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WATERPROOFING OF NUCLEAR CONCRETE STRUCTURES

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ABSTRACT

Candu Energy in recent years performed a number of Condition Assessments and other services related to aging management of nuclear structures including containment structures and safety-related structures of Nuclear Power Plants (NPP), research reactors, and waste storage facilities. Operating Experience (OPEX) shows that one of the major areas of concerns associated with the long term integrity of structures is related to water leakage from or into the concrete structures (e.g. spent fuel bays, water retaining tanks and reservoirs, as well as waste storage structures and waste management facilities).

The paper discusses the effects of water on concrete structures, methods for locating the leaks, repair materials and techniques.

INTRODUCTION

Water retaining structures in CANDU®[1] plants typically contain demineralised water, which is considered aggressive to concrete as it tends to dissolve the cementing agent in concrete thereby degrading it. Typically metallic or non-metallic liners are used to provide a barrier to concrete from demineralised water. However, the aging of liners may result in concrete being exposed to demineralised water. In addition to this, other components of concrete structures (e.g. foundations) as well as underground structures are often exposed to the action of ground water.

Exposure of concrete to moisture facilitates a variety of degradation mechanisms. New guides and regulations on aging management of nuclear Structures Systems and Components (SSC) have been issued in recent years where requirements include provisions for preventive as well as corrective maintenance measures in Aging Management Plans (AMP).

Understanding aging of the structures exposed to water is necessary to develop and implement preventive maintenance. Long lasting repair solutions require elimination of the stressor. However, this may not always be possible and planned repairs need to be qualified for long term performance. With aging plants and nuclear facilities, it becomes increasingly important to have mitigating strategies in place to waterproof the structures. To address this, a database of techniques and materials for detection and repair of leaks in civil structures was recently developed by Candu Energy.

DEGRADATION MECHANISMS OF CONCRETE EXPOSED TO WATER

Of the concrete degradation mechanisms, leaching appears to be the most common one as far as NPP concrete structures are concerned. However, other degradation mechanisms, such as alkali aggregate reaction, erosion, abrasion, cavitation, freeze-thaw degradation, corrosion of reinforcement, etc., can also be facilitated by the presence of moisture.

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Leaching

Demineralised water and acidic groundwater dissolve cementing agents in concrete causing leaching. Leaching starts when water dissolves compounds in pore walls inside concrete. Calcium hydroxide is the most soluble compound in concrete. The leaching process is complex and depends on concrete chemistry as well as exposure conditions.

Over the long term, leaching rarely appears to continue at a constant rate [1]. Eventually the process diminishes when the soluble compounds within the pore walls lessen and when the concentration of dissolved ions in the drainage water flowing through concrete decreases [2]. The leaching rate in concrete is schematically illustrated in Figure 1.

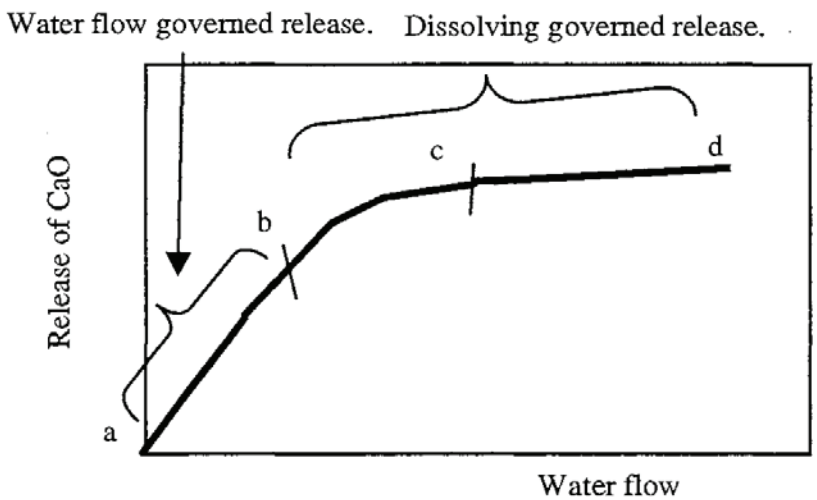

Figure 1 Lime Leached from Concrete vs. Rate of Water Percolation [2]

The rate of leaching depends on the amount of dissolved salts in the water, concrete permeability, and temperature. Solubility of calcium hydroxide decreases with the temperature increase while the rate of leaching increases with the temperature increase. Thus, as shown in Figure 2, the maximum amount of calcium will be leached out of concrete at temperatures of approximately 60°C.

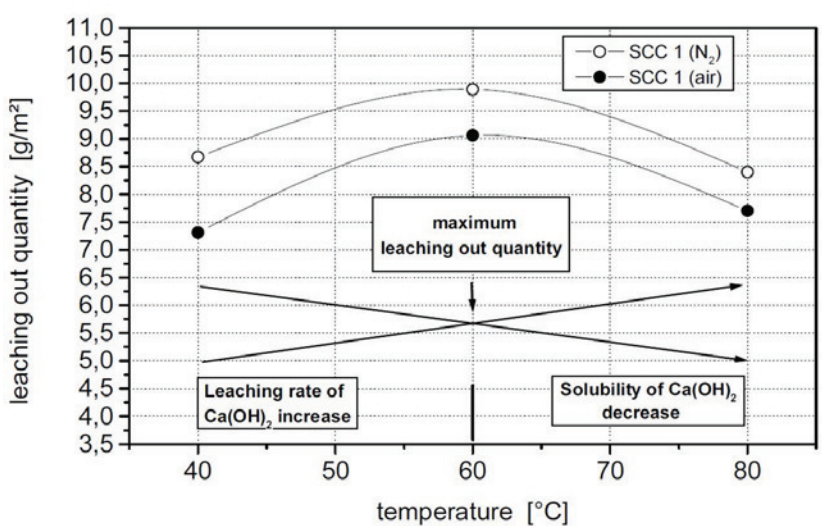

Figure 2 Influence of Temperature on the Leached Out Quantity of Calcium [3]

Leaching increases porosity and permeability of concrete, thus lowering its strength and making concrete more vulnerable to aggressive environments. Leaching may cause local reduction in alkalinity of concrete that might lead to corrosion of reinforcement. When water flows through a crack, leaching might cause dissolution of the concrete along the crack causing an increase in crack width, which may result in increased leakage. Increase in crack width with leaching at different pressures is illustrated in Figure 3.

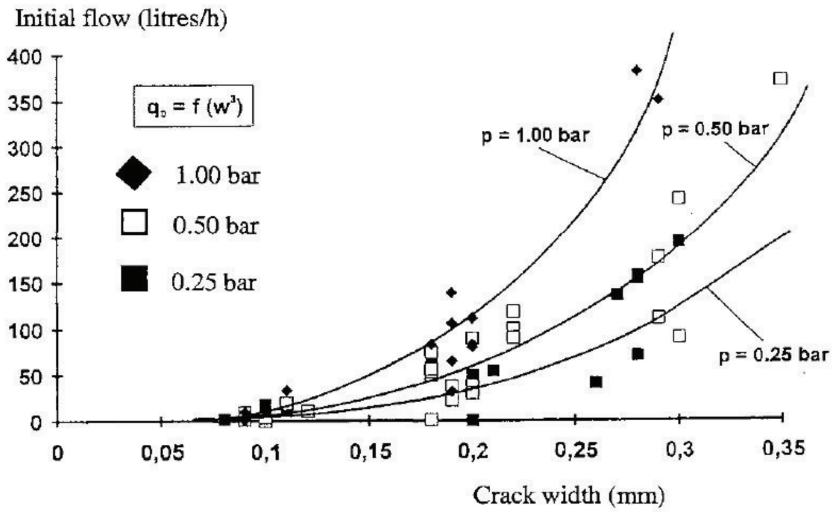

Figure 3 Initial Flow of Water as a Function of Crack Width [2]

An experimental study [2] shows that when solid material is leached from the concrete, porosity of the concrete increases. The strength reduction appeared to be a local phenomenon limited to the parts of the specimens where leaching occurred. Figure 4 shows strength reduction as a function of percentage of leached lime.

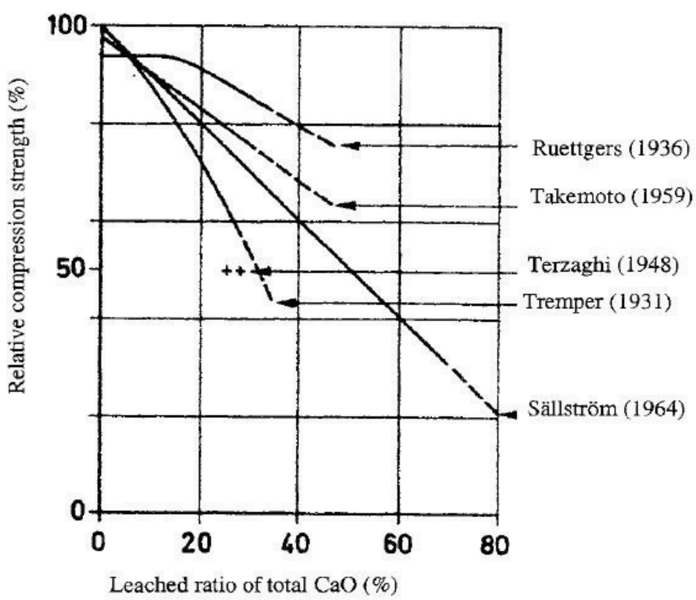

Figure 4 Relationship between Lime Leaching and Compressive Strength [2]

When water evaporates, leaching of lime compounds causes the formation of salt deposits on the concrete surface (calcium carbonate or sulphate), called efflorescence.

Alkali Aggregate Reaction (AAR)

AAR is a deleterious chemical reaction between the aggregates and the surrounding cement paste. The most common form of AAR is a reaction between active silica constituents in aggregates and the alkalis in cement. Gel formed as a result of this reaction has a tendency to increase in volume in the presence of moisture leading to expansion and cracking of concrete that may, under specific conditions, eventually lead to a complete destruction of the concrete mass. Mitigation techniques typically include elimination of exposure to moisture.

Sulphate Attack

Ground water containing sulphates may cause sulphate attack. Sulphate attack process decreases the durability of concrete by changing the chemical nature of the cement paste and properties of concrete and results in expansion and cracking of concrete, leading to progressive loss of strength and mass.

Acid Attack

Acids present in groundwater can react with the calcium compounds in hydrated cement paste to form soluble materials that are easily leached from the concrete, increasing its porosity and permeability. Acid attack may also reduce the alkalinity of concrete at the surface, reduce strength, and cause further deterioration. The extent and rate of deterioration mostly depends on the solubility of the resulting calcium salt.

Freezing and Thawing

Cycles of freezing and thawing can be damaging to concrete if it is in a saturated or in a nearly saturated condition. The freezing of water within the capillary cavities of the cement paste is associated with the expansion that produces hydraulic pressures. After cycles of freezing and thawing, scaling, spalling and pattern cracking may occur. Mitigation strategy includes minimizing concrete exposure to moisture by repairing cracks and waterproofing the concrete surface.

Abrasion/Erosion/Cavitation

Flowing water may cause abrasion, erosion and cavitation of the concrete. Loss of material from the concrete surface may occur with time due to these mechanisms. Erosion is caused by solid particles carried by the water, while cavitation is associated with the damage caused by water flow. The quality of concrete surface is important as far as abrasion and erosion are concerned. Good quality concrete can withstand steady tangential high flow of water. However, as concrete exposed to water disintegrates due to leaching as discussed above, its quality along the water path is reduced, facilitating the loss of material along the flow path over time. Cavitation is associated with formation and collapse of vapour bubbles. Cavitation damage in open channels occurs at velocities greater than 12 m/s, however water flowing at much lower velocities may cause damage in closed conduits [4]. The rate of cavitation damage is usually not steady but rather starts slowly and is followed by a rapid increase and slowing down again.

Salt Crystallization

Structures in contact with fluctuating groundwater are susceptible to deterioration induced by salt crystallization, as groundwater contains large quantities of salt. Salt can cause surface scaling and cracking due to volume changes associated with cycles of salt crystallization and dissolution. Concrete with high permeability is more susceptible to this mechanism.

Corrosion of Reinforcement

Concrete’s high alkalinity protects the reinforcing steel from corrosion; however, when pH is reduced by the intrusion of aggressive ions, corrosion can occur. A reduction in pH can be caused by the leaching of alkaline products through cracks, the entry of acidic materials, or carbonation. Chlorides can be present in constituent materials of the original concrete mix (i.e., cement, aggregates, admixtures, and water), or they might be introduced environmentally (e.g., from surrounding water). Corrosion may 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. Thickness of concrete cover and its permeability (which depends on concrete constituents, compaction, and curing) influence the rate of chloride ion penetration and carbonation, and thus the rate of corrosion.

LEAK DETECTION

Water leaks from or into the NPP structures are typically detected by:

- Visual means (during periodic inspections, walkdowns, surveillance activities, etc.); and
- Observation of water inventory in the structure and/or in the water collection system.

Periodic inspections are typically performed as part of aging management. In Canada, CSA N287.7 [5] and CSA N291 [6] specify requirements for periodic inspections of concrete containment structures and safety-related structures respectively. Periodic inspections are typically performed with established frequency by visual means and may be augmented by non-destructive techniques and destructive testing where applicable.

While moisture may be observed during periodic inspections, more often efflorescence is observed on concrete surfaces signifying the presence of cracks and moisture (see Figure 5).

Figure 5 Signs of Water Leakage

For structures that are not readily accessible, in-service inspections are typically performed by indirect means such as monitoring the aggressiveness of the environment supplemented by other means as required. As far as locating leakage is concerned, sensors can be used to detect leakage as it appears. This is also a prudent measure to be implemented in accessible areas where leakage is expected in order to enable its detection between periodic inspections.

PREREQUISITES FOR REPAIR

Repairs are designed to improve performance of a structure so that it does not fall below acceptable minimum level. However, improper repair can facilitate concrete structure degradation. For example, incorrect selection of the coating system can facilitate degradation by blocking the water inside the concrete. Experience shows that many problems associated with concrete structures originate from design and construction; this is also considered applicable to design and implementation of repairs. Design problems, in addition to the obvious ones such as inadequate design or poor detailing may include others, such as improper material selection and inadequate specification.

The following activities should be undertaken to design successful repair:

- Evaluating degradation;
- Establishing the cause of distress and assessing possibility of eliminating or controlling it, as applicable;
- Establishing prognosis for mitigation of degradation, i.e. if repair can be implemented and if it will be long-lasting and economical;
- Selecting appropriate repair methodology;
- Confirming the methodology by qualification tests and mock-up tests as applicable; and
- Preparing adequate Technical Specifications (TS).

The importance of a clear TS cannot be overemphasized. A TS can be prescriptive or performance based. The purpose of prescriptive requirements is to ensure adequate control over the inputs and processes to assist in achieving required performance. Performance based specification is to ensure that installed repair confirms to the set of minimum criteria governing long-term durability and serviceability. The inputs and outputs of performance base and prescription based specifications are listed in Figure 6.

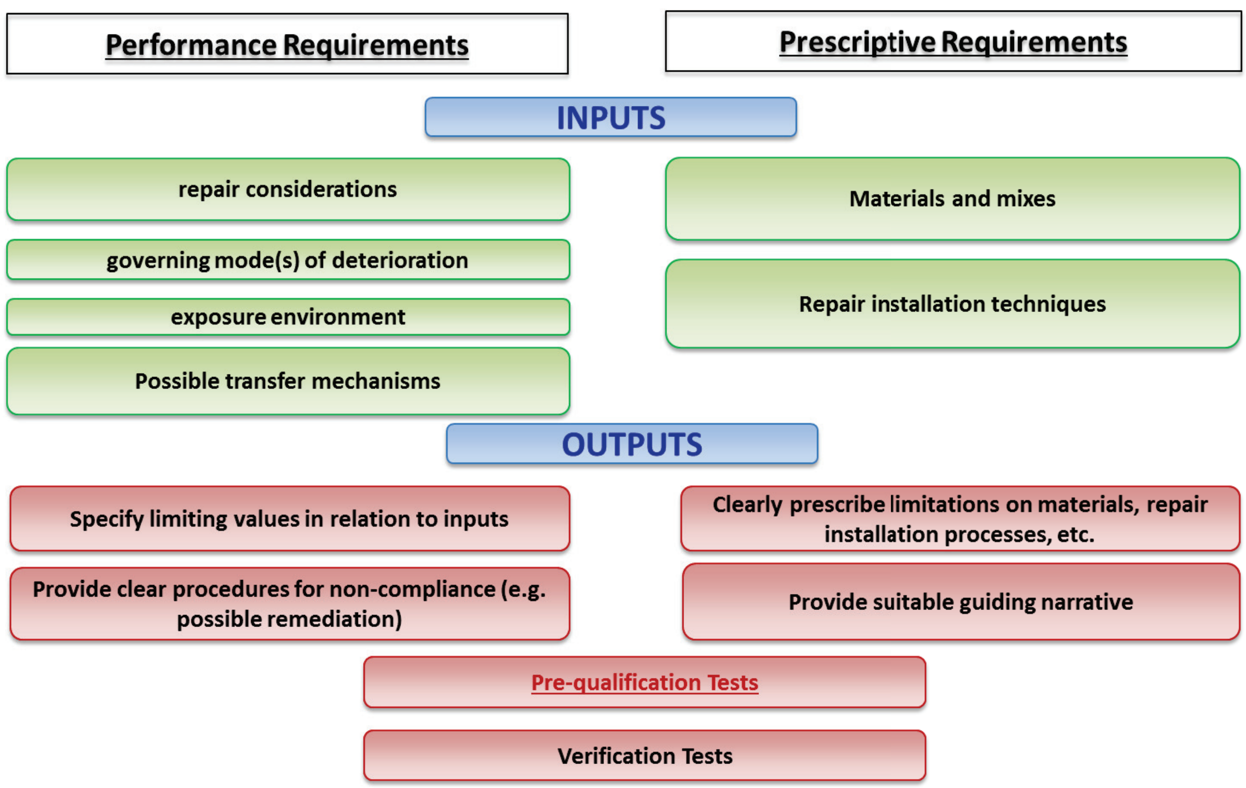

Figure 6 Technical Specification for Repair – Performance Based and Prescription Based

Although the construction industry is moving towards performance based technical specifications, in the nuclear industry, a hybrid specification is often used that is performance based but contains some specific restrictions as required by the standards.

As shown in Figure 6, clear procedures for non-compliance should be defined in the TS. However, as it is often very difficult and costly to improve inadequate repairs, the focus should be on pre-qualification tests and Quality Control (QC). If the repair is being performed for the first time on a specific component or in a specific environment, a mock up should be considered. The requirements for pre-qualification tests, QC and Quality Assurance (QA) should be defined in the TS as well as the requirements for acceptance criteria for pre-qualification tests, QC and QA and responsibility requirements.

For repair of concrete structures it is important to describe geometry of the structure and nearby structures so that appropriate repair methodology can be selected. Anticipated exposure conditions as well as design life of the repair should be defined, based on which appropriate repair technique and material qualified to meet specified requirements can be selected.

In order to ensure the longevity of repairs, the requirements for them should be specified by an Engineer with appropriate qualifications as per nuclear standards, e.g. CSA N287.1 [7]. This is also applicable to the Engineer, who is to oversee and accept the repairs.

REPAIR

Waterproofing is typically performed by the individual treatment of discontinuities such as cracks and joints such as those shown in Figures 7 through 10, and/or by a concrete surface treatment (i.e., application of water proofing sealant, coating or a membrane) as shown in Figures 11 through 15.

Figure 7 Joint Sealant Replacement on Spent Fuel Canisters' Base Slab

Figure 8 Reactor Building Joint Replacement

Figure 9 Polyurethane Injection of the Crack

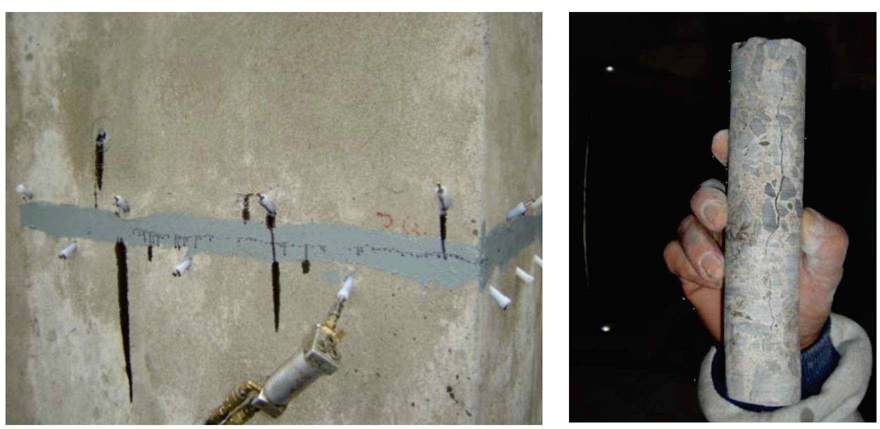

Figure 10 Epoxy Injection of the Crack and QC tests

Figure 11 Application of FRP Sheets Followed by Application of Protective Coating, Ring Beam

Figure 12 Installation of Bitumen Waterproofing Membrane

Figure 13 Crystalline Material Application to Waterproof Wall in Contact with Soil

Figure 14 Coating Application for Waterproofing of Spent Fuel Canister

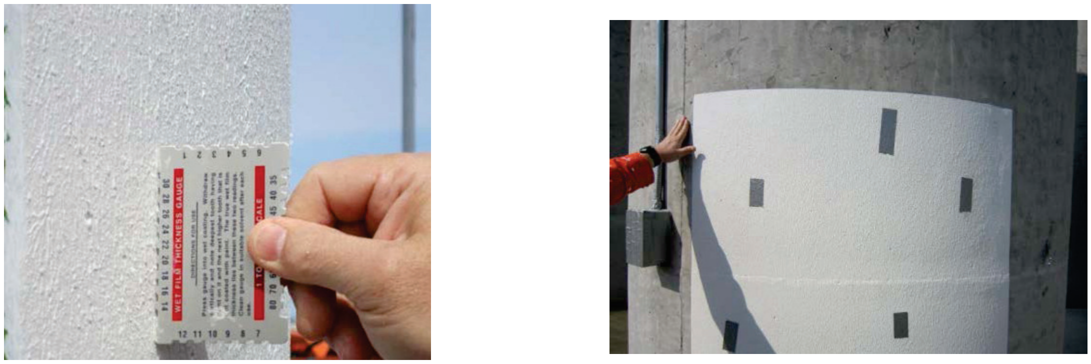

Figure 15 Prequalification Test Patch for Coating Application on Canisters

Depending on the situation and by taking into account the damage and accessibility, consideration can be given to using either one of the methods or a combination of the two. An example of the combination of the methods can be injection of the cracks with application of protective coating to provide further barrier to leakage. For additional waterproofing of some structures sealants and coatings can be used in combination or a coating system may include fibre reinforce polymer (FRP) sheets.

Compatibility of materials used for a combined repair scenario should be ensured. Selecting the most viable and economical repair technique should be based on both the engineering assessment and the cost associated with repair.

Leakage is experienced by many structures in various industries and experience from those industries can be used in nuclear, where applicable. Some commercial type materials can be used in nuclear applications outside of the containment structure provided that a thorough review of the manufacturer's information, analysis of tests and exposure conditions that materials are qualified to is performed. It is necessary to confirm intended application and applicability of qualification testing for a specific application. This is important as, for example, qualification tests may have been performed on concrete substrate but material is to be applied on top of previously applied coating. In this case, the results of material qualification tests would not be applicable.

Materials should be selected considering the anticipated exposure conditions and longevity. Compatibility of materials needs to be ensured. If possible materials by different manufacturers should not mix in the same repair scenario unless their satisfactory performance was demonstrated by tests and long-term field application. It is important to ensure that tests are representative of actual field applications and ambient conditions. For example, liners and coatings are typically applied as a system and should be qualified as such including substrate (e.g. concrete or steel), number and consistency of layers, presence of primer, film thickness of each layer, ambient conditions and time of application and curing of each layer.

Materials selection should ensure non-interference with any normal operations or safety functions, for example by deteriorating and causing clogging of the filters of sumps [8]. Materials selected for repair must meet specification requirements for the intended application. Furthermore, materials for use inside the Reactor Building shall be qualified to appropriate nuclear standards, e.g. CSA N287.2 [9]. As a minimum, material should be tested to a Design Basis Accident (DBA) scenario and for adhesion due to the potential risk of damage to or interference with safety-related system if material detaches from its substrate. Other qualification tests may include radiation resistance, elasticity, chemical resistance and decontamination, impact resistance, fire resistance, abrasion resistance, heat aging, and immersion as applicable.

As far as repairs of leaking structures are concerned, both the materials for concrete repairs in general as well as materials used in nuclear industry are of interest. Thus, the database developed by Candu Energy includes materials that have been successfully used for protection and waterproofing of concrete structures and those specifically qualified for nuclear applications.

CONCLUDING REMARKS

To ensure a successful and long lasting repair, the cause of degradation should be understood and addressed whenever possible.

It is prudent to approach all repairs on a case-by-case basis since the root cause, operating environment, and material properties may vary. The applicability of the technique and material should be confirmed for a specific job. Improperly selected materials and inadequate installation of the repairs are the major causes of repair failures and may be responsible for facilitating a structure's degradation. Therefore, the importance of prequalification tests for materials and application techniques as well as review of their field performance cannot be overemphasised.

As it is often impractical to mitigate inadequate repairs, the technical specification should clearly define all necessary requirements including those for prequalification tests and quality control during repair. Evaluation of the structure, selection of repair techniques and materials, specification of repair as well as its implementation and acceptance should be performed by trained and experienced personnel.

ACKNOWLEDGEMENT

The photographs used in the paper are of projects completed for AECL.

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