Effects of AAR on Seismic Assessment of Nuclear Power Plants for Life Extensions

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1 ABSTRACT

In Nuclear Power Plant (NPP), the containment system represents an ultimate barrier to fission product releases to the environment. As part of the containment system, CANDU™6 NPPs use a fully prestressed concrete Reactor Building (R/B) that is designed to contain the pressure build-up that might result from accident scenarios.

Several NPPs are approaching the end of their original design life and as service life is being extended, containment improvements are performed in order to meet the Probabilistic Safety Assessments (PSA) related targets. As part of the PSA work, Seismic Margin Assessment (SMA) is performed as seismic requirement has increased for some plants. Thus, new Floor Response Spectra (FRS) for the R/B containment structure need to be developed, which in addition to new seismic requirements should consider current condition of the R/B structure including possible aging related degradation.

Alkali Aggregate Reaction (AAR) was identified as applicable Aging Related Degradation Mechanism (ARDM) for one of the plants and investigation was performed in order to establish the means of accounting for AAR in the development of FRS for R/B to be used in SMA work.

2 INTRODUCTION

In Nuclear Power Plants, the containment structure provides an ultimate barrier to fission product releases to the environment. The design has been performed and the operating strategies are in place to ensure that this final barrier is effective. It is very important to understand that the containment capabilities and the margins in performance of the containment to resist beyond design loads and severe accidents and to improve containment performance are being considered.

Several NPPs are approaching the end of their original design life and as service life is being extended, containment improvements are performed in order to meet the PSA related targets. As part of the PSA work, SMA is performed as seismic requirement may have increased for some plants. To perform SMA work, new FRS for the R/B containment structure has to be developed, which in addition to new seismic requirements needs to consider current condition of the structure including possible aging related degradation. AAR was identified as applicable ARDM for one of the plants. Alkali reactive aggregate was used for construction and, although measures were implemented to mitigate possible reaction, evidences of AAR were found in some parts of the concrete.

Investigation was performed in order to establish the means of accounting for AAR in the development of FRS for R/B to be used in SMA work. Review of studies and experiments to determine effects of AAR on mechanical properties of concrete and evaluation of the effects of restraint provided by the reinforcing and prestressing steel was established.

3 CANDU[1]6 CONTAINMENT STRUCTURE

The R/B consists of the containment structure and the internal structure. The containment structure is designed to satisfy mainly three functional requirements:

- to house the reactor and auxiliary systems and protect them from environmental conditions and severe accidental loads;
- to provide radiation protection during operation and accident conditions;
- to withstand the design accident pressure and to provide containment of radioactive materials following a release within the containment envelope.

As shown in Figures 1 and 2, the containment structure consists of a base slab, perimeter wall, ring beam and upper dome. These are all prestressed post-tensioned structural elements. The post-tensioning tendons are protected from corrosion with cement grout pumped into the sheaths.

The base slab sits on the sub-base and tendon gallery structure. A sliding membrane is provided under the base slab to facilitate radial deformation during the prestressing of the base slab. A central shear key and a set of radial shear keys are provided in the base slab for transferring the horizontal and torsional forces due to seismic and accident loads.

The perimeter wall has four buttresses. These buttresses are provided to anchor the perimeter wall horizontal post tensioning grouted tendons. Two large openings are left in the perimeter wall during construction to permit and facilitate the installation of larger pieces of equipment such as the Calandria and the steam generators. These openings are closed after the installation of heavy equipment, and the closing sections act as integral parts of the perimeter wall to which they are connected by a system of horizontal and vertical prestressing cables and reinforcing steel connections.

The ring beam gives support to the upper dome and to the top of the perimeter wall. The ring beam consists of two parts. The first part of the ring beam supports the lower dome and the perimeter wall. The second part of the ring beam supports the upper dome. All the prestressing cables for the upper dome and the vertical cables of the perimeter wall are anchored in the ring beam. The R/B upper dome completes the weather cover and the pressure-retaining component of the containment.

4 ALKALI AGGREGATE REACTION

AAR is a deleterious chemical reaction between the aggregates and the surrounding hydrated cement paste. Gel formed as a result of reaction has a tendency to increase in volume in presence of humidity and, under specific conditions, might lead to expansion and cracking of concrete.

AAR occurs only in the presence of water. Minimum Relative Humidity (R.H) inside the concrete should be about 85% at 20°C for the reaction to proceed (Fornier, et.al.,2000, Neville, 1996).

4.1 Assessment Results of R/B Containment Structure

AAR was identified early in the life of one of the CANDU reactor buildings. R.H. inside R/B is between 5 and 20%. Thus, the concrete inside the R/B is kept under very dry condition. Dousing tank located inside the lower dome (see Figure 1) is lined from the inside with fiber reinforced epoxy liner to protect the concrete from water contained in the tank. Recent assessment of the dousing tank did not reveal any major problems with regards to the protective liner. The outside surface of the R/B was protected from moisture by application of sealant.

Currently, there are no evidences of deterioration or changes in concrete properties of the R/B structure due to AAR. Expansion of concrete is insignificant.

Examined cores from the base slab and the dome of the R/B showed signs of AAR, i.e. presence of gel and cracks through some aggregate particles. Two concrete cylinders (one from the dome and one from the base slab) were tested for expansion under 100% Relative Humidity (R.H.) and 38°C. After about fifteen weeks, average annual expansion rates were of 0.014 % for the dome and 0.018% for the base slab. Expansion test carried out on a cylinder from the base slab submerged in Na_2O_{eq} at 38 °C showed after 24 weeks an expansion of 0.15%. These tests are typically used for screening aggregates to determine their potential reactivity; however, these tests are not suitable to predict the expansion of actual structures. Expansion measured using vertical and horizontal extensometers installed in concrete of the actual R/B structure was 0.00287% for the wall, 0.0057% for the lower dome and 0.0014% for the foundation.

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[1] CANDU is a trade-mark of Atomic Energy of Canada Limited (AECL)

4.2 Effect of AAR on Properties of Concrete

In case of plain (unreinforced) concrete, expansion and cracking due to AAR adversely affect the tensile strength and, to a lesser extent, compression strength and modulus of elasticity (Pantazopoulou and Thomas, 1999, Pantazopoulou and Thomas, 2000). In reinforced or prestressed concrete the effects of AAR are more complex. Unlike in case of plain concrete, where expansion due to AAR generates tensile stresses in concrete, in reinforced or prestressed concrete structures, the expansion generates tensile stresses in the reinforcing/ prestressing steel and compressive stresses in surrounding concrete (Smaoui, et.al., 2004).

The total expansion due to AAR and its rate depend on type of structural member, degree of chemical reactivity, environment, and location and volume of reinforcement. Thus, distribution of AAR in a concrete structure is often highly variable, both with regard to appearance and intensity (Ballivy, 2000). Considering variations in humidity and restrain conditions, expansion associated with AAR cannot be expected to be the same for different elements and even throughout the same elements of the R/B.

4.3 Effect of Restraint

As shown by many experiments and investigations (Pantazopoulou and Thomas, 2000, Ballivy et. al., 2000, Clark, 1990, Uijl and Kaptijn, 2002, Swamy, 1990) the overall confinement by reinforcing/prestressing steel reduces the overall expansion.

Laboratory experiments on reinforced concrete cubes (Ballivy et. al., 2000) have shown that the difference between vertical and horizontal deformation in reinforced concrete was very small, however, this is probably due to equivalent amount of reinforcement in both directions. Experiments on reinforced concrete beams (Jones and Clark, 1998) showed that compressive strength and elastic modulus of cores removed from the direction of restraint were significantly greater than those removed perpendicular to the main restraint.

Expansion can be completely eliminated in the direction of the load for average stresses of about 5 MPa with accompanying decrease of the degrading influence of AAR on concrete's mechanical properties (Pantazopoulou and Thomas, 2000, Hughes, 2001). Prestressing forces measured after construction of the R/B base slab were 3.5 MPa in vertical direction and 6 MPa in horizontal direction. Thus, even after consideration of long-term losses of the prestressing, it is unlikely that R/B would expand in the circumferential direction, while only minor expansion might be possible in the vertical direction.

Restraint also has implications on the interpretation of expansion tests of cores. Expansion of a core recovered from structure is dependent on restraint, which is relieved when core is extracted: the greater previous restraint to a core, the greater its subsequent expansion (Clark, 1990). Thus, free expansion of 0.15% (1.5 mm/m) of the cylinder sample from the R/B base slab submerged for 24 weeks in Na_2O_{eq} at 38°C does not provide an estimate on the future expansion of the R/B.

4.4 Modulus of Elasticity

Experiments (Ballivy, 2000, Jones and Clark, 1998, Smaoui, 2006) have shown that tensile strength and modulus of elasticity in reinforced concrete are more affected by AAR than compressive strength. To determine conservative value for the modulus of elasticity to be used for seismic calculations for the R/B, results of accelerated laboratory studies as well as testing of cores from AAR affected structures were reviewed.

Results of a few tests and studies encountered below were plotted in Figure 3 and show the effect of expansion on modulus of elasticity. Other reviewed results are generally in the same range as those shown in Figure 3.

Testing of prisms with different type of aggregate showed that modulus of elasticity decreases as expansion progresses as shown in Figure 3, however, there is no effect for a very small expansion (below 0.02%) (Swamy and Al-Asali, 1988). Laboratory testing of samples in UK (Hobbs, 1985) have shown that expansion of up to 0.3% have caused reduction in the elastic modulus of 20-40%. Testing of cylinders extracted from reinforced concrete specimens with AAR accelerated in the laboratory (Ballivy, 2000, Fan, et.al., 1998) demonstrated reduction in modulus of elasticity in the range of 17 to 31%. Laboratory tests on concrete cylinders with Quebec City limestone have shown average reduction in modulus of elasticity of 21% in compression and in tension at expansion of 1 mm/m (Smaoui, et. al, 1996). Other studies cited in (Jones and Clark, 1998) have shown decrease in modulus of elasticity in the range of 10 to 30% associated with 1 mm/m expansion. A number of studies were undertaken to determine concrete properties to be used in analyses of AAR affected turbine generator foundation of Unit 1 Ikata NPP in Japan (Shimizu, et. al., 2005a and 2005b, Takakura T, 2005, Takakura M, 2005, Murazumi, 2005a and 2005b). The maximum expansion of the structure was measured to be 1 mm/m (Shimizu, et. al., 2005a). The decrease in modulus of elasticity based on tests of cores extracted from the structure was 33%(Shimizu, et. al., 2005b).

5 CONCLUSION

Based on this investigation and considering geometry and current condition of the post-tensioned R/B, no change in modulus of elasticity to account for AAR is necessary for generation of seismic FRS. It is considered prudent to include a possible reduction in modulus of elasticity of about 15% in order to account for possible local variations in material characteristics, environment of exposure, and chemical reactivity.

Measured compressive strength of the R/B concrete (51 MPa) is higher than the strength used in original design calculations (35 MPa). Thus, an increase in the modulus of elasticity also needs to be considered for seismic FRS generation for R/B for life extension.

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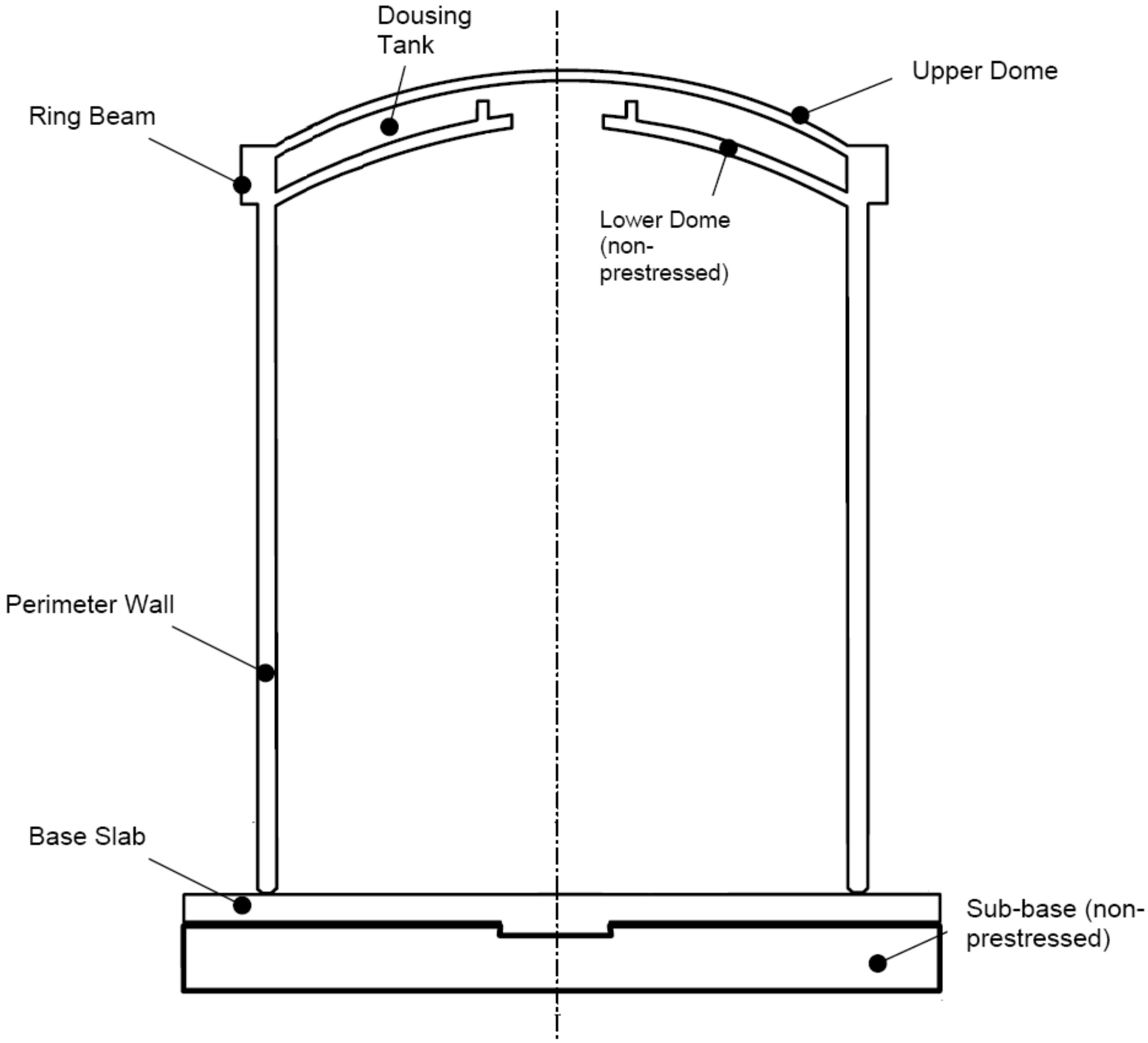
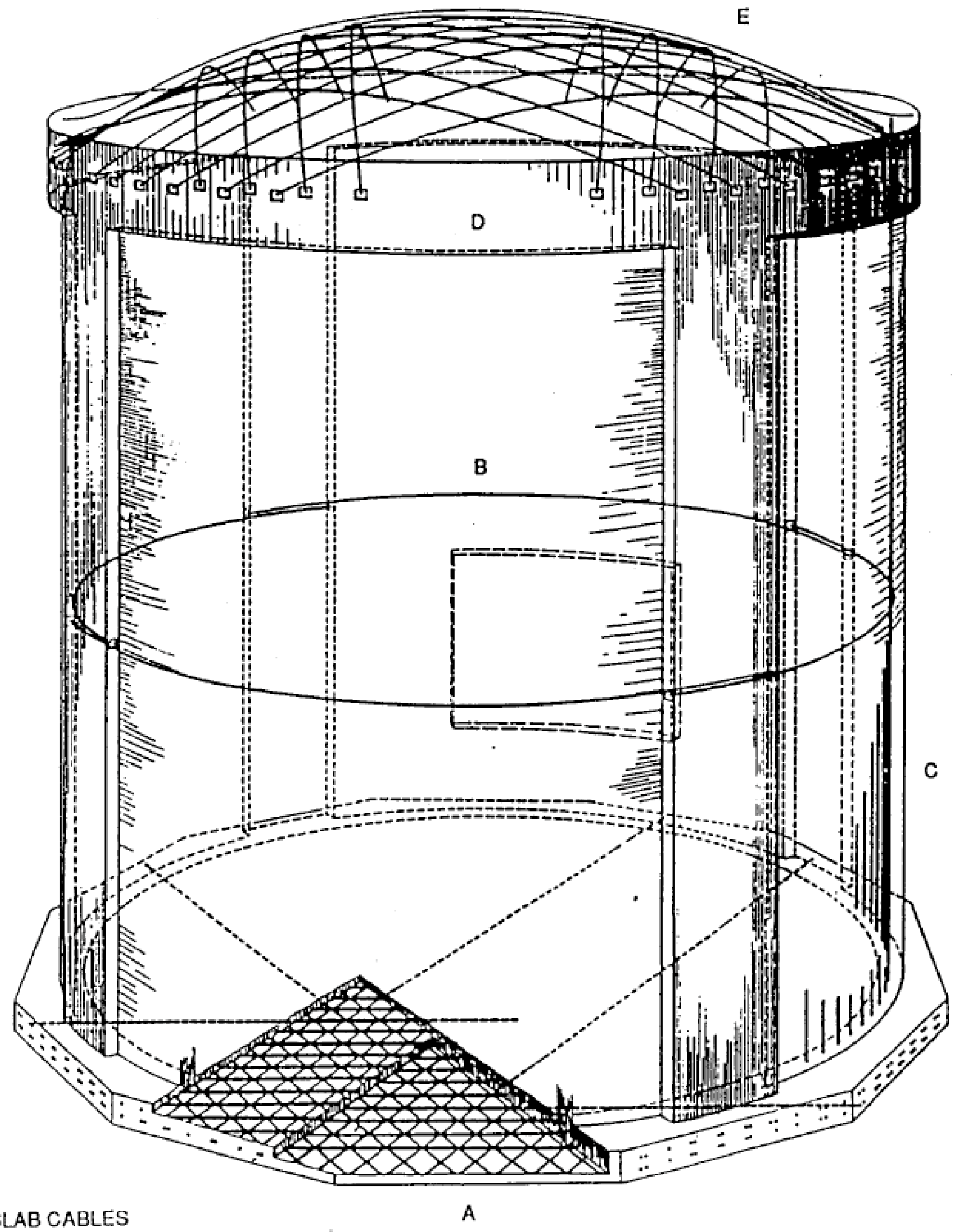


Figure 1 CANDU 6 Reactor Building Prestressed Containment Structure



LEGEND
A BASE SLAB CABLES
B HORIZONTAL WALL CABLES
C VERTICAL WALL CABLES
D RING BEAM CABLES
E DOME CABLES

Figure 2 General Arrangement of Pre-stressing Cables

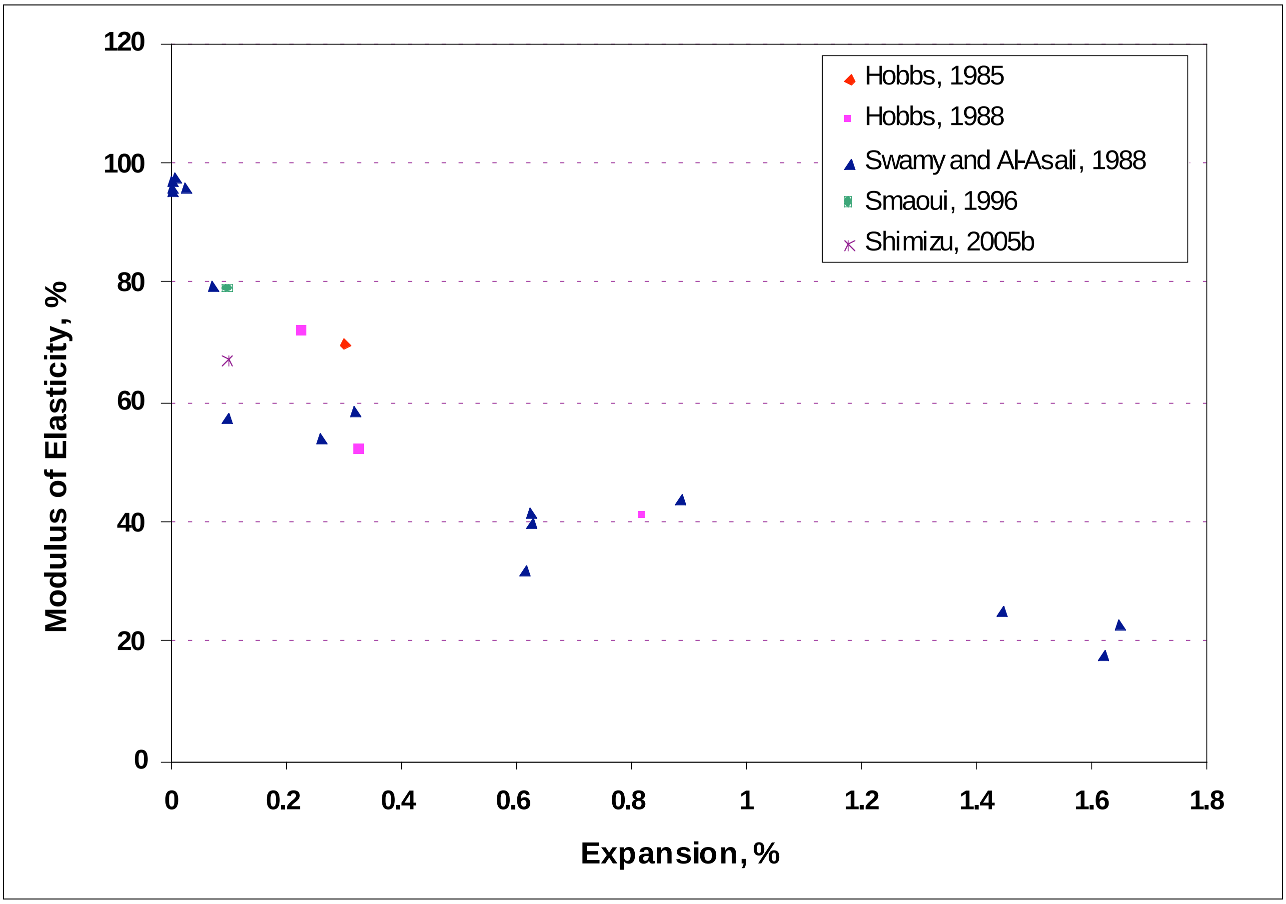


Figure 3 Effect of Expansion due to AAR on Elastic Modulus