product of the reaction is a gel that forms around the aggregate particles; it imbibes water from the pore fluid and expands triggering a progressive damage of the material. The rate of expansion depends primarily on the available alkali content of concrete. Other factors influencing the kinetics of the reaction are the relative humidity, temperature and the confining stress.

In order to adequately describe the behaviour of reinforced concrete affected by AAR a finite element model of the reactor building is developed. The analysis is conducted by employing a non-linear continuum theory that incorporates a chemo-mechanical coupling.

In this approach, the reinforced concrete is considered as a composite medium comprising the concrete matrix and a set of families of reinforcement. The overall macroscopic behaviour is then defined by employing suitable averaging procedures. In the framework employed for the analyses of G2 structures, the concrete is assumed to be strengthened with two orthogonal sets of reinforcing steel bars as is in general the case for G2.

The formulation addresses the main stages of the deformation process, i.e. a homogeneous deformation mode as well as that involving localized deformation, associated with formation of macro-cracks. In the former case, i.e. prior to cracking, the problem is formulated by invoking a volume averaging procedure. After the onset of localization, the representative volume incorporates the fractured zone and the adjacent 'intact' material, both reinforced with steel bars. In this case, the stiffness of the reinforcement network and the criterion of yielding are both assessed in a discrete sense, by considering the bending characteristics of individual bars rigidly embedded in the adjacent intact material.

The concrete itself is assumed to suffer from continuing alkali-aggregate reaction. The mathematical description of the effects of the reaction is based on chemo-plasticity and invokes the assumption that the formation of expansive phases results in progressive degradation of both strength and deformation properties of the material. The governing constitutive relations have been incorporated in a finite element code.

5.2 Mathematical Formulation of the Numerical Model Describing AAR

The specific form of the constitutive relation for describing the AAR-affected reinforced concrete is elaborated in the report by Gocevski & Pietruszczak (2011), as well as in the recent paper submitted for publication in CJCE by Pietruszczak, Ushaksaraei and Gocevski (2011). In this approach, the material is treated as a composite medium comprising the AAR-affected concrete matrix (*m*) and two orthogonal families of reinforcement (sets *1* and *2*, respectively).

For concrete matrix, the formulation incorporates a scalar parameter ζ which is a measure of the continuing reaction and is defined as

$$\zeta(t) = \frac{\in(t)}{\bar{\in}}; \qquad \bar{\in} = \in(t \to \infty) \tag{1}$$

Here, $\in(t)$ is the volumetric expansion of concrete and $\bar{\in}$ is a material parameter that defines the maximum value of $\in$, for a given alkali content, in the stress free state. The evolution law is assumed in a simple linear form

$$\dot{\zeta} = \gamma(\bar{\zeta} - \zeta) \quad \text{for} \quad t \geq t_0 \quad \Rightarrow \quad \zeta = \bar{\zeta}(1 - e^{-\gamma\langle t - t_0 \rangle}); \qquad \zeta = 0 \quad \text{for} \quad t < t_0 \tag{2}$$

where $\bar{\zeta}$ is the state variable associated with the chemical equilibrium, γ is a material constant describing rate of the reaction, and t_0 is the initiation time.

The value of $\bar{\zeta}$ depends, in general, on the confining pressure, temperature and relative humidity.

The formulation of the constitutive relation that governs the chemo-mechanical interaction follows the framework established in an earlier article by Pietruszczak and Gocevski (2002). Following a standard plasticity procedure, the constitutive relation can be obtained as

$$\dot{\boldsymbol{\varepsilon}} = [C]\dot{\boldsymbol{\sigma}} + \boldsymbol{\Gamma}\dot{\zeta}; \qquad \boldsymbol{\Gamma} = \mathbf{b} + \frac{1}{H}\frac{\partial f}{\partial \zeta}\frac{\partial Q}{\partial \boldsymbol{\sigma}} = \frac{\partial}{\partial \zeta}[C^e]\boldsymbol{\sigma} + \frac{1}{H}\frac{\partial f}{\partial \zeta}\frac{\partial Q}{\partial \boldsymbol{\sigma}} + \frac{1}{3}\bar{\in}\boldsymbol{\delta} \tag{3}$$

where

$$[C] = [C^e] + \frac{1}{H}\frac{\partial Q}{\partial \boldsymbol{\sigma}}\left(\frac{\partial f}{\partial \boldsymbol{\sigma}}\right)^T; \qquad H = -\left(\frac{\partial f}{\partial \boldsymbol{\varepsilon}^p}\right)^T \frac{\partial Q}{\partial \boldsymbol{\sigma}} \tag{4}$$

In the equations above, f is the yield function, $[C]$ is the elastoplastic compliance operator, H is the plastic hardening modulus and $\boldsymbol{\delta}$ is the Kronecker's delta.

For reinforced concrete, the problem is formulated in two stages (Pietruszczak & Winnicki 2003; Pietruszczak, S., & Gocevski, 2002). Stage I deals with the homogeneous deformation mode prior to cracking of the concrete matrix, whereas stage II involves a localized deformation associated with formation of macro-cracks.

- ***Stage I (prior to cracking)***

The problem is referred to the frame of reference $\mathbf{x}^*$, such that x_2^* and x_3^* are along the axes of reinforcement (Figure 4).

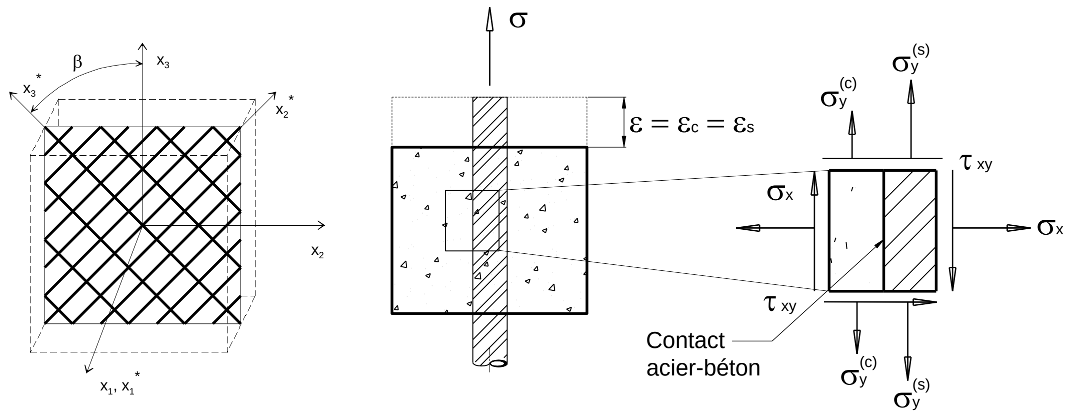


Figure. 4. Schematic representation of the composite medium (Stage I): local (**x***) and global (**x**) coordinate systems

The average macroscopic stress/strain rates for the composite body are defined through the volume averaging procedure (Hill, 1963), i.e.

$$\dot{\boldsymbol{\sigma}}^* = \eta_1\dot{\boldsymbol{\sigma}}_1^* \; + \; \eta_2\dot{\boldsymbol{\sigma}}_2^* \; + \; (1-\eta_1-\eta_2)\dot{\boldsymbol{\sigma}}_m^* \; ; \quad \dot{\boldsymbol{\varepsilon}}^* = \eta_1\dot{\boldsymbol{\varepsilon}}_1^* \; + \; \eta_2\dot{\boldsymbol{\varepsilon}}_2^* \; + \; (1-\eta_1-\eta_2)\dot{\boldsymbol{\varepsilon}}_m^* \qquad (5)$$

where η_1 and η_2 represent the volume fractions of the respective sets of reinforcement, whereas $\dot{\boldsymbol{\sigma}}_k^*, \dot{\boldsymbol{\varepsilon}}_k^* \;\; (k=1,2,m)$ are the averages of stress/strain rates in the constituents involved. Both these local fields are assumed to be homogeneous within themselves. The reinforcing steel is considered to be an elastic–perfectly plastic von Mises material obeying an associated flow rule, while the behaviour of concrete matrix is governed by eq.(2).

The macroscopic constitutive relation can be established as

$$\begin{aligned} \dot{\boldsymbol{\varepsilon}}^* = [C^*]\dot{\boldsymbol{\sigma}}^* + [\bar{C}^*]\boldsymbol{\Gamma}^*\dot{\zeta}; \quad & [C^*]=\{\eta_1[C_1^*][B_1]+\eta_2[C_2^*][B_2]+(1-\eta_1-\eta_2)[C_m^*][B_m]\}; \\ & [\bar{C}^*]=\{\eta_1[C_1^*][\bar{B}_1]+\eta_2[C_2^*][\bar{B}_2]+(1-\eta_1-\eta_2)([C_m^*][\bar{B}_m]+[I])\} \end{aligned} \qquad (6)$$

Here, $[C^*]$'s are the compliance matrices and the details on the specification of operators $[B]$ and $[\bar{B}]$, that are defined by imposing some explicit kinematic constraints, are provided in Pietruszczak & Winnicki (2003).

Apparently, the macroscopic stress/strain rates can be transformed to an arbitrarily chosen global Cartesian system by following the standard transformation rules.

The above equation defines the response of the composite prior to formation of macro-cracks in the concrete matrix. In reinforced concrete structures, the cracking is typically associated with the *tensile* stress regime. Once a macro-crack forms, the formulation of the problem follows the procedure outlined below.

- ***Stage II (after formation of a macro-crack)***

The representative volume of the material comprises now the 'intact' reinforced concrete intercepted by a macro-crack of a given orientation ***n*** (Figure 5). The latter represents a composite medium within itself as it consists of a zone of fractured concrete reinforced with steel bars. A volume averaging procedure can be used again for specifying the macroscopic rates, i.e.

$$\dot{\boldsymbol{\sigma}} = \mu_i \dot{\boldsymbol{\sigma}}_i + \mu_f \dot{\boldsymbol{\sigma}}_f \, ; \qquad \dot{\boldsymbol{\varepsilon}} = \mu_i \dot{\boldsymbol{\varepsilon}}_i + \mu_f \dot{\boldsymbol{\varepsilon}}_f \tag{7}$$

Here, i refers to the intact material outside the localization zone, f denotes the material in the fractured zone and μ's represent the corresponding volume fractions.

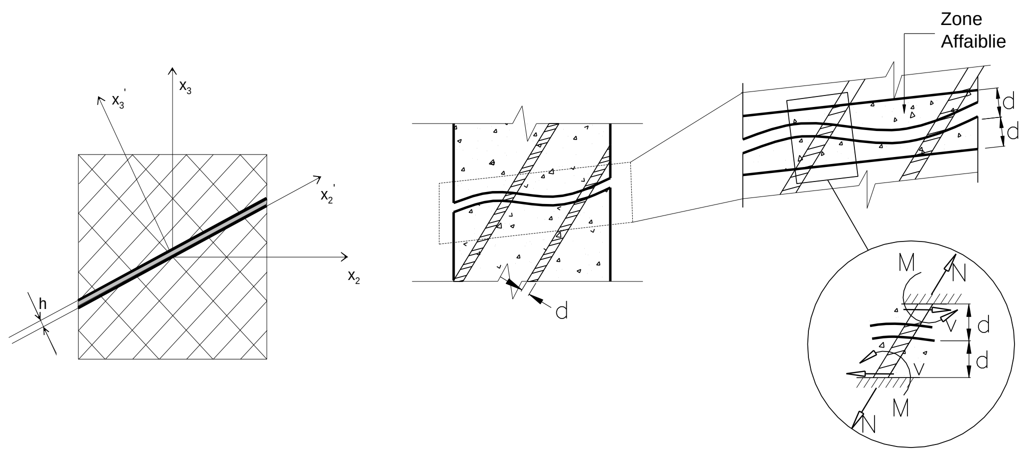


Figure 5: Schematic representation of the composite medium (Stage II): local base $\mathbf{x}'$ associated with the fractured zone

All quantities are referred to the global coordinate system **x.** The strain rate in the fractured zone can be expressed in terms of velocity discontinuities $\dot{\boldsymbol{g}}$. The constitutive relations governing the average macroscopic response of the composite is be defined as

$$\dot{\boldsymbol{\varepsilon}} = ([C] + \mu[N][K]^{-1}[N]^T)\,\dot{\boldsymbol{\sigma}} + [\bar{C}]\boldsymbol{\Gamma}\dot{\zeta} \tag{8}$$

Here, $[K]$ is the stiffness of the fractured zone and $\mu = \mu_f / h$ represents the ratio of the area of the fractured zone to the representative volume of the sample. Thus μ is, in fact, independent of h.

The approach outlined above requires an assessment of the mechanical properties of the fractured zone, viz. operator $[K]$. This zone is composed of the damaged concrete and the network of reinforcement. The details on the description of mechanical characteristics are provided in the article by Pietruszczak & Winnicki (2003).

The particular formulation employed here to describe the nonlinear behaviour of concrete matrix is similar to that outlined by Pietruszczak et al. (1988). It invokes a non-associated flow rule and the yield surface is expressed in a functional form:

$$f = \bar{\sigma} - \alpha(\zeta)\,\beta(\xi)\,k(\theta)\,\bar{\sigma}_c = 0; \quad \dot{\xi} \propto \left(\frac{1}{2}\dot{e}^p_{ij}\dot{e}^p_{ij}\right)^{1/2}; \quad \bar{\sigma}_c = \frac{-a_1 + \sqrt{a_1^2 + 4a_2\,(a_3 + I / f_c)}}{2a_2}\, f_c \tag{9}$$

In the equations above a's are material constants normalized with respect to axial compressive strength (f_c); $I = -I_1\,, \bar{\sigma} = (J_2)^{1/2}, \theta = \frac{1}{3}\sin^{-1}(3\sqrt{3}\,J_3 / 2\bar{\sigma}^3)$, where I_1 and (J_2, J_3) are the basic invariants of the stress tensor and stress deviator, respectively. The degradation of strength properties is governed here by the variable $\alpha(\zeta)$. In general, all degradation functions, for elastic module as well as strength, are assumed in a simple linear form

$$E = E_0\left[1-(1-B_1)\zeta\right]; \qquad \nu = \nu_0\left[1-(1-B_2)\zeta\right]; \qquad \alpha = 1-(1-B_3)\zeta \tag{10}$$

where B's are material parameters. Finally, in the simulations presented below, the parameter $\bar{\zeta}$ is taken as a function of the confining pressure only, and its evolution is described via an exponential form

$$\bar{\zeta} = e^{-A_1\sqrt{\frac{\langle -tr(\boldsymbol{\sigma})\rangle}{3 f_c}}} \tag{11}$$

where A_1 is a material constant.

The material model was verified by simulating the results of a series of laboratory tests performed by Pang & Hsu (1995) and Vecchio & Collins (1982). The experiments involved testing RC panels in pure shear with different reinforcement ratios and different concrete strength.

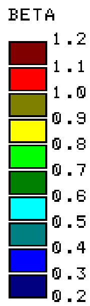
The constitutive relation was incorporated in the finite element code COSMOS/M and a number of boundary value problems were solved in order to validate the numerical procedure (see Pande & Shin, 2003). In particular, large scale laboratory tests conducted by Mitchell, Hunzinger & Cook (2002) were simulated and the results compared.

Damage assessment is based on the value of BETA (β) defined as:

$$\beta = \bar{\sigma} / (h(\theta)\bar{\sigma}_{\boldsymbol{c}}) \tag{12}$$

in which $\bar{\sigma}$ and θ are functions of the invariants of the stress deviator and $\bar{\sigma}_c$ designates the maximum value of $\bar{\sigma}$ corresponding to a given stress and $\theta = /\pi 6$.

From laboratory testing of samples extracted at the Beauharnois power plant, it was observed that for values of the Stress Intensity Factor (β) obtained from the analysis it may be concluded:

	- β < 1.0 corresponds the stable strain hardening stress states and no mechanical damage in this local area for β < 0.6 (Ref. Beauharnois) - - 1.0 > β > 0.6 describes the deformation mode associated with formation of micro cracks in strain hardening regime. For β > 0.9 dense micro cracking is observed (Ref. Beauharnois) - - β > 1.0 corresponds the failure mode associated with the formation of macro cracks in the unstable strain softening regime.

It needs to be emphasized that the commercially available finite element codes are not, in general, adequately equipped to address the complexity of the problem. In particular, they lack elaborated constitutive relations for dealing with the description and the evolution of complex material properties.

Examples of application of the numerical model at G-2 NPP in analyzing the reactor building behavior are presented in the next section.

5.3 Application of the Numerical Model in the analysis of the AAR-affected reinforced concrete at Gentilly-2 NPP

In order to assess the current stress/deformation state and to identify the aging mechanisms which may impair proper functioning of a nuclear power plant, an elaborate structural analysis including numerical simulations of various aging/degradation mechanisms was carried out (Gocevski 2003; Gocevski & Gdela 2011). With a step by step simulation the concrete behaviour for the entire operational life span of the power plant was analysed. The obtained results are in accordance with the finding of numerous in-situ measurements and conclusions of several inspections for the period from the plant construction in 1976 up until today (2010). In order to predict the future effect of concrete degradation to the structural behaviour of the power plant structures the simulations were extended for the period of the next 25 years (up to 2035). Therefore, the model is able to predict degradation of the AAR affected concrete from the time of the plant construction up until the plant decommissioning. This future of the numerical analysis make the numerical model suitable for its incorporation in the Aging Management Program (AMP) of the concrete containment structure developed for the G-2 NPP. The primary objective of the AMP is to ensure that the requirements of CSA Standard N278.7-08 are met and will continue to be met for the period through which the structure will remain operational.

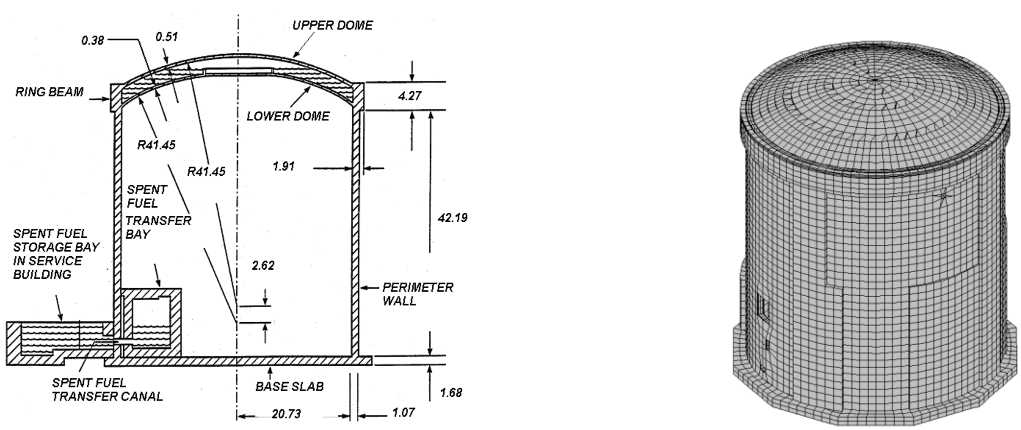
The analyses were conducted in the non-linear static and dynamic range and examined the effects of crack propagation induced during the construction stage, the loss of prestressing, swelling of concrete due to alkali-aggregate reaction, as well as initiation/propagation of cracks due to imposed temperature gradients and seismic loads. The 2003 studies concluded that swelling of concrete due to alkali-aggregate reaction is the potentially most damaging aging mechanism. Therefore, with the recent studies of 2010 and 2011 more emphasis was directed toward defining long term effects of AAR concrete swelling on present and future safe performance of the reactor building. In particular the following was studied in details with the enhanced 2003 numerical model:

- The propagation of cracks (now penetrating, on average, about 100mm into the containment walls) and the changes of pre-stressing over time,

- The possibility for formation of concrete splitting cracks in the plane of the post-tensioning cables due to degradation of tensile strength of the concrete affected by the AAR,
- The ultimate pressure capacity (UPC) and the air tightness of the reinforced concrete envelope and the spent fuel exchange room,
- The spent fuel storage pool and the spent fuel exchange room under self-weight, 50 years of continuing AAR, and seismic load typical for the region of Gentilly-2 NPP

In the paper only the results describing the aging of the pre-stressed concrete of the containment building will be presented and discussed.

The air tightness and the ultimate pressure capacity are directly affected by the formation and a slow propagation of micro and macro cracks through the concrete walls of the containment structures. For uninterrupted and safe operation of the power plant it is important to predict the time-history of their occurrence and penetration in order to assess the need for implementing some remedial measures to maintain the air tightness of the building, as imposed under the safety requirements of the Canadian Commission of Nuclear Safety (CCNS). The structure geometry and its finite elements discretisation are shown in Figure 6, was analyzed using the constitutive model for AAR-affected reinforced concrete, as discussed earlier. The material properties are presented in Table 1.



(a) (b)

Figure 6: Containment building: (a) cross-section and (b) FE Discretization

An important component in determining the state of the structure at the present time and in the future (year 2035) is the evaluation of the rate of free expansion in concrete. This has been assessed based on the results of some laboratory tests as well as the strain measurements obtained from the strain gages placed in concrete during the construction of the containment.

Table 1. Material properties

Concrete Elastic Properties	E = 34.5 GPa; υ = 0.2
Concrete Compressive Strength (nominal) (actual)	 f_{co} = 35 MPa f_{c2035} = 58 MPa
Concrete Tensile Strength (nominal) (actual)	 f_{to} = 2.72 MPa f_{c2035} = 1.5 MPa
Post-tensioning	1.06 nominal
Reinforcement	E=200 GPa; υ = 0.3; σ_y = 400 MPa

The perimeter wall has circumferential post-tensioning tendons and vertical tendons while the upper dome consists of three layers of superimposed tendons, the latter placed in such a way that the tendons form spherical equilateral triangles. The equivalent initial compressive stresses in the concrete sections were evaluated based on spacing of the cables in the structural elements. The average values were estimated as: 10.7 MPa for the two perpendicular principal components in spherical plane of the superior dome, 5.9 MPa for circumferential and 3.5 MPa for vertical direction of the wall, and finally 4.4 MPa and 2.3 MPa for the inferior and superior part of the ring beam, respectively.

The results describing the response of the structure under own weight, post-tensioning, and the continuing AAR are shown in Figures 7-12. Figure 7 present the distribution of damage factor, β , at the time after the construction and before the AAR effects were manifested. Figures 8 to 12 presents the distribution of damage factor, β , after 12, 17, 25, 35 and 50 years of ongoing reaction.

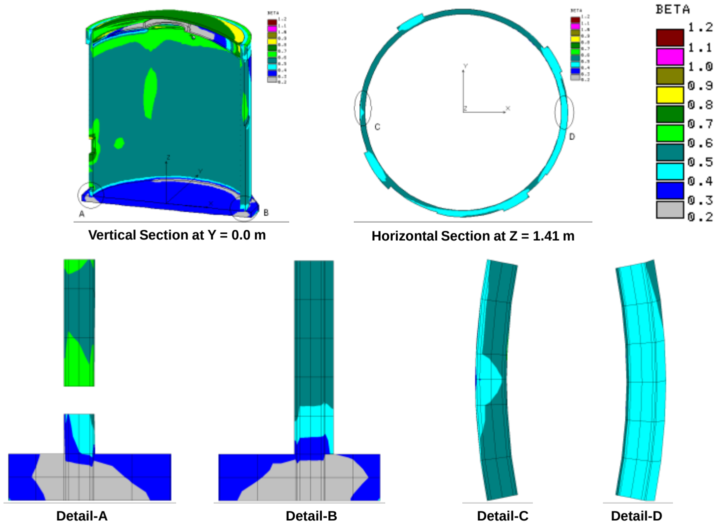


Figure 7: Distribution of coefficient β due to self-weight and post-tensioning after the construction of the plant

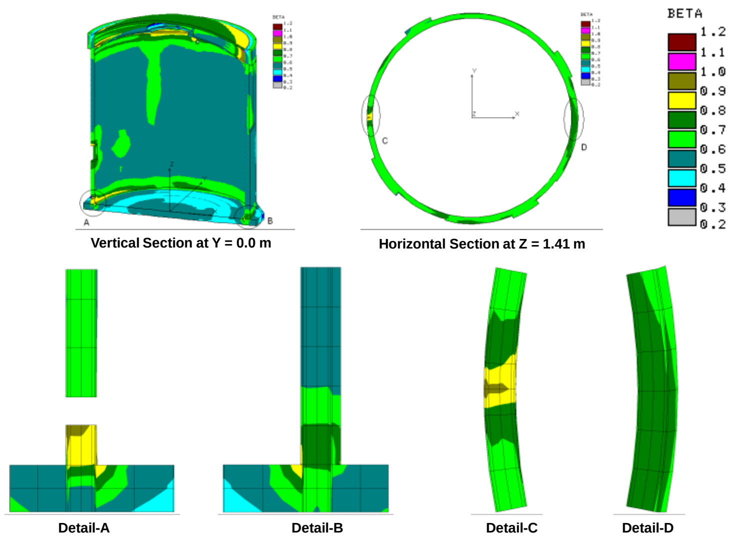


Figure 8: Distribution of coefficient of deterioration β due to self-weight, post-tensioning and after 12 years (1997) of combined AAR and creep effects

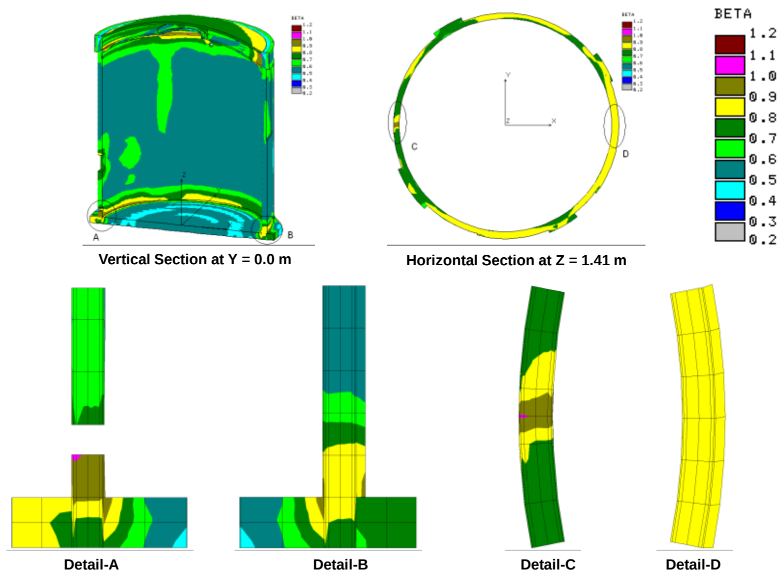


Figure 9: Distribution of coefficient of deterioration β due to self-weight, post-tensioning and after 17 years (2002) of combined AAR and creep effects

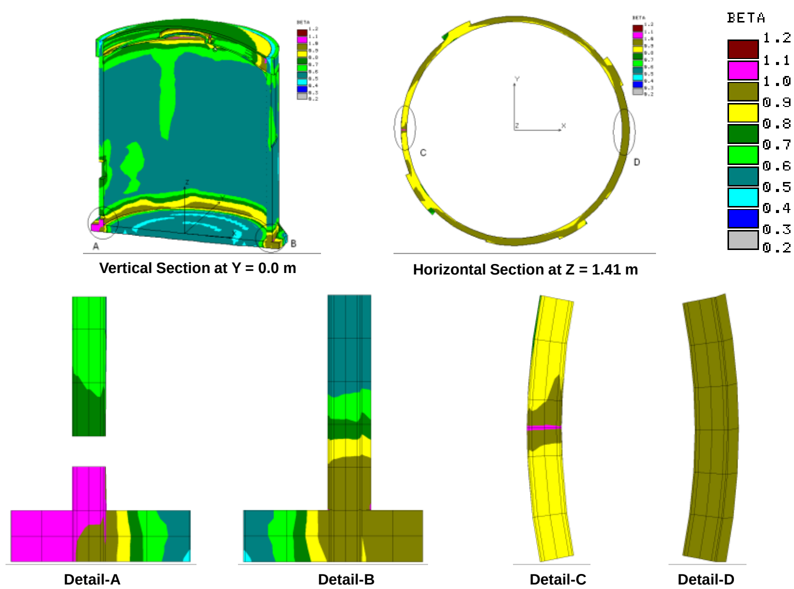


Figure 10: Distribution of coefficient of deterioration □ due to self-weight, post tensioning and after 25 years (2010) of combined AAR and creep effects

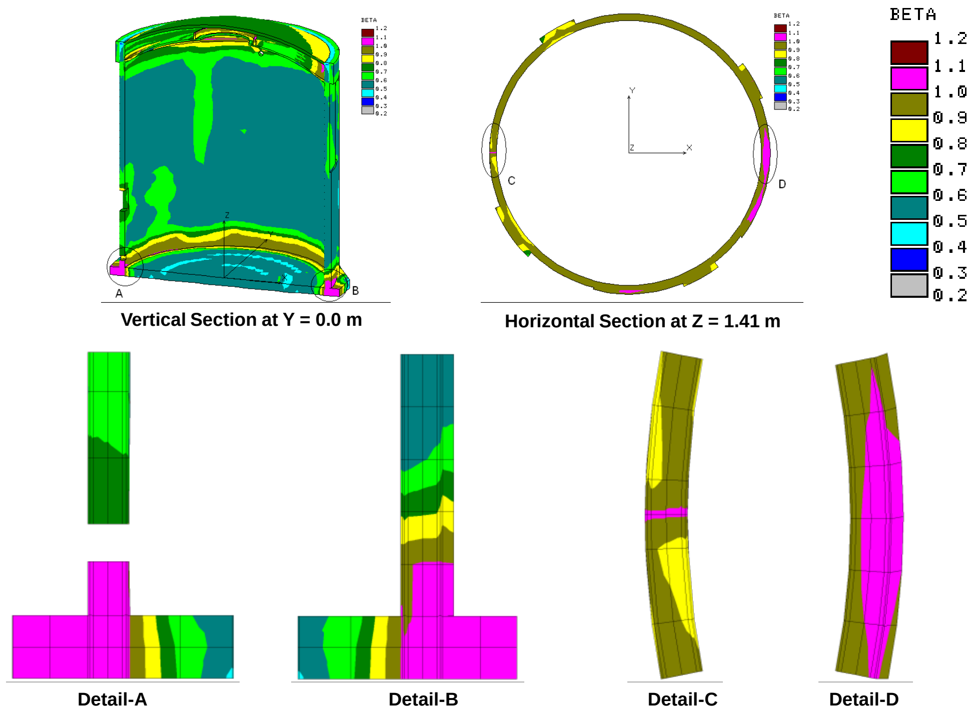


Figure 11: Distribution of coefficient of deterioration due to self-weight, post-tensioning and after 35 years (2020) of combined AAR and creep effects

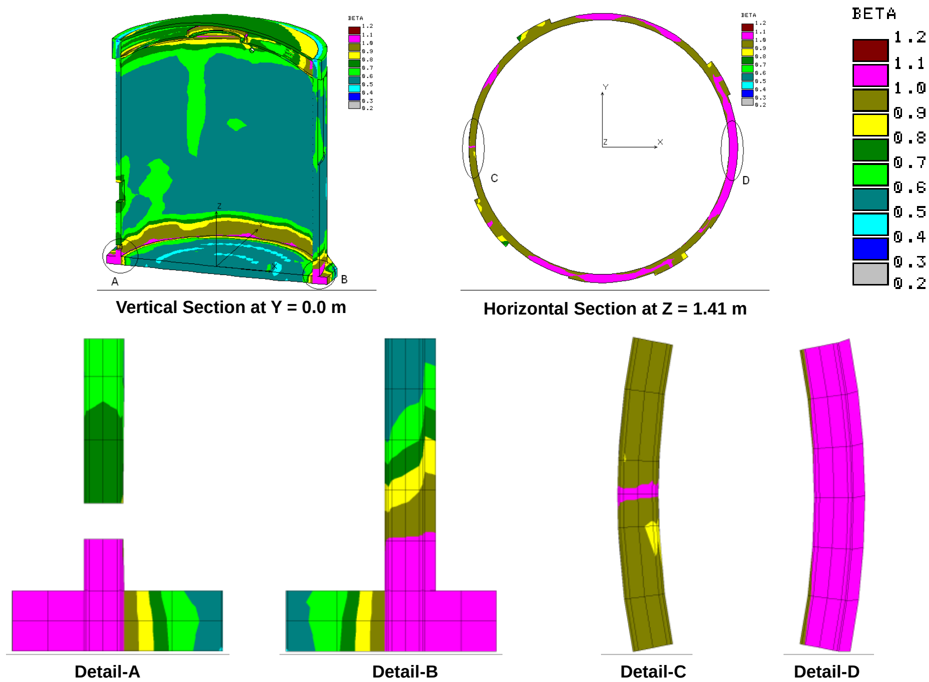


Figure 12: Distribution of coefficient of deterioration β due to self-weight, post-tensioning and after 50 years (2035) of combined AAR and creep effects

Note that the values of $\beta > 1$ are indicative of an unstable response associated with formation of macrocracks. The results indicate the presence of a damage zone, which at some locations penetrates through the entire thickness of the wall. However, the macrocracks are not more than 0.35mm wide.

Figure 13 shows the displacements at the junction of the base slab and the wall of the containment building. The restrain of the structural elements due to the post-tensioning influences the concrete swelling. The swelling of the base slab is more extensive than the expansion of the wall because the equivalent initial compressive stresses in the concrete slab, evaluated based on the post-tensioning, is lower than the one in the walls. The confinement building was not designed to accommodate this difference in the expansions. Hence, the multiple vertical cracks were observed at the junction of the wall and the base slab which were also precisely predicted with the numerical analysis.

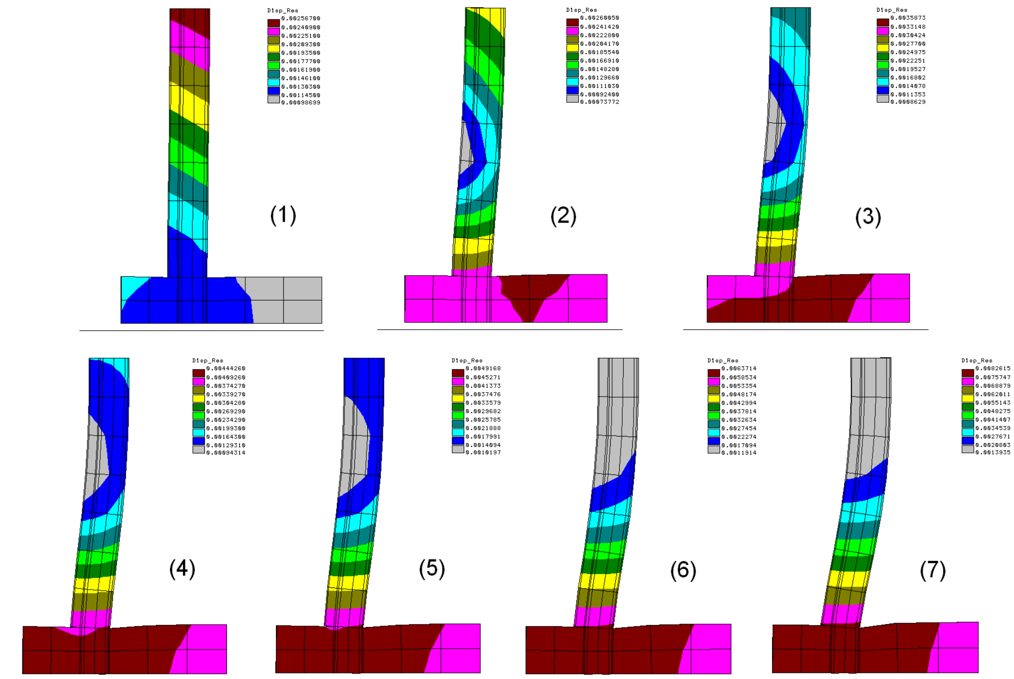


Figure 13: Displacement in resultant direction (deform factor = 150) at (1) G+PT-1985, (2) after 12 years of AAR (1997), (3) 17 years (2002), (4) 22 years (2007), (5) 25 years (2010), (6) 35 years-2020, and (7) 50 years (2035)

The possibility of concrete splitting (delaminating) in the planes of post-tensioning was observed in the evaluation of existing pre-stressed structures (Gocevski, 1993, 2000). The elevated two directional post-tensioning, producing 14.9 MPa compressive stresses in relatively thin section of “voussoir en tête” in the main cantilever roof beam of the Montreal’s Olympic stadium, was responsible for creation of multiple parallel splitting in the wall of the hollow beam. The potential of concrete splitting in the walls of the containment structure may occur as a result of constant reduction of the tensile strength of the AAR affected concrete. Figure 14 shows tensile stresses of 1.0 to 1.5 MPa in the radial direction of the walls. The preliminary analysis shows that the concrete tensile strength might decrease to a value of 1.5 MPa by the year 2020 as a result of AAR. Therefore, there is a likelihood of concrete splitting (delaminating) in the wall of the containment building before the end of the second life of the power plant. The concrete splitting in the planes of post-tensioning would be expected to occur in the wall around the combustions transfer tunnel (detail A in Figure 14) and in many other areas of the wall in the containment building as indicated by the details B, C and D of Figure 14.

Meanwhile, it should be stressed that the stage of the AMP implementation also involves a detailed exceptional and inaugural analysis where questions raised in previous studies and discussed above will be thoroughly examined and answered. The operating experience (such as from Crystal River NPP regarding their issues with the reactor building concrete splitting; US NRC, 2011) will also be taken into consideration. There is a high level of confidence that the

AMP at G-2 will successfully manage all those issues and other which might arise during the second lifecycle of the plant. Hydro-Québec has necessary expertise and tools for responding to those challenges through a structured process in a systematic way.

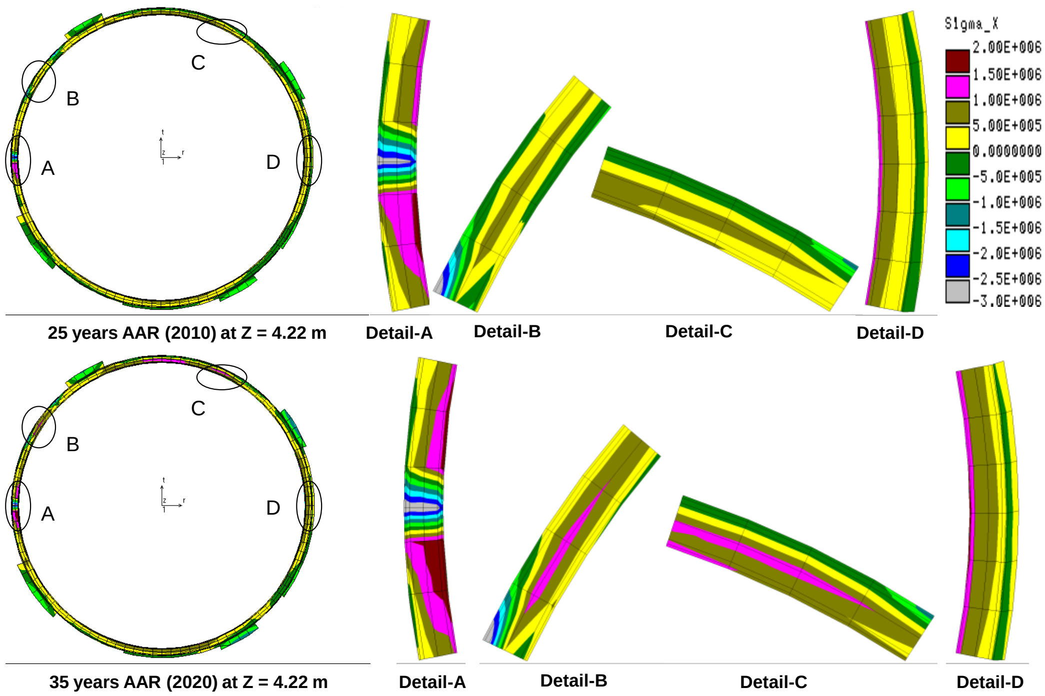


Figure 14: Stress in radial direction at horizontal section at elevation 4.22 m from the base slab due to self-weight, post-tensioning and after combined AAR effects in the concrete

6. Conclusions

The Aging Management Program of the concrete containment structure developed for the G-2 NPP as a part of preparation of the refurbishment project takes into consideration all the relevant degradation mechanisms. It particularly focuses on Alkali-Aggregate Reaction (AAR) as a mechanism which is not well known in the nuclear power industry. The AMP defined a four level approach in inspecting, monitoring and assessing the containment structure: a) visual inspection, b) instrumentation and non destructive examination, c) sampling and destructive evaluation and d) structural analysis using a numerical model based on finite elements. The fourth level is especially developed for dealing with the AAR issue. It is a novel approach where the numerical model, as a powerful tool helping decision-making, is integrated into the whole AMP in a structured manner. It is a living process where results of the first three levels of inspection provide inputs for the numerical model and its calibration. It enables an accurate prediction of behaviour of the concrete containment structure under impact of the relevant degradation mechanisms including AAR. Such an approach allows better defining corrective and mitigating actions while required. The designed AMP provides a reasonable assurance of an adequate aptitude of the G-2 concrete containment structure in fulfilling its safety function during the second life cycle of the plant.

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