STRATEGY FOR 100-YEAR LIFE OF THE ACR-1000 CONCRETE CONTAINMENT STRUCTURE

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ABSTRACT

The purpose of this paper is to present the Plant Life Management (PLiM) strategy for the concrete containment structure of the ACR-1000[1] (Advanced CANDU Reactor) designed by AECL (Figure 1). The ACR-1000 is designed for 100-year plant life including 60-year operating life and additional 40-year decommissioning period of time. The approach adopted for the PLiM strategy of the concrete containment structure is a preventive one, key areas being: 1) design methodology, 2) material performance and 3) life cycle management and ageing management program.

In the design phase, in addition to strength and serviceability, durability is a major requirement during the service life and decommissioning phase of the ACR structure. Parameters affecting durability design include: a) concrete performance, b) structural application, and c) environmental conditions.

Due to the complex nature of the environmental effects acting on structures during the service life of project, it is considered that true improved performance during the service life can be achieved by improving the material characteristics. Many recent innovations in advanced concrete materials technology have made it possible to produce modern concrete such as high-performance concrete with exceptional performance characteristics.

In this paper, the PLiM strategy for the ACR-1000 concrete containment is presented. In addition to addressing the design methodology and material performance areas, a systematic approach for ageing management program for the concrete containment structure is presented.

Key words:
Ageing Management Program, Deterioration Mechanism, Durability Design, Evaluation Methodology, High-Performance Concrete, Instrumentation, Life Cycle Management, Plant Life Management, Service Life,

INTRODUCTION

Safety-related nuclear power plant (NPP) concrete structures are designed, constructed and operated in such a way that, under the expected environmental influences, they maintain their safety, serviceability, durability and acceptable appearance during an explicit or implicit period of

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1 ACR-1000™ (Advanced CANDU Reactor™) is a trademark of Atomic Energy of Canada Limited (AECL)

time without requiring unforeseen high costs for maintenance and repair (CEB-FIP Model Code, 1990)[3].

Aging of reinforced concrete structures due to service conditions, aggressive environments, or accidents may cause their strength, serviceability and durability to decrease over time. Therefore, a PLiM programme is required to ensure the continued safety and economic operability of the plant during its life. Traditionally, regular and systematic inspection of the structure and all its components are provided through the intended plant life through an Ageing Management Program (AMP).

Due to the complex nature of environmental effects on structures and the corresponding response, it is believed that true improved performance during the design life of a structure cannot be achieved by Ageing Management Program (AMP) alone, but must also involve durability design and improving the materials characteristics. Therefore, in addition to AMP, durability design and material performance of the structure are key elements in plant life management. This approach can be considered as a life cycle management plan of the plant through the design, construction, operation and decommissioning phases of the project.

In this paper the PLiM strategy of achieving a 100-year plant life for ACR-1000 concrete containment structure is described.

ACR-1000 CONTAINMENT STRUCTURE

The containment structure is part of the containment envelope and provides final protection to the public against radioactive emissions. The ACR-1000 containment structure constitutes the exterior structure of the reactor building. It consists of vertical cylindrical perimeter wall, founded on a base slab and the top, closed by a hemispherical dome. The perimeter wall and dome are prestressed concrete structures with post-tensioning tendons in the horizontal and vertical directions as well as reinforcing bars in both directions. The inside surfaces of the containment structure are lined with a carbon steel liner. The base slab is a reinforced concrete structure. The containment structure is illustrated in Figure 1.

The containment structural performance is achieved through achieving acceptable level of a) safety and stability through strength design and b) serviceability; the ability of structure for acceptable deformation and crack control. In addition to normal operating loads, the containment structure is designed to withstand loadings from a number of low-probability external and internal events, such as earthquakes, tornadoes, aircraft crash, accident pressures and pipe break loads.

The ACR containment structure is designed and constructed to operate for a 60-year service life plus an additional 40-year for the decommissioning phase.

ACR STRATEGY FOR PLiM

The AMP is often referred to as an appropriate procedure(s) to be followed during service life of the structure. It is evident that the life performance of the structure not only relies on the AMP during the service life, but also is strongly influenced by the design strategy and material characteristics. For a new plant, the Plant Life Management Program (PLiM) starts in the design process and then continues through plant operation and decommissioning. Hence PLiM must provide not only AMP but also provide requirements on material characteristic and the design criteria as well.

Obviously aging is a time dependent process. However, a new feature in the theory of safety is the incorporation of time into the design problems (Sarja & Vesikari 1996)[7]. Therefore, PLiM should be considered as a time dependent process during design, material selection and AMP (see Fig. 2).

As shown in Figure 2, PLiM can be conceptually pictured as a series arrangement of key elements; Design, Material, and Ageing Management Program. As a chain, it fails if any one link fails. Therefore, assuming the effectiveness of 1) Design Methodology, 2) Material Performance and 3) Ageing Management Program as, E_D, E_M, and E_{AMP} respectively, PLiM program effectiveness can be expressed as:

$$E_{PLiM} = E_D E_M E_{AMP}$$

Since the effectiveness of each element is most likely less than one, therefore the effectiveness of the PLiM programme will be lower than individual effectiveness. Therefore, it is essential to maximize the effectiveness of each key element of the process.

The strategy for the ACR-1000 PLiM programme to achieve the 100-year plant life is based on the holistic approach illustrated in Figure 3. The strategy addresses the following key areas:

- Design Requirements and Specifications
- Design for Durability
- Concrete Material Performance
- Life Cycle Management
- Ageing Management Program
- Instrumentation & Monitoring

DESIGN REQUIREMENTS AND SPECIFICATIONS

In the development of the Advanced CANDU Reactor design, particular attention is paid to specifying structural performance and long-term durability including concrete performance as part of technical requirements. Figure 4 shows an overall view of design requirements process for ACR –1000 concrete containment structure. As can be seen from this figure, in addition to structural design requirements, durability design requirements has a major role in the design requirements and technical specifications. Obviously, design requirements include material selection since it has strong impact on the durability of the structure.

Design for Durability

Modern building codes are increasingly based on the performance of buildings (Performance Based Design). Most of the current durability problems of concrete structures could have been avoided with systematic durability design (Krauss 1994[5]). In fact, the introduction of systematic durability design means better utilization of existing research results for systematized control of the service life of concrete structures during design. Durability calculations enable not only priority ranking of materials and structural factors, but also produce numerical values of factors for intended service life (Sarja & Vesikari 1996, Naus & Oland 1996)[6,7].

The objective of durability design for ACR-1000 containment structure is:

- To achieve capability of maintaining the serviceability of the structure over a specified time (Service life + Decommissioning phase)
- To initially design the structure to meet above the minimum requirements in order to ensure that the minimum design requirements are met at the end of plant life

Figure 5 (CEB 1997 [4]) shows schematically the expected plant life performance to achieve maintaining the serviceability of the structure and to meet minimum design requirements at the end of the plant life.

Concrete material performance, structural design application and environmental conditions are the key factors affecting durability. Material performance includes selection, mixing and curing procedures. Depending on the structural application of concrete [e.g. whether it is used as mass concrete, high-strength concrete, impact-resistant concrete etc.], the durability design will be affected. Obviously environmental conditions such as corrosive environment, and alkali-aggregate activity, have major impact on durability design. The method of durability design can be (1) deterministic, (2) stochastic or (3) lifetime safety factor. The principles of these methods are given by Sarja & Vesikari 1996[7].

ACR-1000 containment is designed to achieve long-term durability by providing protection against concrete deterioration, corrosion of the reinforcing bars, embedded steel parts and stress corrosion of prestressing tendons. Protection of reinforcement against corrosion in severe environment is provided by suggested concrete cover based on parameters affecting corrosion (i.e., humidity, freeze-thaw, chlorides, etc.) and crack control during the plant life of the containment. Durable concrete is also achieved by using high-performance concrete to meet special performance and uniformity requirements.

CONCRETE MATERIAL PERFORMANCE

Many recent innovations in advanced concrete materials technology have made it possible to produce modern concrete with exceptional performance characteristics. The concrete performance strongly relies on three key factors a) material ingredients, b) mix design and c) concrete processing. Modern concretes such as High-Performance Concrete are widely used in concrete industry. High-performance concrete (HPC) is defined as concrete which meets special performance and uniformity requirements that cannot always be achieved by using only the conventional materials and normal mixing, placing and curing practices (Ahmad et. al. 1994)[2]. For example, the base slab of the containment structure is poured in one-piece, and in order to control cracks resulting from thermal gradients, the base slab will use HPC by using a concrete mix design which will generate significantly lower heat during the hydration process. Another area of application in the ACR-1000 of the use of HPC is in the containment wall to improve durability and resistance to impact loads. A research program is currently being carried out by AECL on the application of HPC for ACR-1000 containment structure.

AGEING MANAGEMENT PROGRAM (AMP)

An Ageing Management Program (AMP) is being developed for the ACR-1000 containment structure at the basic design phase. An overall view of AMP is shown in Figure 7. Since many environmental factors affect the degradation mechanisms of materials, they are being considered during design phase. It is expected that this plan will be updated for each specific project considering the actual site and plant conditions.

The major elements of the program are: deterioration mechanisms, evaluation methodology, evaluation criteria, and instrumentations and monitoring (inspection) plans. These element are described below:

Deterioration (Ageing) Mechanism

An understanding of the potential deterioration mechanisms provides useful information during the design phase. Figure 6 (CEB 1997 [4]) shows deterioration mechanisms that can occur in both concrete and reinforcement. As can be seen from this figure, deterioration may occur in fresh concrete as well as hardened concrete. It is evident that the different deterioration mechanisms do not necessarily start at the same time. Also the rate of deterioration is influenced by the cause of the degradation mechanism.

For the ACR-1000, the deterioration mechanisms that could affect the concrete containment structure generic design, such as thermal effects and corrosion are considered in the design specifications.

Evaluation Methodology

Evaluation methodology adapted from ACI Committee 349[1] is used as a baseline for ACR-1000 containment structure. This methodology provides recommendations for the development of an evaluation procedure for nuclear safety-related structures. Techniques proven to be useful in the evaluation include visual inspection, nondestructive testing, destructive testing and analytical methods.

Instrumentations and Monitoring

ACR containment structure will have an instrumentation and inspection program for the purpose of increasing safety, reliability, durability and decreasing operating maintenance costs.

Most common types of embedded instrumentation enable measurement of strain, stress, temperature, and indication of corrosion activity in the prestressing tendons. In addition to long-term monitoring, due to early-age characteristics of fresh concrete, short-term monitoring such as heat generated by cement hydration and thermal gradient is essential particularly for large pour concrete in containment structure. An inspection program will also be specified to enable early detection of concrete degradation.

SUMMARY AND CONCLUSIONS

- PLiM should be addressed in all phases of the project: design, construction, operation and decommissioning.
- Key elements to be considered include: design requirements, material selection, and Ageing Management Program
- ACR is designed for Durability Requirements in addition to strength and serviceability
- ACR is designed to above minimum requirements in order to meet minimum design requirements at the end of plant life
- Improved material such as High-Performance Concrete is specified for the ACR-1000 containment structure.
- Instrumentation and monitoring requirements are considered in design phase

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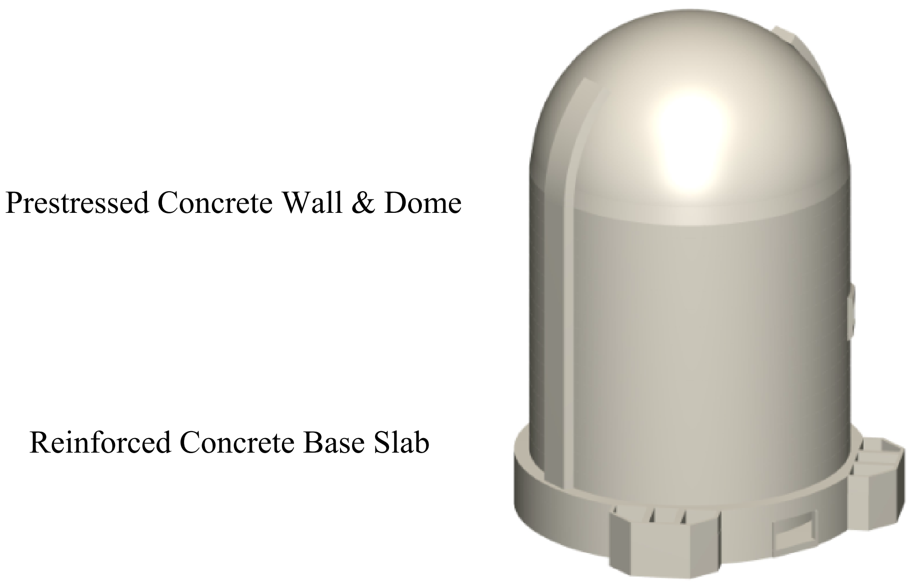

Figure 1: ACR Prestressed Concrete Containment Structure

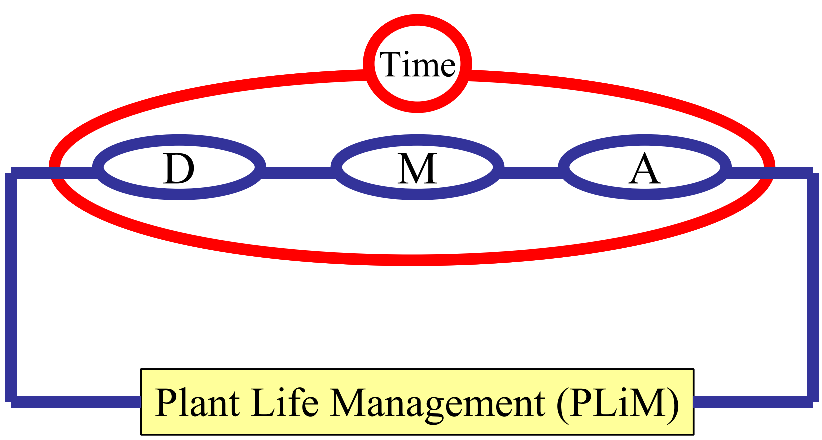

Figure 2: Time Dependent Key Factors, Design (D), Material (M) and AMP (A) for PLiM

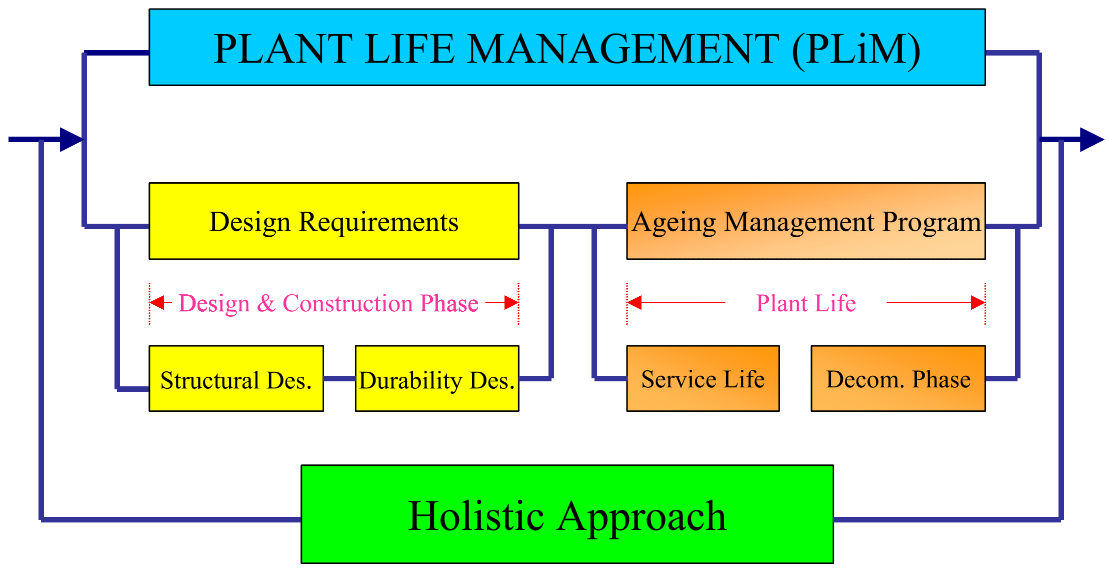

Figure 3: Concept Map for ACR PLiM

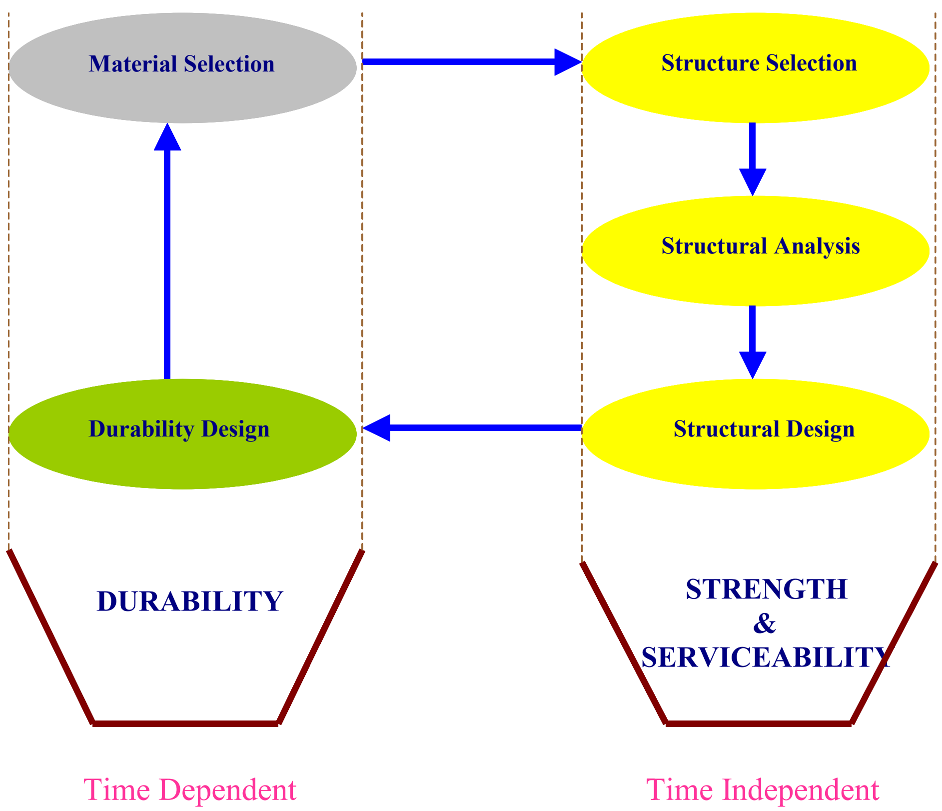

Figure 4: ACR Design Requirements

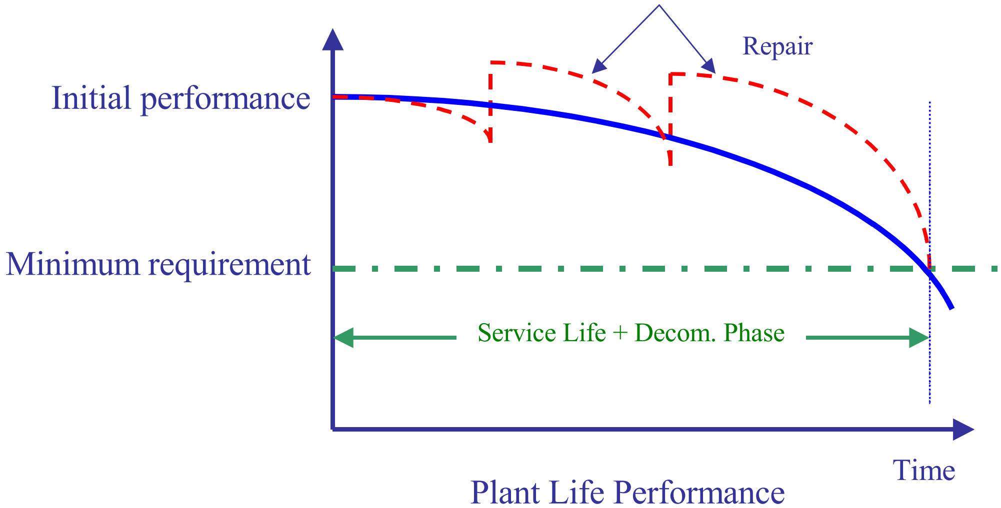

Figure 5: Plant Life Performance adapted from CEB

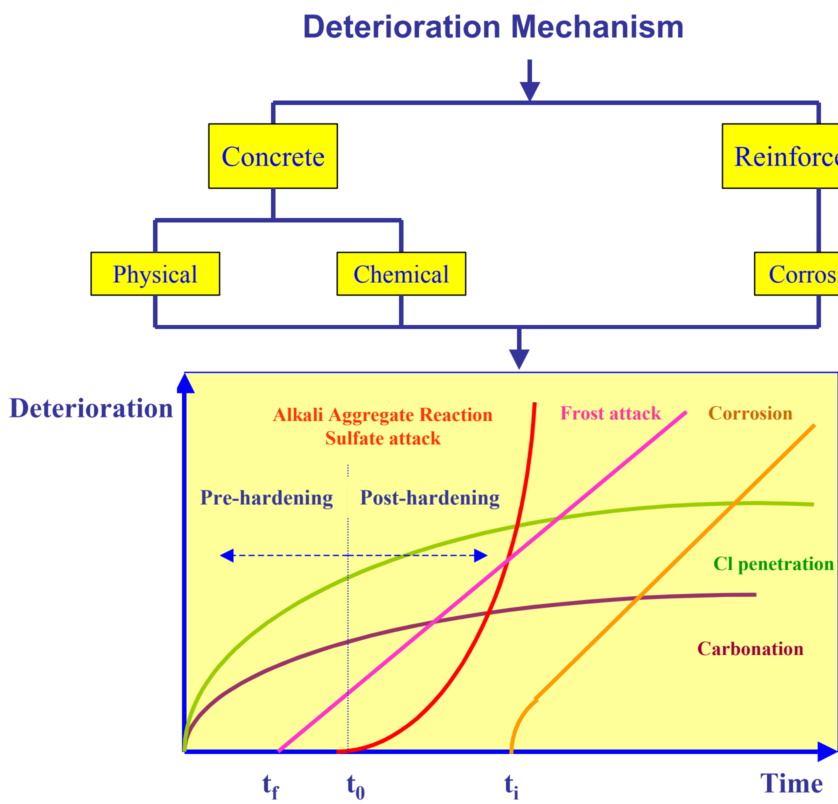

Figure 6: Deterioration Mechanisms in Concrete and reinforcement

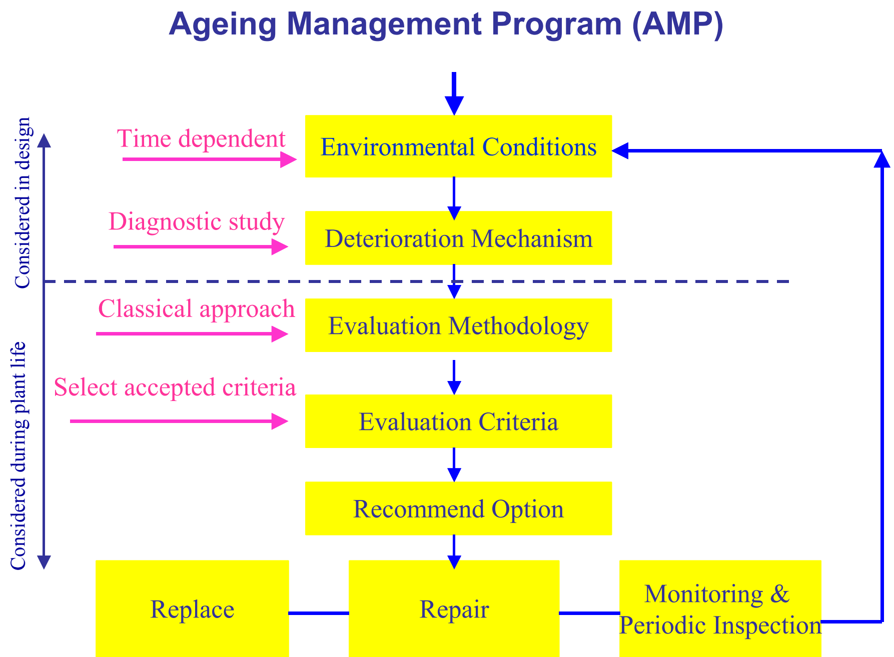

Figure 7: ACR Concrete Structure AMP during Design Phase and Plant Life