Nuclear Engineering and Design 277 (2014) 248–264

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

A proposed aging management program for alkali silica reactions in a nuclear power plant

Victor E. Saouma*, Mohammad A. Hariri-Ardebili

Department of Civil Engineering, University of Colorado, Boulder, United States

ARTICLE INFO

Article history:
Received 1 November 2013
Received in revised form 1 June 2014
Accepted 4 June 2014

ABSTRACT

Drawing from publicly available information, this paper addresses the alkali silica reaction management of Seabrook nuclear power plant.

The essence of the reaction is first examined, followed by a summary of findings, current and planned work. Then, the authors draw on their experience in ASR to first comment on the current work, and then complete the paper with what they would recommend.

An important observation is that ASR constitutes a major challenge to the nuclear industry, and a thorough understanding of the State of the Art is essential before a holistic approach is undertaken. It is neither a simple nor an inexpensive challenge, yet a most critical one that industry and regulators must confront. This paper is only a breach into such an effort.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

It is a matter of public record that Seabrook nuclear power plant (NPP) appears to be suffering from alkali silica reaction (ASR) in a localized zone of its subbasement. Drawing exclusively from publicly available information from the Agency wide Document Access and Management System (ADAMS), the authors provide an unsolicited personal and independent opinion on the management of this problem based primarily on the senior author's experience with ASR (Saouma and Perotti, 2006; Saouma et al., 2007, 2014; Puatatsananon and Saouma, 2013; Saouma, 2013).

First ASR will be briefly explained, then the presence of ASR in nuclear power plants will be discussed, followed by the role of irradiation on ASR. Issues pertaining to the life-extension of NPP will be discussed in general, followed by a factual presentation of the role of ASR in Seabrook NPP (as published in ADMAS). The paper will conclude with the authors personal comments on some of the actions presently taken, and finally what they would personally recommend.

* Corresponding author. Tel.: +1 3034921622.
E-mail address: saouma@colorado.edu (V.E. Saouma).

http://dx.doi.org/10.1016/j.nucengdes.2014.06.012
0029-5493/© 2014 Elsevier B.V. All rights reserved.

2. What is ASR

ASR was first identified by Stanton (1940) as a cause for concrete deterioration and is likely the leading cause of dam concrete deterioration. This slowly evolving internal concrete damage causes millions of dollars in damage worldwide, given that no (economically) feasible method is available to stop the reaction. More recently, there has been evidence of ASR in nuclear power plants (see below).

Alkali–silica reaction is an acid–base one. The acid reactant is silica in the solid state, the basic one are potassium and/or sodium hydroxide in the pore solution, and calcium hydroxide in the solid state. The reaction medium is water. The product of the reaction is a calcium potassium silicate hydrate, or a calcium sodium silicate hydrate (Dron and Privot, 1992).

Alkalis are present in cement in the form of sodium oxide NaO_2, potassium oxide K_2O. These oxides are initially found within the anhydrous phases (i.e. in the absence of water) of the cement, and then dissolve in the pore liquid during the process of hydration into $Na^+ + OH^-$ and $K^+ + OH^-$ forming sodium or potassium hydroxyl ions respectively. Since these ions are not constituents of the cement hydration process, they accumulate in the pore solution. Hence, the alkali themselves do not participate in the reaction, but it is rather their corresponding hydroxyl ions. It should be noted that there is increasing evidence that alkali can also be found in some aggregate where they "cohabit" with silica as long as the pH is below a certain critical value (Bérubé et al., 2002; Constantiner and Diamond, 2003).

Silica (Si) comprises about 65% by weight of the accessible portions of the earth's crust. It occurs both "free", that is as a solid crystalline oxide from which other essential elements are absent, as well as in silicates, in which silicon and oxygen are combined with other elements, of which aluminium, magnesium, calcium, potassium, sodium, iron and hydrogen are the most important. Hence, silica is the main constituent of most aggregates in the form of silicon dioxide (SiO_2). Whereas the majority of silicon dioxide is stable, the poorly crystallized silica are thermodynamically unstable with respect to the crystalline phase, and prone to react with the cement hydroxyl ions on the surface of the aggregate and produce silanols (Si—OH groups).

Initially, each atom of silicon is connected to the lattice by four siloxane bonds and will be ruptured by OH^- ions. Hence, in the first stage there is a hydrolysis of the reactive silica (siloxane) by OH^- ions to form an alkali–silica gel. In this hydrolysis reaction the high pH pore fluid reacts with Si—O—Si bonds to form silicic acid (silanol bonds) and alkali silicate gel. The dense and impermeable aggregates react very slowly.

$$\underbrace{-\overset{|}{\underset{|}{\mathrm{Si}}}-\mathrm{O}-\overset{|}{\underset{|}{\mathrm{Si}}}-}_{\text{Siloxane}}+\underbrace{\mathrm{R}^+ + \mathrm{OH}^-}_{\text{Hydroxyl ions}}\longrightarrow\underbrace{-\overset{|}{\underset{|}{\mathrm{Si}}}-\mathrm{O}-\mathrm{R}}_{\text{Alkali-silicate (gel)}}+\underbrace{\mathrm{H}-\mathrm{O}-\overset{|}{\underset{|}{\mathrm{Si}}}-}_{\text{Silicic acid}} \qquad (1)$$

where R^+ denotes an alkali ion such as Na^+, K^+ or Ca^+ (which is dominant at "room temperature", while the former two are prevalent in accelerated tests.

The silicic acid is weak, so that it immediately reacts with further hydroxyl liberating water and negatively charged *Si—O—*. Readily abundant and mobile sodium, potassium and calcium ions will diffuse in the gel to balance the negatively charged species.

$$\underbrace{\mathrm{H}-\mathrm{O}-\overset{|}{\underset{|}{\mathrm{Si}}}-}_{\text{Silicic acid}}+\underbrace{\mathrm{R}^+ + \mathrm{OH}^-}_{\text{Hydroxyl ions}}\longrightarrow\underbrace{-\overset{|}{\underset{|}{\mathrm{Si}}}-\mathrm{O}-\mathrm{R}}_{\text{Alkali silicate (gel)}}+\underbrace{\mathrm{H_2O}}_{\text{Water}} \qquad (2)$$

The resultant alkali silicate (alkali silicate gel) is hygroscopic (expands in the presence of water), except for $R = Li$,

$$\underbrace{-\overset{|}{\underset{|}{\mathrm{Si}}}-\mathrm{O}-\mathrm{R}}_{\text{Alkali-silicate (gel)}}+\underbrace{\mathrm{nH_2O}}_{\text{Water}}\longrightarrow\underbrace{-\overset{|}{\underset{|}{\mathrm{Si}}}-\mathrm{O}^- + (\mathrm{H_2O})_n + \mathrm{R}^+}_{\text{Expanded alkali silicate (gel)}} \qquad (3)$$

Eqs. (1)–(3) follow the notation of Ichikawa and Miura (2007), whereas Chatterji (2005) further addresses the complexity of this chemical reaction. The kinetics of this reaction was recently examined by Saouma et al. (2014).

Different scenarios are possible: a "finite" supply of alkali or silica, or an "infinite" supply of both. In the latter case, the reaction continues for a very long (yet theoretically finite) time, and this has been observed in some dams such as Fontana (US), Chambon (FR) or Salanfe (CH) dams (Charlwood, 2012). In the former case, the reaction duration is governed by the lower concentration of silica *or* alkali.[1] It is of no concern whether the higher concentration is nearly infinite, as the reaction will eventually cease. Though it is well known that for the reaction to occur, the relative humidity (RH) must be greater than about 80%, water must nonetheless diffuse from the pores to enter into contact with the dry gel (Poole, 1992). Excessive swelling results in cracks, however there is a lack of consensus as to whether cracks initiate inside or around the aggregate; this initiation has no impact on the numerical modeling of ASR at the macro scale.

Finally, an excellent source of information about ASR can be found in the *ASR Reference Center* web page maintained by the Federal Highway Administration (FHWA, 2013) (with emphasis on pavement).

3. ASR in nuclear power plants

Despite the lack of publicity, some nuclear power plants reactors are starting to show signs of ASR.

In Japan, the (reinforced concrete) turbine generator foundation at Ikata No. 1 NPP (owned by Shihoku Electric Power) exhibits ASR expansion and has thus been the subject of many studies. Takatura et al. (2005a) reports on the field investigation work underway: location, extent of cracking, variation in concrete elastic modulus and compressive strength, expansion in sufficient detail to adequately understand the extent of damage. The influence of ASR on mechanical properties (in particular, the influence of rebar) and on structural behavior has been discussed by Murazumi et al. (2005a) and Murazumi et al. (2005b), respectively. In the latter study, beams made from reactive concrete were tested for shear and flexure. These beams were cured at $40^d gr$C and 100% relative humidity for about six weeks. Some doubt remains, however, as to how representative such a beam is for those NPP where ASR has been occurring for over 30 years. A study of the material properties introduced in the structural analysis was first reported by Shimizu et al. (2005b). An investigation of the safety margin for the turbine generator foundation has also been conducted (Shimizu et al.,

[1] This is analogous to an analysis of reinforced concrete beams in flexure. If the reinforcement ratio ρ exceeds the balanced one (ρ_b) then failure is triggered by crushing of the concrete (irrespective of the total area of steel); otherwise, failure is triggered by yielding of the steel (irrespective of concrete strength).

2005a). Moreover, vibration measurements and simulation analyses have been performed (Takatura et al., 2005b). Takagkura et al. (2005) has recently reported on an update of the safety assessment at this NPP.

In Canada, Gentilly 2 NPP is known to have suffered ASR (Orbovic, 2011). An early study by Tcherner and Aziz (2009) actually assessed the effects of ASR on a CANDU™ 6 NPP (such as Gentilly 2). In 2012 however, following an early attempt to extend the life of Gentilly 2 until 2040 (with an approx. \$1.9B overhaul), Hydro-Quebec announced its decommissioning after 29 years for economic reasons.

As late as 2007, it was reported that *to date, no incidences of ASR-related damage have been identified in U.S. nuclear power plants* (Naus, 2007).

Finally, more recently there has been mounting evidence of ASR in a US nuclear power plant. This will be separately addressed below.

4. Role of irradiation on ASR

It has long been known that irradiation affects concrete properties; the classical work by Hilsdorf et al. (1978) remains pertinent today given the complexity of conducting supportive experiments.

The possibility that nuclear irradiation can significantly increase the reactivity of silica-rich aggregates (hence the potential for ASR) was first raised by Ichikawa and Koizumi (2002). Let's begin by the author's summary of the state of knowledge in 2002:

- Gamma rays do not affect concrete properties up to a dose of 10^{10} Gy).[2]
- Irradiation of fast neutrons to a dose of more than $\sim 10^{19}\ n/\text{cm}^2$ results in deterioration of concrete. Irradiation causes the aggregates to expand and the cement paste to shrink.
- The degree of shrinkage at a dose of $5\times10^{19}\ n/\text{cm}^2$ is about 2% and 0.3% for Portland and alumina cement, respectively.
- The degree of aggregate expansion strongly depends on the type of aggregates. Expansion at a dose of $5\times10^{19}\ n/\text{cm}^2$ is roughly 1% for limestone and flint, while 0.1% for serpentine.
- The expansion of concrete composed of Portland cement paste and aggregates is greater than that estimated from the volume ratio of aggregates and the degrees of expansion and shrinkage.
- The difference between the estimated and observed degrees of expansion strongly depends on the mineral composition in the aggregates. This difference is higher for aggregates with higher SiO_2 content).
- The difference for concrete with silica-rich flint is about five times higher than that with limestone.
- Concrete with quartzite sand shows severe expansion after irradiation of $3\times10^{19}\ n/\text{cm}^2$, though crystalline quartz reveals only a small expansion. The degradation in concrete mechanical properties due to fast neutron irradiation is greater for concrete showing a higher degree of expansion.
- The decrease in tensile strength due to irradiation is more pronounced than the decrease in compressive strength.

These results indicate that the degradation of concrete by fast neutrons is not simply due to the individual deterioration of cement paste and aggregates, but rather to complex reactions of irradiated cement and aggregates.

[2] One Gray, Gy, is the absorption of one joule of energy, in the form of ionizing radiation, per kilogram of matter, i.e. 1 Gy = 1 J/kg = 100 rads.

It is thus suggested that the decrease in the resistance to nuclear radiation by increasing the SiO_2 content in aggregates provides a strong indication that the deterioration is due to an acceleration of the alkali-silica reaction caused by nuclear radiation.

Based on these premises, the authors conducted an experimental program, which led to concluding that:

1. Nuclear radiation significantly increases the reactivity of silica-rich aggregates to alkali. This does not necessarily imply however that ASR will occur since other requisite conditions may not be present.
2. Concrete surrounding the pressure vessel receives the highest radiation dose; in assuming that the lifetime of a commercial nuclear power plant is 60 years, the integrated absorbed dose of the concrete is about 10^9 Gy for gamma rays, which is much lower than the critical dose.

Though not specifically addressing ASR, the work by Vodák et al. (2004) is worth reporting. In focusing on the impact of irradiation on the strength of an NPP concrete, the authors investigate the overall effect of irradiation of concrete. They determined that when the concrete used in the construction of Temelin's NPP (Czech Republic) was exposed to γ-irradiation of 6×10^5 Gy (6×10^7 rads) (i.e. which corresponds to 57 years of normal NPP operation time), a degradation in mechanical properties had occurred. More specifically, results indicated that the compressive, splitting-tensile and flexural strengths of the concrete decreased with the dosage level, reaching reductions of about 10%, 5% and 5%, respectively, at the maximum dose. Of more relevance to the topic of this paper however is the finding that irradiation generates a succession of chemical reactions, leading to a decrease in the size of pore space and hence inhibiting the ability of concrete to absorb some of the ASR gel produced prior to expansion.

A more recent study by Ichikawa and Kimura (2002) examined the effect of electron-beam irradiation on the reactivity of plagioclase (generally present in volcanic rock) to ASR. It was determined that irradiation of plagioclase with a 30-keV electron beam at a dose in excess of 0.9×10^9 Gy converts a crystalline plagioclase to an amorphous one 35 times more reactive to alkali than the crystal. This observed high reactivity indicates that the deterioration of irradiated concrete by alkali-silica reaction is indeed possible even for aggregates that would otherwise be inert to ASR without irradiation.

In summary, indications suggest that radiation effects on concrete degradation are minimal for the first 40 years; however, a structural life extension to 60–100 years may prove problematic and moreover the data to fully support this concern are insufficient (Fujiwara et al., 2009).

5. Life extension

According to the Atomic Energy Act of 1954 (NUREG-0980, 2013), and Nuclear Regulatory Commission (NRC) regulations, the operating licenses for commercial power reactors are issued for 40 years and can be renewed for an additional 20 years, with no limit to the number of renewals. The original 40-year license term was selected on the basis of economic and antitrust considerations rather than technical limitations. Henceforth, many plants have sought (and obtained) a 20-year life extension. In the United States, the average structural life is 32 years (U.S. Energy Information Administration, 2013).

Also in the U.S., most NPP have already had a life extension from 40 to 60 year, and serious consideration is now being given to a further extension to 80 years. It is in this context that Graves et al. (2013) offered a comprehensive evaluation of potential aging-related degradation modes for light-water reactor materials and components. This work was based on the levels of existing technical and operating experience, knowledge, the expected severity of degradation, and the likelihood of occurrence. The report produced thus detailed an *expanded materials degradation analysis* of the degradation mechanisms capable of affecting concrete.

The report concluded that three (of the five) high-ranked degradation modes could potentially affect the concrete containment, which is the safety-related structure of primary interest.

Creep of the post-tensioned concrete containment.
Irradiation of concrete (which, as shown below, may accelerate ASR).
Alkali–silica reaction *Though this degradation has been well documented through operating experience (for bridges and dams in particular) and the scientific literature, its high ranking in this EMDA analysis underscores the need to assess its potential consequences on the structural integrity of the containment.*

A similar study was conducted in France, a country that contains 58 NPP. This group of plants has an average age of approximately 27 years, spanning a range of 13 to 34 years. Once again, the focus herein lies in the operations of NPP beyond 40 years, and possibly 60 years (Gallitre et al., 2010). With structural aging thus being a concern, it has been recognized that ASR is indeed one of the leading causes of aging-related problems. ASR prevention however has not historically been subject to special requirements in the design and construction of French NPP, and all recommendations for preventing these disorders date back only to 1994 (Coppel et al., 2012). To assess the "theoretical" ASR risk, a methodology was developed by the EdF electric utility in the 1990's based on three parameters:

1. Calculation of active alkali content in the concrete mix according to French LCPC 1994 recommendations. The active alkali content of concrete comprises active alkali from all concrete components (cement, aggregates, water, etc.). This calculation yields the following for the classification of concretes:
   - A1: Active alkali content < 2.2 kg/m^3 of concrete
   - A2: Active alkali content between 2.2 and 3 kg/m^3 of concrete
   - A3: Active alkali content > 3 kg/m^3 of concrete
2. Aggregate qualification according to the French LCPC 1994 recommendations. Aggregate qualification is performed from original quarries used for the given site construction. Aggregate qualification yields the following in terms of aggregate classification:
   - NR: Non-reactive aggregate
   - PR: Potentially reactive aggregate
   - PRP: Potentially reactive with pessimum effect (flint, chart)
3. The environmental description of the concrete structure under consideration includes:
   - H: Humidity exposure (relative humidity > 80%)
   - T: Temperature exposure ($T > 35\,^\circ$C)
   - N: Normal exposure ($T < 35\,^\circ$C and relative humidity <80%)
   - A: Alkali exposure (from a system containing alkalis)
   - M: Marine or industrial water exposure

The risk of ASR is then determined from Table 1.

All 58 NPP in France have been assessed for potential ASR expansion, and only four out of a total of 19 are considered to be at potential risk; these four are essentially located on the Loire River, where aggregates are known to contain a relatively high percentage of silica. For cases of serious concern, practically

Table 1
Theoretical risk of ASR in NPP (Coppel et al., 2012).

Active alkali content	A1					A2					A3				
Environ.	N	H	T	A	M	N	H	T	A	M	N	H	T	A	M
NR	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
PR	0	1	1	4	2	1	3	3	4	3	1	4	4	4	4
PRP	0	0	0	2	1	0	x	x	2	1	x	1	1	2	1

"Theoretical" risk of ASR: 0, Negligible; 1, Low; 2, Medium; 3, High; 4, Very high; x, Specific pop-out risk.

no solution exists; however, since this phenomenon progresses slowly, it can be detected through observation (such as pop-out or concrete expansion) when the structure has been instrumented (Gallitre and Dauffer, 2010). If ASR is detected, then its evolution can reasonably be monitored through crack length measurements inside a fixed area using the so-called "trihedron" method. One of three conclusions is deemed possible (Gallitre and Dauffer, 2010):

- In the medium term, no dangerous consequences arise as a result of the large amount of reinforcement in the concrete.
- In a longer term, inspections may be intensified should signs be detected, and more sophisticated analysis may be undertaken if necessary.
- In the long term, tightness may be improved, if necessary, by means of either a metallic or organic coating.

The authors would disagree with these conclusions since a solid conclusive understanding of the evolution of this reaction and its impact on NPP structural integrity is necessary *before* granting a license extension.

6. Seabrook nuclear power plant

6.1. Reported issue

This section will provide detailed information on the first reported nuclear power plant in the U.S. known to possibly suffer from ASR. All information reported has been gathered exclusively from the ADAMS, the official record-keeping system through which the U.S. Nuclear Regulatory Commission provides access to publicly available documents. It is worth mentioning that ML121250588 (2012) does outline the regulatory framework and general acceptance criterion for NRC oversight and review.

Description NextEra Energy Seabrook, LLC submitted an application for renewal of the Seabrook Station NPP Unit 1 operating license for another 20 years (beyond the current licensing date of May 15, 2030) (ML12160A374, 2012). This renewal process consisted of two concurrent reviews, i.e. a technical review of safety issues and an environmental review. For the safety review, the License Renewal Rule process and application requirements for commercial power reactors are based on two key principles: (a) that the current regulatory process, continued into the extended period of operation, is adequate to ensure that the continuing license basis of all currently operating plants provides an acceptable level of safety, with the possible exception of the detrimental effects of aging on certain systems, structures, and components (SSCs), and possibly a few other issues related to safety only during the period of extended operation; and (b) each plant's continuing license basis is required to be maintained.

As part of the license renewal process, an aging management program (AMP) is to be identified that is determined to be acceptable to manage potential problems such as ASR.

In 2009–2010, it was determined that groundwater infiltrated into the annular space between the concrete enclosure building and concrete containment. The bottom 6 ft of the concrete containment wall was in contact with groundwater for an extended period of time. Cracks due to the alkali-silica reaction had been observed in various Seabrook plant concrete structures, including the concrete enclosure building ((ML12160A374, 2012), Fig. 1).

As a consequence, the NRC identified ASR as an open item indicating that it had not been adequately addressed in the Structures Monitoring AMP (OI 3.0.3.2.18-1).

A total of 131 cores (4″ diameter, 14″–16″ deep) in the affected areas were tested to determine their compressive strength and modulus of elasticity and then compared with test results from standard concrete cylinders cast during the original concrete construction placements. In addition, petrographic examinations, as per ASTM C856, were performed. It was determined that the areas affected were highly localized, and core samples extracted from adjacent locations did not show signs of ASR. Furthermore, when the core lengths were evaluated (i.e. depth into the wall), it was observed that cracking was most severe at the exposed surface and reduced towards the center of the wall (ML12199A295, 2012). As a consequence, the NRC initiated an *Open Item* (OI 3.0.3.2.18-1) related to the AMP.

As a result of this identification of ASR, it was reported that NRC officials informed the power plant's owners that in order for the plant to gain approval for its license extension, proof needed to be provided concerning the impact ASR will have on the plant as it ages, as well as the steps adopted to mitigate ASR in the plant's concrete structures, if necessary (Chiaramida, 2013). Moreover, the NRC made it clear that a final decision on the license renewal application would not be announced until concrete degradation issues identified at the plant had been satisfactorily addressed, (Haberman, 2013).

Root cause investigation A root cause investigation was performed and led to determining that (ML13151A328, 2013):

RC1 – ASR developed because the concrete mix designs unknowingly utilized a coarse aggregate that, in the long term, would contribute to the Alkali Silica Reaction. Although testing was conducted in accordance with ASTM standards, these standards were subsequently found to be limited in their ability to predict slow reactive aggregates that produce ASR in the long term.

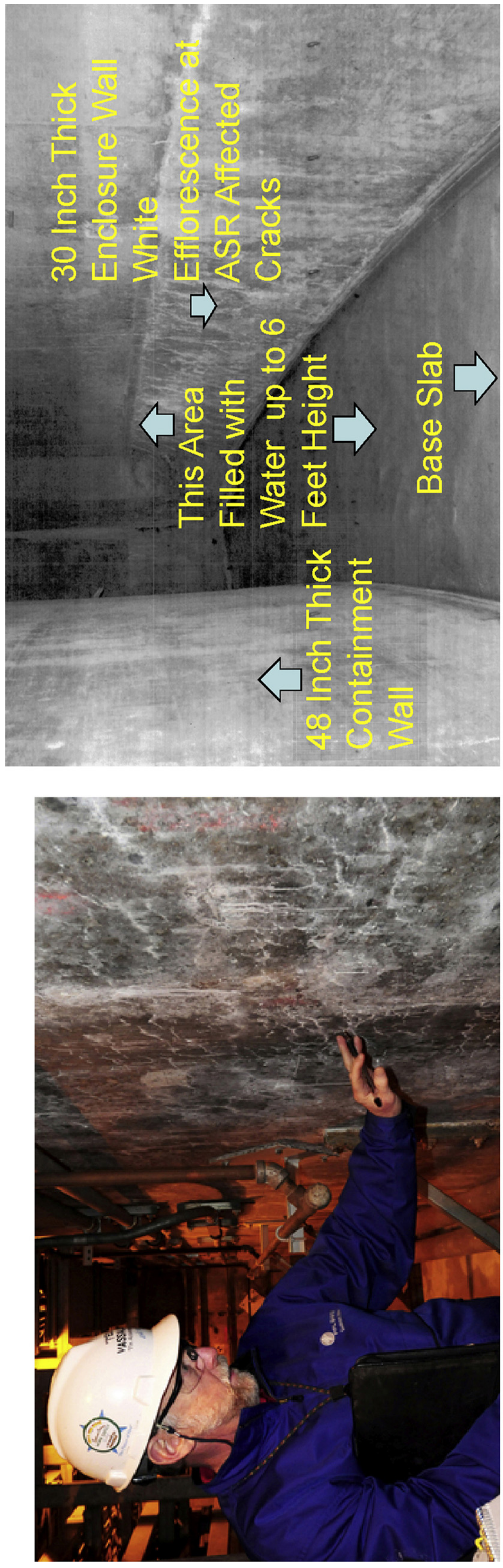
RC2 – Based on the long-standing belief that ASR is not a credible failure mode due to the concrete mix design, the conditions imposed on reports involving groundwater intrusion or concrete degradation, along with the structural health monitoring program, did not consider the possibility of ASR development.

One contributing cause was nonetheless identified: failure to prioritize groundwater elimination or mitigation resulted in a greater concrete area being exposed to moisture.

Material degradation Initial testing of extracted core samples indicated reductions in the modulus of elasticity values from those assumed in the original design. The first compressive strength tests from the electrical tunnel were compared to the original test cylinders cast during construction of the Control Building in 1979. This comparison also appeared initially to indicate an approximately 22% decrease in compressive strength. Extracted cores were expected to yield compressive strength values 10–15% lower than cylinder test results.

When additional cores were tested from both ASR-affected and non-ASR-affected areas, the tested compressive strengths were essentially the same, a finding consistent with the industry literature, which predicts minimal impact to tested compressive strength levels at relatively low ASR expansions. The modulus of elasticity equaled approximately 47% of the expected value (ML121160422, 2012; ML13151A328, 2013).

Structural integrity and testing In the most recent report ML13151A328 (2013), it was stated that the purpose of testing is to assess the impact of ASR on out-of-plane shear performance and reinforcement anchorage (lap splice) performance. Test specimens will use the walls in the Electrical Tunnel as the reference location for the Seabrook Station, and the walls will be modeled as reinforced concrete beams constructed in order to



(a) Observed Map Cracks

(b) Identification of damage

Fig. 1. ASR in Seabrook nuclear power plant (ML12199A300, 2012).

be similar to the reference location walls. It is anticipated that testing will provide data to assess the effects of ASR on shear and reinforcement anchorage performance; whenever necessary, testing will assess the effectiveness of retrofit techniques in improving the structural capacity of beams at various levels of ASR degradation.

The following information will be developed by the Shear Test Program:

- Shear capacity of ASR-affected reinforced concrete beams: determines the extent to which shear performance of the reinforced concrete beams has been affected as a function of ASR degradation.
- Flexural stiffness of ASR-affected reinforced concrete beams: determines the extent to which flexural stiffness of the reinforced concrete beams has been affected as a function of ASR degradation.
- Efficacy of retrofit technique: determines the effectiveness of the given retrofit technique in enhancing shear performance as a function of ASR degradation. Test results may then be used to determine whether any margin exists between the actual (experimentally determined) shear strength of reinforced concrete beams and the calculated shear strength (by applying relevant provisions in the design code, ACI 318-71).

Regrettably, most figures and important information pertaining to these tests were blacked out.[3]. The earlier report (ML121160349, 2012) on tests performed at the University of Texas at Austin must now be consulted in order to grasp the meaning of this test.

Test beams were fabricated to represent the Seabrook structural elements and had both varying levels of ASR and control beams with no ASR. The reinforcement detail depicts the lack of through-thickness reinforcement in tunnel walls and enables an in-depth study of shear and anchorage behavior at both the current and future levels of ASR degradation, Fig. 2.

Preliminary results are shown in Fig. 3(a), along with the application of test results in Fig. 3(b).

Finite element studies A finite element model of the most limiting area was developed to address the potential of an adverse dynamic response associated with the apparent modulus of elasticity tests conducted on the extracted core samples. According to this model, a differential analysis of the structure with various modulus changes could be performed (ML13151A328, 2013). This analysis concluded that (ML121160422, 2012) the *maximum acceleration profiles within the structure response spectrum are not significantly affected by ASR properties and moreover that the distribution of forces and moments is not significantly altered by ASR properties. It can thus be concluded that load distribution and seismic response is negligibly affected by ASR*.

Design *vs* **analysis** Throughout the report, safety is indeed very strictly adhered to in the spirit of the relevant codes (mostly ACI). It should be kept in mind that those codes were written primarily for the (usually linear elastic) *design* of new structures, and as a result of safety requirement, it is a binary outcome: pass or fail. Since the concepts of working stress design methods (based on allowable strength), or load resistance factor design (ASCE/SEI 7, 2010) have been adopted (ACI and AISC codes amongst others), much progress has been made. In the framework of earthquake engineering retrofitting, Performance based Earthquake Engineering was introduced (FEMA-444, 2006). In this new paradigm, and through nonlinear analysis different levels of damage are considered, Fig. 4.

Plans and schedule Current plans include the following (ML121160422, 2012):

1. Shear and lap splice testing at the University of Texas at Austin to conduct series of full-scale concrete beam tests in order to provide representative test data of the in situ strength of restrained concrete elements. Beams will be instrumented to measure load and deflection at incremental steps up to failure. The test data will be used to derive the ASR impact on concrete design parameters for varying levels of ASR. Design parameters for ASR-affected concrete will then be compared to ACI Design Code requirements and reconciled with Seabrook design basis calculations.
2. Pullout and breakout tests.
3. Expansion testing of coarse aggregates to establish both the extent of aggregate reaction to date and expected additional reactivity/expansion in the future. The following tests will be performed: ASTM C 1260 - Mortar Bar Expansion Test - and ASTM C 1293 - Concrete Prism Test.
4. Monitoring: NextEra will inspect 20 previously crack indexed locations at six-month intervals until a rate can be established. Changes in crack size and crack indices will be trended and reevaluated in accordance with the Structural Monitoring Program. The long-term management of conditions via established crack index thresholds, indicating at which point action will be taken.
5. The Aging Management Program for License Renewal will initially focus on criteria to be implemented for periodic inspections of the 20 previously crack indexed locations, at 6-month intervals.

Inspection team review of the corrective action plan (ML13221A172, 2013) has determined that:

1. Unreliability of core tests according to the operator, and continued reliance on large scale component testing (i.e. "from cores to components").
2. Inability to deplete silica from prism tests.
3. Reliance on FHWA (2010) to set a threshold of 1 mm for crack width.
4. Challenge in correlating the large scale structural component testing with the results at Seabrook, and extraction of cores to improve the correlation through petrography and mechanical testing.
5. Recognition of the potential for some undetected out-of-plane crack formation that can result in an adverse impact on structural performance.

This constituted a brief factual summary of what was retrieved from ADAMS within a reasonable amount of time and effort.

6.2. Authors comments

Based on the observations forwarded above and the current State-of-the-Art, the authors would like to offer a few carefully chosen observations. It should be emphasized that these are being provided without full knowledge of the precise conditions and may indeed be (partially) erroneous; they have been grouped as follows:

[3] NextEra decided to withhold proprietary information from public disclosure as it alleged that the *information requested to be withheld represents the product of several years of intensive NextEra Energy Seabrook efforts and moreover a considerable expenditure. This information may be made available to the market in the event nuclear facilities or other regulated facilities identify the presence of ASR. For potential customers to duplicate this information, similar technical programs would have to be conducted, and significant staffing, with the requisite talent and experience, would have to be allocated. The extent to which this information is available to potential customers hinders NextEra Energy Seabrook's ability to sell products and services that use this information*

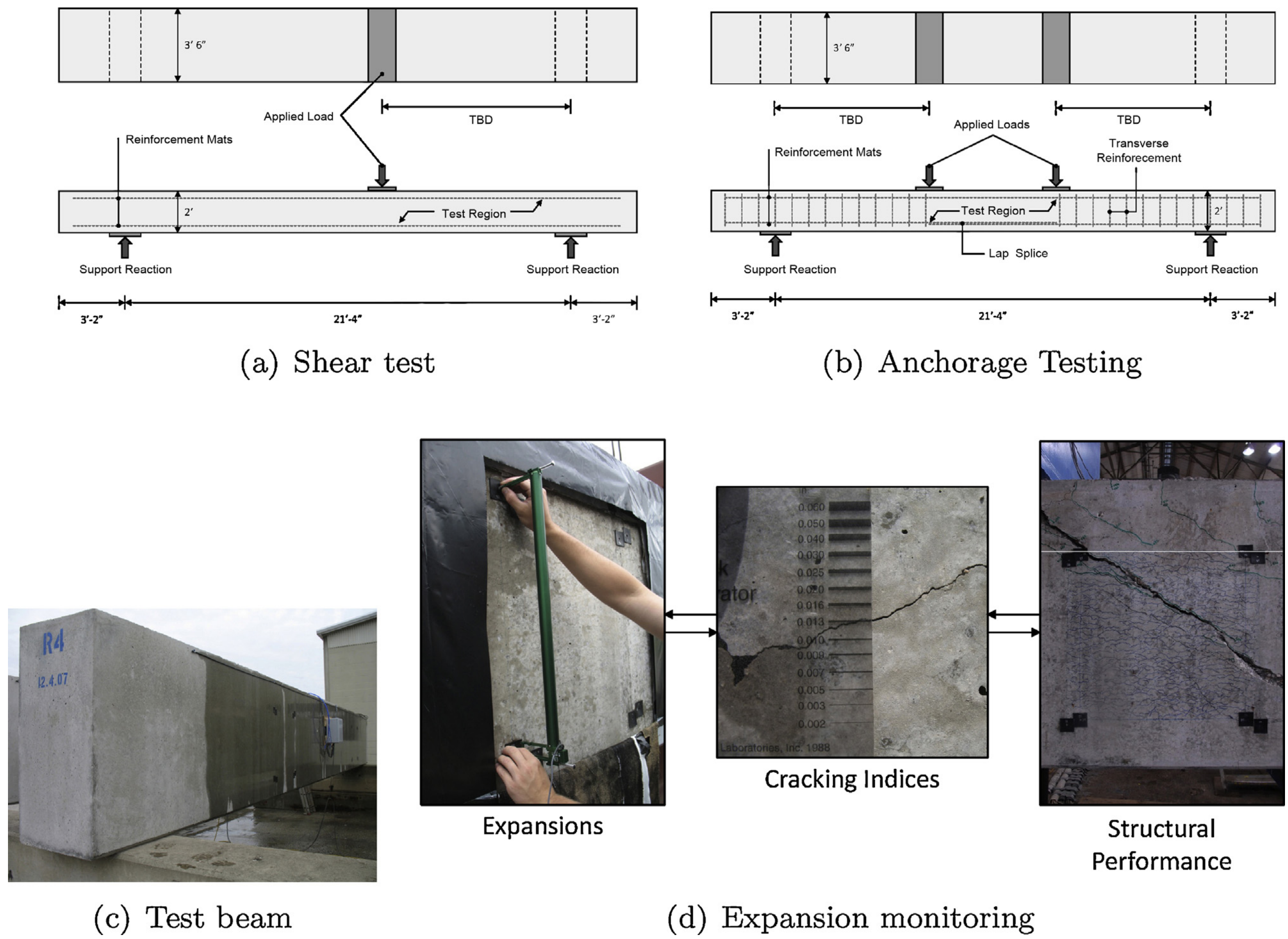


Fig. 2. Experimental tests at UT-Austin (ML121160349, 2012).

Literature survey Whereas the authors may indeed be aware of the recent papers which constitute the State-of-the-Art in ASR (based mostly on work by the French), there is little indication that some of the basic premises have been accounted for (Larive, 1998; Multon and Toutlemonde, 2006; Sellier et al., 2009). Given the complexity of this problem, as well as its novelty and the potential implications of the slightest accident, the available literature should be consulted.

ACI code The ACI-318 code, i.e. *Building Code Requirements for Structural Concrete*, must be interpreted with great care. A NPP is not exactly a building, hence reference should be readily made to its special provisions, which under certain conditions may allow for departure from established equations.

Kinetics At the present time and within the range of NRC expectations, simply considering the worst case scenario is no longer satisfactory; it is absolutely essential for the kinetics, i.e. the

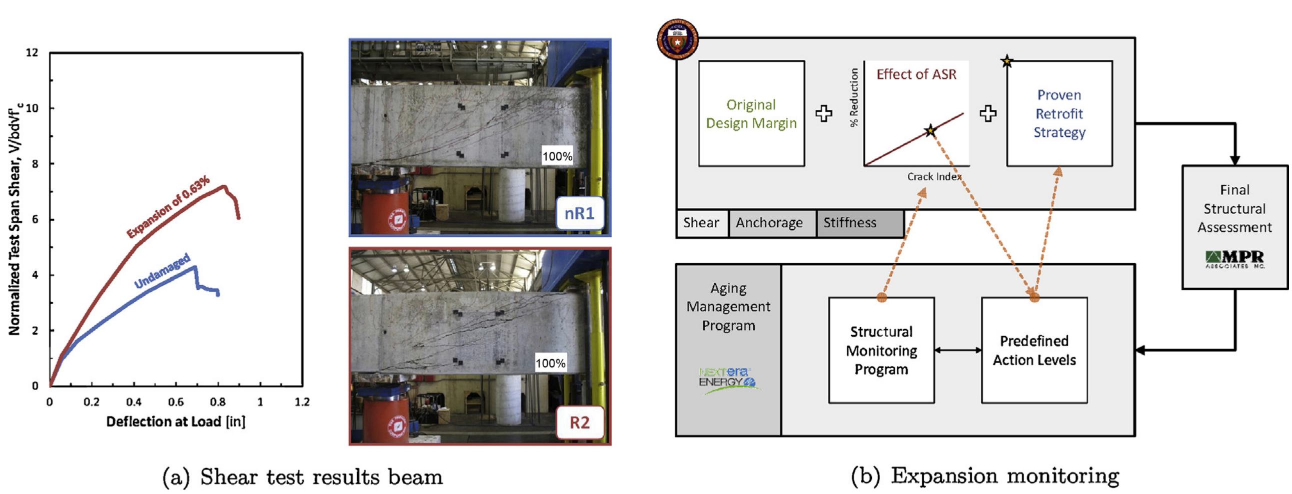
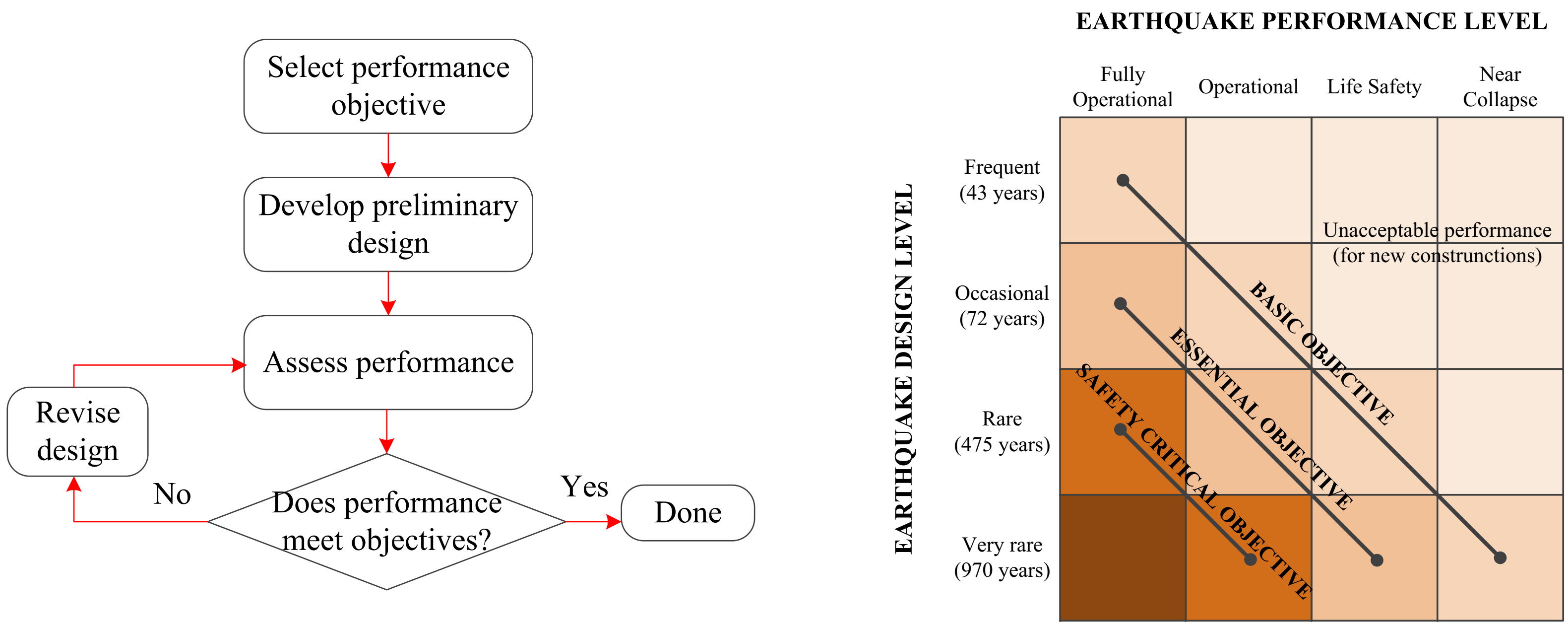


Fig. 3. Tests results ML121160349 (2012).



(a) General concept

(b) Application to earthquake engineering design

Fig. 4. Concept of performance based earthquake engineering design (FEMA-444, 2006).

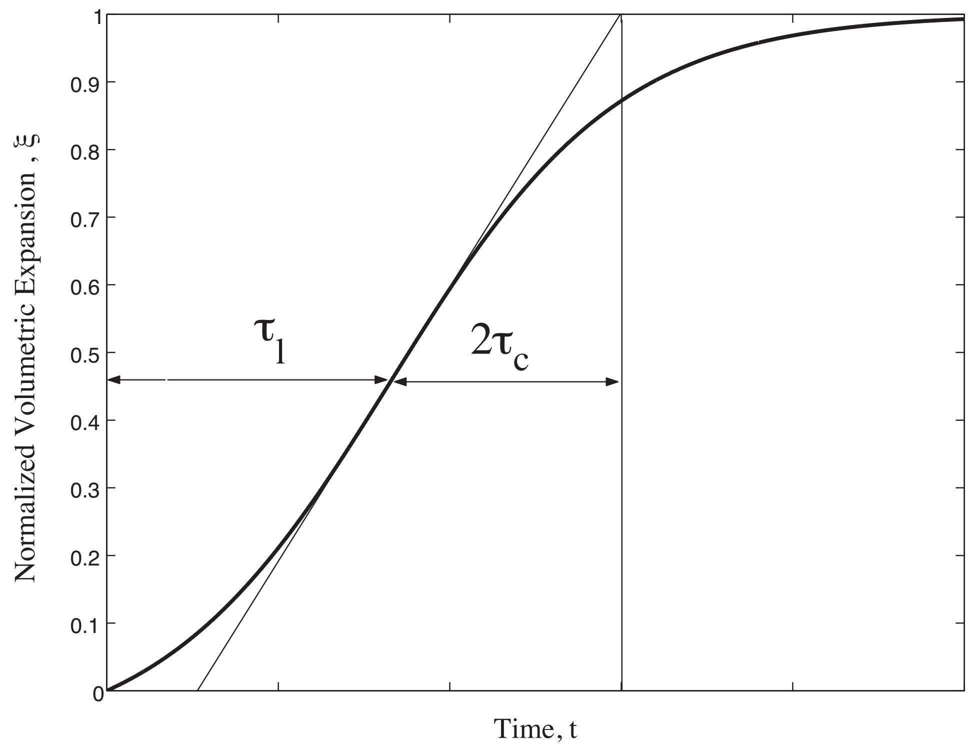


Fig. 5. Theoretical expansion curve Larive (1998).

temporal evolution of ASR expansion (and its consequences), to now be anticipated. Predictions may be approximate, but they can most certainly be adjusted/refined over time on the basis of future measurements (not to be confused with observations). While mortar bar tests (ASTM 1260 and 1293) can still be performed, no indication is available that these test results will be used to improve long-term predictions or for that matter improve the interpretation of structural element test results. It is well established (Larive, 1998) that the ASR-induced expansion may be approximated by a sigmoid curve, Fig. 5, and as such it is critical to determine the NPP's current reaction stage (Saouma, 2013).

Exhaustion of the reaction Not surprisingly, attempts to predict the reaction exhaustion failed. This is indeed a "hot topic" which was addressed by Sellier et al. (2009) and slightly refined (through numerical analysis by Saouma (2013). The method will soon be further assessed by a newly established RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structures) on the *Prognosis of deterioration and loss of serviceability in structures affected by alkali-silica reactions* chaired by the author (RILEM, 2014).

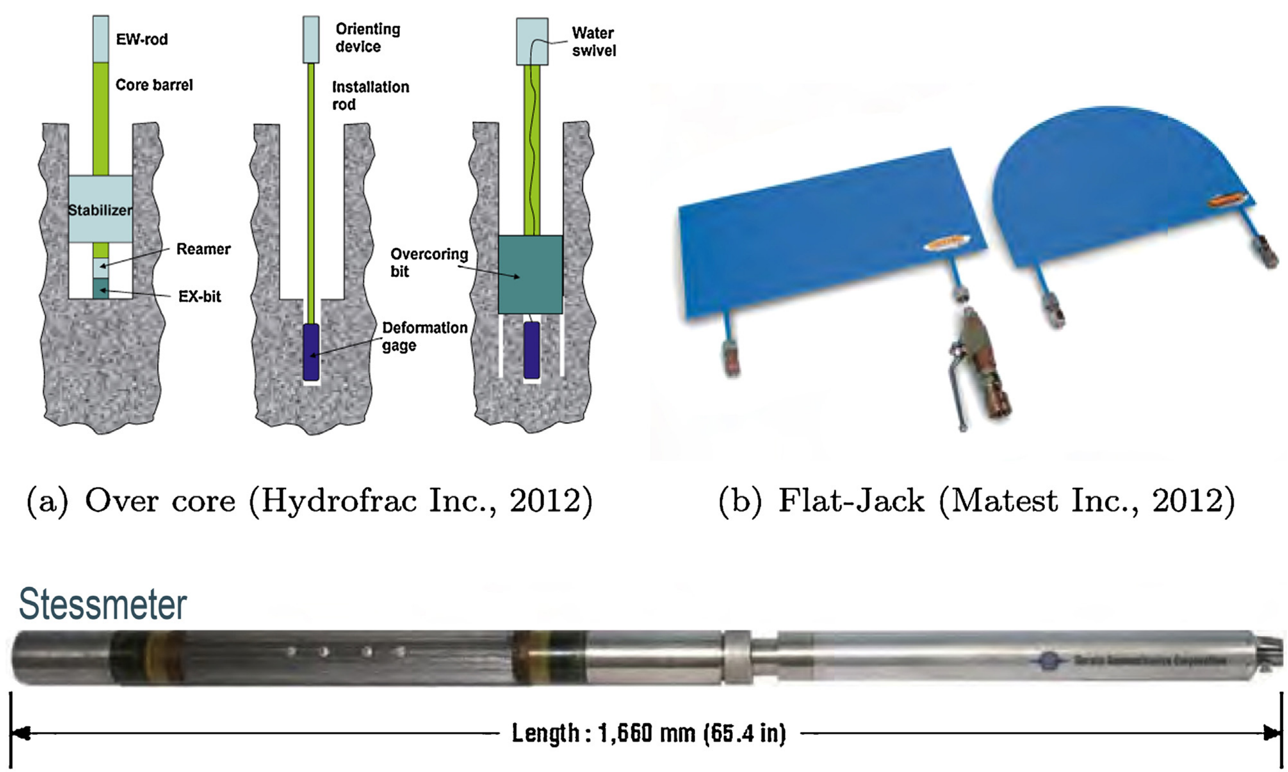
Long-term *in situ* measurements are essential:

Stresses As a result of ASR, such as in dams, the confined structure will develop internal strains (and thus stresses). These internal ASR-induced expansive strains may eventually lead to structural cracks (whether visible or not) and should be monitored. Techniques for such measurements are available: flat jacks, over-coring or stress-meters, Fig. 6. In addition, strain gauges could easily be mounted on the rebar in order to measure the time-dependent increase in strain.

Deterioration should be measured *in situ* using anyone of modern existing techniques:

- Pulse velocity measurement of the dynamic elastic modulus, as this has proven to be a good indicator of ASR reaction (Swamy and Al-Asali, 1988; Saint-Pierre et al., 2007; Sargolzahi et al., 2009).
- Nonlinear Impact Resonance Acoustic Spectroscopy (NIRAS) as more recently developed by Leśnicki et al. (2013) and Chen et al. (2010) and which appears to be very promising for in-situ assessment. Currently, additional research is being conducted at the Infrastructure Technology Institute of Northwestern University on a related topic by Profs. Qu and Bažant (Northwestern, 2014).

Surface cracks Surface crack measurements are considered as highly relevant. In citing Swamy (1997): *Surface cracks on ASR-affected structures are not true measure of the effects of ASR. Random and irregular cracking is an inevitable consequence of the chemical reactivity if no stiff element such as reinforcing steel is present to control cracking. In practice, the irregular pattern of large exposed surfaces is greatly influenced and modified by the presence of drying shrinkage from wetting/drying cycles, by internal freezing and thawing and restrained cracking due to moisture and thermal gradients. Surface cracking is thus a visible external characteristic but unreliable for the quantitative evaluation of structural deterioration.* It is further stated that: *Analysis of crack patterns and cumulative additions of crack widths over a period of time can thus be very misleading, and cannot be adopted as a "simple and cost-effective method of determining the magnitude of ASR damage to a structure"*. Furthermore, Swamy and Al-Asali (1988) report that: *The pulse velocity tests show that the core of the concrete is as much affected by ASR as the outer surfaces. Whilst the concrete surface shows visible cracking, which penetrates into the body of the concrete, the core does not show any cracking due to swelling; however, its properties appear to be*



(a) Over core (Hydrofrac Inc., 2012)

(b) Flat-Jack (Matest Inc., 2012)

(c) Stress-Meter (Serata Geomechanics, 2005)

Fig. 6. Field stress measurements.

affected in the same way as the external surfaces. It should also be noted that ASR initiate as micro cracks around the aggregates, this will severely deteriorate the interior of the concrete, and ultimately would there be a macro/structural cracks which daylight on the surface and which could be observed by DRI (Alnaggar et al., 2013).

Threshold crack width of 1 mm to trigger "structural evaluation" (term not defined). A widely recognized model for fracture of concrete is the one of Hillerborg et al. (1976) illustrated in Fig. 7. The fracture process zone of concrete has a w_2 of the order of 0.1–0.3 mm (Hoover et al., 2013). Thus, by the time the crack opening on the surface has reached 1 mm, intensive internal cracking may have occurred.

Effect of confinement is addressed in two contexts:

Core testing Testing concrete cores extracted from structures, in which confining stresses are present, is routinely performed in dams. Should it be necessary to make adjustments for the unconfined results, instructions can be found in the classical paper by Kupfer and Gerstle (1973) and the dozens of subsequent papers. On the other hand, it has been well established that the elastic modulus decrease in ASR-affected concrete determined from cores exceeds the modulus value measured (indirectly) in structural components (beams).

Effect on ASR It has been demonstrated that the reduced presence of ASR inside the wall is due to the confinement effect, though this is only partially correct (at about 8 MPa, the ASR expansion is entirely inhibited). It is known that ASR expansion is volumetric (Multon, 2004), hence the expansion is likely to reorient itself in the direction of least confinement, i.e. radial. Rivard and Ballivy (2000) determined that the confinement by reinforcing steels reduces the overall free expansion; hence deformation in the unreinforced direction (such as out of plane) is likely to be greater than along reinforced one. This condition is likely to be more pronounced in the absence of shear reinforcement. Similarly, Multon et al. (2005) determined that the local effects of stirrups were hardly significant on vertical and transverse deformations. A numerical simulation would be necessary to quantify this effect.

Laboratory tests **Recovered cores vs. cylinders** The authors rightfully suggest that extracted cores are expected to yield compressive strength values 10% to 15% lower than the cylinder test results, however this is not a comment in ASTM C42/C42M-13 (2013) but rather of ACI 318 (2011). Furthermore, values can be highly dependent on the orientation with respect to the casting direction (Larive, 1998). Yet, it should be kept in mind that compressive strength decrease is one of the most insignificant manifestation of ASR in terms of structural impact.

Material: mortar bar tests (ASTM 1260 and 1293) will be performed. Let's recall here that coarse aggregates react much more slowly than fine aggregates (Sellier et al., 2009). Two questions must therefore be raised: a) What is the potential future expansion? and b) When would this expansion occur? The answer to the first question requires crushing the aggregates, while the second answer implies accelerated tests on the recovered cores (which could last over a year).

Structural component An ambitious test plan has been envisaged.

1. It is stated that the laboratory test could duplicate field conditions through carefully selecting the concrete mix. This is quite puzzling since ASR is a time/temperature (i.e. thermodynamically driven) dependent reaction. It would almost be impossible to assert that such a laboratory concrete specimen is representative of the NPP concrete with a reasonable degree of comparison. Furthermore, it is doubtful that the percentage of maximum expansion in the field would be the same as that in the laboratory test. One of the most comprehensive research studies on the response of reinforced concrete beams subjected to ASR was conducted by Multon et al. (2005), in which specimens were kept at constant temperature and relative humidity and monitored for an extensive period of time. Some researchers (Xie et al., 2002) have indeed used crushed glass to accelerate the expansion; however, such a concrete will undoubtedly exhibit different mechanical properties than a specimen without glass. Moreover, it may not be sufficient to achieve mechanical properties that are representative of Seabrook structures, since ASR will also induce microcracks that are difficult to duplicate. To the greatest extent possible, specimens should be kept under controlled humidity and temperature conditions along with the mortar bar specimens.
2. The interaction of shear and ASR has already been established since the work of Ahmed et al. (1998), who investigated the shear resistance of 80 × 130 × 1,300 mm reinforced concrete beams with 12-mm diameter reinforcement affected by ASR. Indeed many researchers have reported an increase in the shear strength of ASR affected beams as a result of the "prestressing effect".

   However, care should be exercised since excessive ASR-induced tension may fracture the rebar during a sudden failure (depending on the type of reinforcement), as occurred in Japan (Mikata et al., 2012).
3. Flexural testing of the reinforced concrete beam without shear reinforcement leads to an unstable failure. Results will highly depend on the load type (load, stroke or strain control), with this being a fracture mechanics driven phenomenon. Accordingly, the ASR-induced reduction in fracture energy G_F is far greater than the reduction in other mechanical properties (Miki et al., 2013). This mechanical property of the concrete should also, as much as possible, be similar in both the laboratory and field tests. Ideally, nearly pure shear tests under confinement should be performed. Tests similar to the one conducted by the senior author (Slowik et al., 1998) (Puntel and Saouma, 2008) and illustrated in Fig. 8 are recommended.
4. Similarly, anchor failure in concrete is a fracture (mechanics) dominated phenomenon that has been extensively studied by numerous researchers, most recently by Kobayashi et al. (2013).
5. It is not clear how the actual load and confinement in the field would translate into point loads in the laboratory tests to fully replicate in situ conditions.

Finite element No details have been given regarding this most critical task (figure containing mesh, model and program capabilities). It is important that the code first be validated and proven capable of simulating the essential features characterizing ASR.

1. Environmental conditions of the concrete: temperature and humidity.
2. Constitutive models: (a) solid concrete (tension, compression, creep, shrinkage); (b) cracks/joints/interfaces.
3. Load history

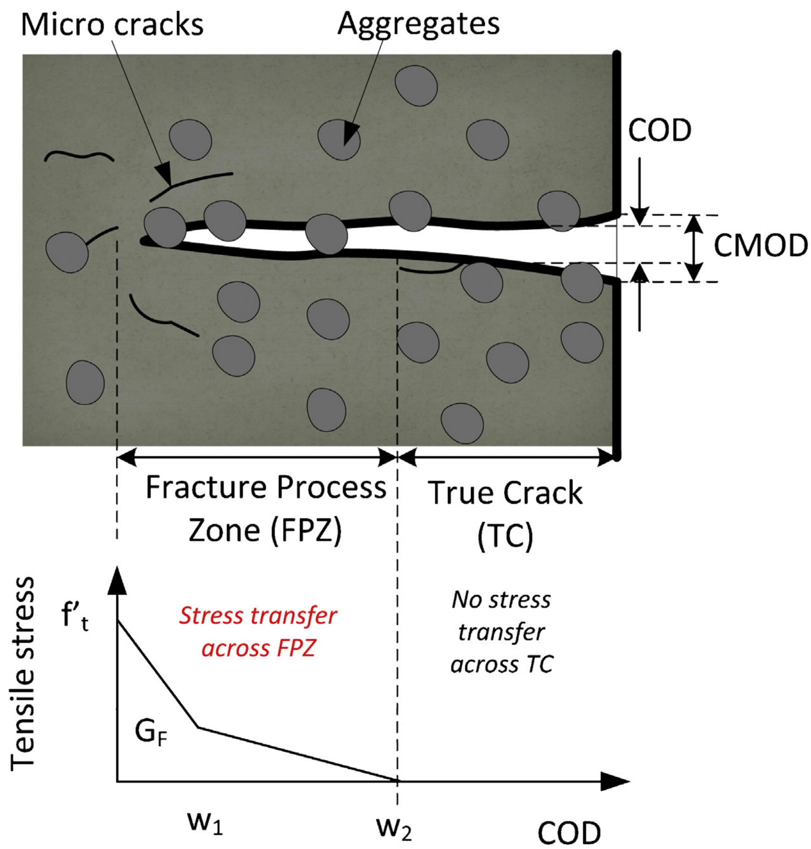


Fig. 7. Hillerborg's model for concrete fracture.

4. Mechanical boundary conditions: (a)Structural arrangement; (b) Reinforcement; and (c) anchorage

As for the seismic validation, one key question is whether the dynamic analysis simply used the deteriorated mechanical properties, or whether it started with the statically determined *in situ* stresses at the point where the seismic load is applied.

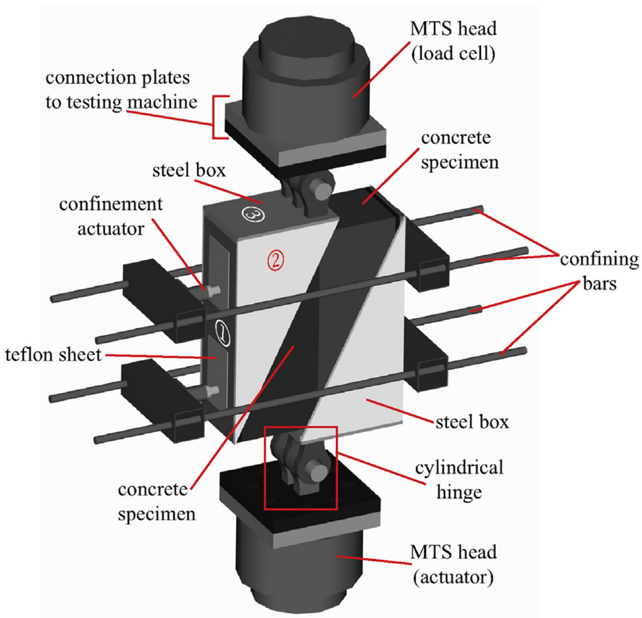
Corrosion of the rebar may have occurred if the groundwater had contained chloride. This condition can be checked if the concentration of free chloride exceeds a certain threshold (about 700 ppm), which in turn will sufficiently lower the pH of concrete (from roughly 13 to 11) and thus depassivate the steel and initiate corrosion. Numerical models for chloride diffusion, carbonation, reinforcement corrosion and ensuing splitting of the concrete have been proposed by the author (Hansen and Saouma, 1999a,b; Puatatsananon and Saouma, 2005).

6.3. Authors suggestions

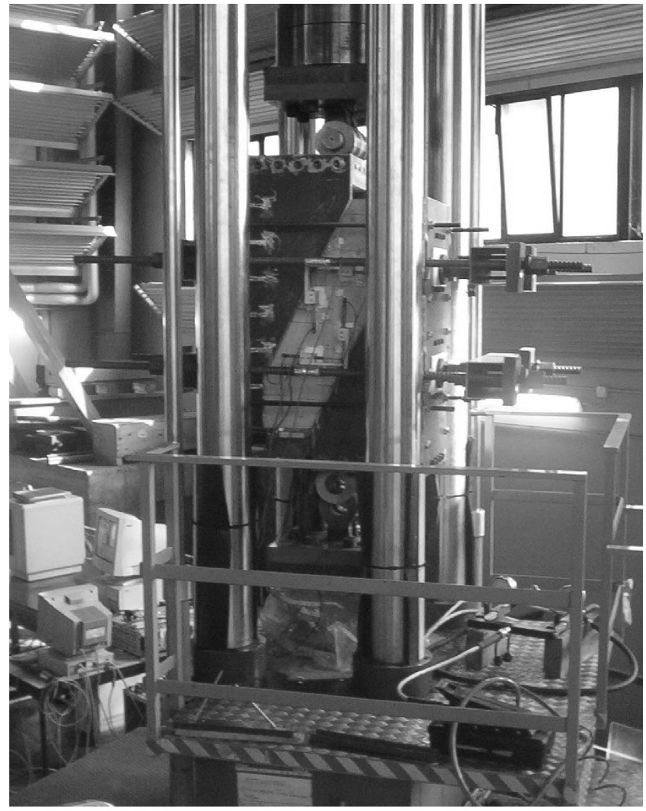
In summarizing the preceding comments, the authors would like to suggest the following actions:

1. Minimize the importance of surface crack measurements.
2. Perform one-time tests to measure the internal relative humidity (gauges exist to measure both RH and temperature) and free chloride concentration.
3. Conduct long-term (multiple years) monitoring (especially away from the surface) of:
   - Dynamic elastic properties through any of the most appropriate and/or feasible means: pulse velocity, impact echo, or other
   - *In situ* stresses
   - Out-of-plane surface deformation (possibly through laser measurements)
   - Strains in rebar (by simply scraping the concrete surface and installing a few strain gauges with a long life span).

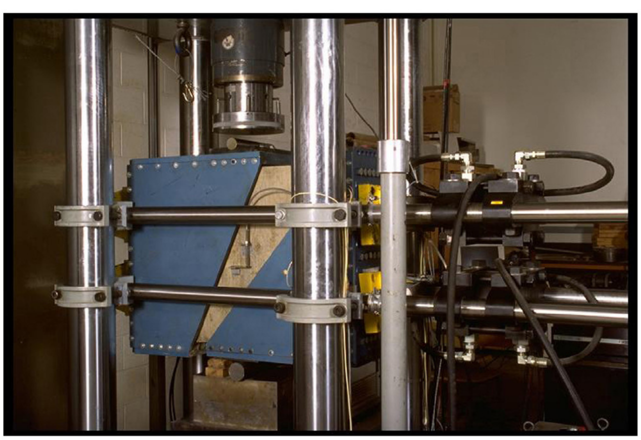
   These tests could potentially be performed in inaccessible areas (especially when using the probe):
4. Perform tests in an attempt to measure the residual expansion (both magnitude and kinetics), as described in (Saouma, 2013).
5. Completely ignore compressive strength tests and instead rely exclusively on tensile strength, Young's modulus and, most importantly, on fracture energy G_F.
6. Conduct a coupled heat/moisture transport analysis of both the large scale testing specimen and the wall in at Seabrook to better correlate ASR expansion with local conditions (Poyet et al., 2006). A separate analysis may also include the chloride diffusion to address possible corrosion (Hansen and Saouma, 1999a) (Hansen and Saouma, 1999b).
7. Conduct a nonlinear finite element analysis in keeping in mind that serviceability is of primary interest (i.e. focus on deformation and cracking) for shear and failure on the anchors. The code should first be validated with benchmark problems, such as those listed in Saouma and Sellier (2010). Then, and only then, can the result be "trusted". Also of importance herein is the kinetics (i.e. capturing the rate of damage progression and its impact on the serviceability / safety of NPP operations) and the formation/development of shear cracks (which require a



(a) Schematic shear test (Puntel and Saouma, 2008)



(b) Experimental setup for reverse cyclic load effects on shear failures



(c) Confined shear test under unidirectional shear (Slowik et al., 1998)

(d) Shear crack under confinement

Fig. 8. Suggested pure shear tests.

modern fracture mechanics approach). Another finite element simulation should assess the seismic integrity of the reactor in accounting for the built-up stresses caused by ASR.

Last but not least, it is essential to gain a holistic view of the irrevocable ASR deterioration by means of correlating expansion tests, nonlinear finite element simulations, laboratory tests and field measurements. This is a dynamic process that should be updated every few years in order to ensure the NPP safety through year 2050 (Fig. 9(a)), via a proper Aging Management Program. Better yet, such a study should be conducted within the new paradigm of performance based engineering. Fig. 9(b) is a preliminary suggestion where the level of damage is expressed in terms of both anticipated gel expansion multiplier of a reference value X and complexities of the prognosis studies.

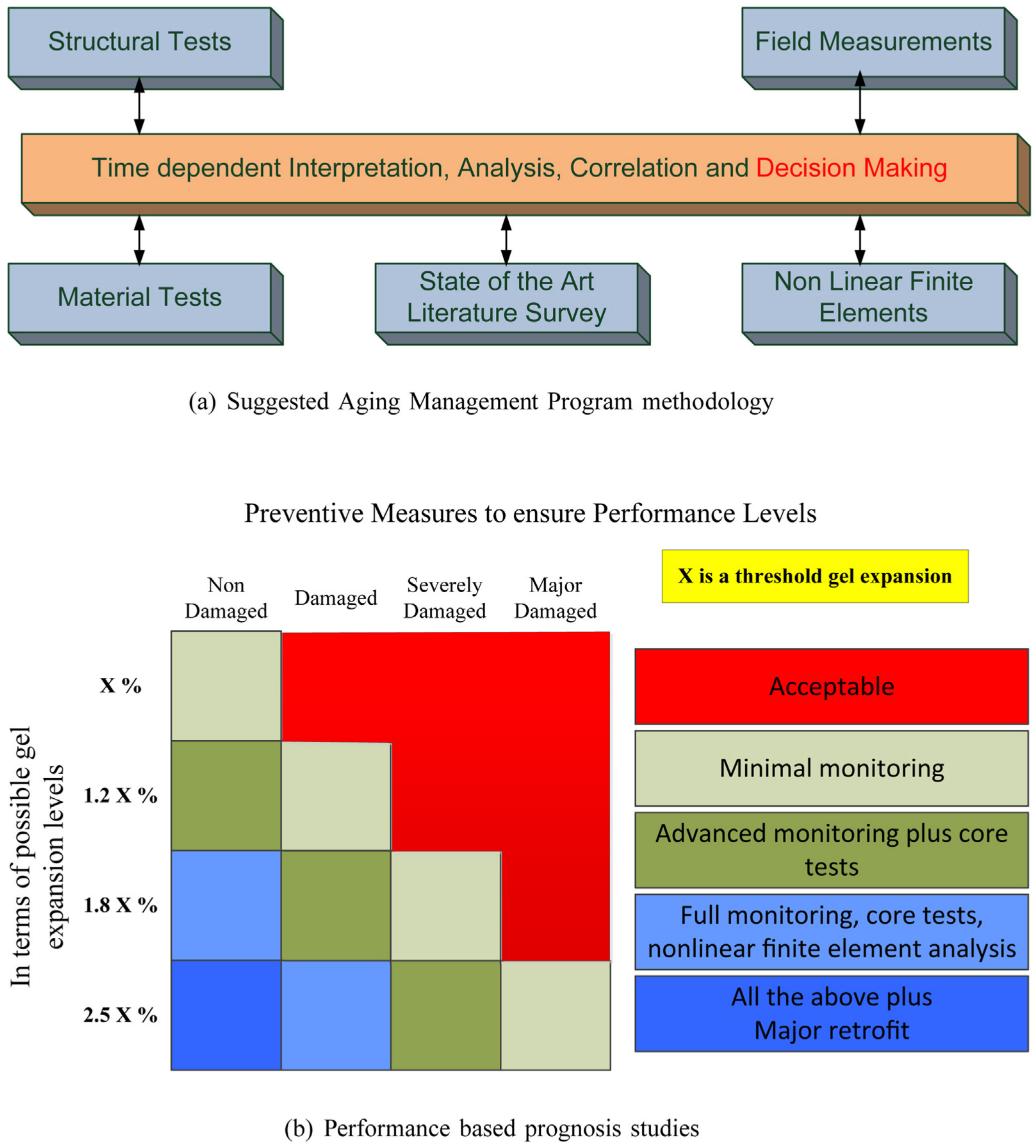


Fig. 9. Proposed paradigms for proper aging management studies.

7. Conclusions

In summary, the authors agree that indeed "Seabrook ASR affected structures are operable but degraded" (ML121220109, 2012), however given the uncertainty of the rate and extent of degradation a major challenge is to anticipate the evolution of the reaction, and more importantly, its impact on the structural integrity of the reactor (both serviceability and strength). Answer to this critical question requires an uncompromising understanding of the State of the Art to properly and safely propose and aging management program.

This paper constituted an attempt to cast a different and independent look at Seabrook based on the authors extensive backgrounds in ASR, modelling and testing. The existing body of publicly available literature was critically reviewed, and some observations and comments made. However, some of them may be premature and not based on full and up to date information as some are restricted.

Major concerns remain on the over-reliance on surface crack observation and structural component testing, lack of modern finite element simulation, and proper analysis of cores.

References

ACI 318, 2011. Building Code Requirements for Reinforced Concrete (ACI 318-83). American Concrete Institute.

Ahmed, T., Burley, E., Rigden, S., 1998. The static and fatigue strength of reinforced concrete beams affected by alkali–silica reaction? ACI Mater. J. 95 (4), 376–388.

Alnaggar, M., Cusatis, G., DiLuzio, G., 2013. Lattice discrete particle modeling (LDPM) of alkali silica reaction (ASR) deterioration of concrete structures. Cement Concrete Compos. 41, 45–59.

ASCE/SEI 7, 2010. Minimum Design Loads for Buildings and Other Structures. Technical Report. American Society of Civil Engineers.

ASTM C42/C42M-13, 2013. Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete.

Bérubé, M., Duchesnea, J., Doriona, J., Rivestb, M., 2002. Laboratory assessment of alkali contribution by aggregates to concrete and application to concrete structures affected by alkali–silica reactivity. Cement Concrete Res. 32, 1215–1227.

Charlwood, R. (2012). Personal communication.

Chatterji, S., 2005. Chemistry of alkali–silica reaction and testing of aggregates. Cement Concrete Compos. 27, 788–795.

Chen, J., Jaayapalan, A., Kim, J., Kurtis, K., Jacobs, L., 2010. Rapid evaluation of alkali–silica reactivity of aggregates using a nonlinear resonance spectroscopy technique. Cement Concrete Res. 40, 914–923.

Chiaramida, A., 2013. Lab to Test Seabrook's Concrete Problems, http://www.newburyportnews.com/local/x1862027937/Lab-to-test-Seabrooks-concrete-problems (retrieved: June 2013).

Constantiner, D., Diamond, S., 2003. Alkali release from feldspars into pore solutions. Cement Concrete Res. 33, 549–554.

Coppel, F., Lion, M., Vincent, C., Roure, T., 2012. Approaches developed by edf with respect to the apprehension of risks of internal expansion of the concrete on nuclear structures: Management of operating power plants and prevention for new power plants. In: NUCPERF 2012 on Long-Term Performance of Cementitious Barriers and Reinforced Concrete in Nuclear Power Plant and Radioactive Waste Storage and Disposal, Cadarache, France.

Dron, R., Privot, F., 1992. Thermodynamic and kineic approach to the alkali-silica reaction: Part I. Concepts. Cement Concrete Res. 22, 941–948.

FEMA-444, 2006. Next-Generation Performance-Based Seismic Design Guidelines. Technical Report. Federal Emergency Management Agency.

FHWA, 2010. Report on the Diagnostics, Prognosis, and Mitigation of Alkali–Silica Reaction (ASR) in Transportation Structures. Technical Report FHWA-HIF-09-004. Federal Highway Administration.

FHWA, 2013. FHWA ASR Reference Center. http://www.fhwa.dot.gov/pavement/concrete/asr/reference.cfm

Fujiwara, K., Ito, M., Sasanuma, M., Tanaka, H., Hirotani, K., Onizawa, K., Suzuki, M., Amezawa, H., 2009. Experimental study of the effect of radiation exposure to concrete. In: 20th International Conference on Structural Mechanics in Reactor Technology (SMIRT 20), Espoo, Finland. SMIRT20-Division I, Paper 1891.

Gallitre, E., Dauffer, D., 2010. Ageing management of French NPP civil work structures. In: International Workshop on Ageing-Management of Nuclear Power Plants and Waste Disposal Structures, Toronto, Canada, AMP 2010 - EFC Event 334.

Gallitre, E., Dauffer, D., Lion, M., 2010. La tenue du genie civil/vision 60 ans. In: SFEN ST7: Sminaire Gnie-civil et Nuclaire: de la Conception l'Exploitation, Toronto, Canada (in French).

Graves, H., Le Pape, Y., Naus, D., Rashid, J., Saouma, V., Sheikh, A., and Wall, J., 2013. Expanded Materials Degradation Assessment (EMDA), vol. 4: Aging of Concrete. Technical Report NUREG/CR-ORNL/TM-2011/545, US Nuclear Regulatory Commission.

Haberman, S., 2013. Seabrook Station Nuclear Plant License Advancing, http://www.seacoastonline.com/articles/20130515-NEWS-305150371 (retrieved: June 2013).

Hansen, E., Saouma, V., 1999a. Numerical simulation of concrete deterioration: Part I. Chloride diffusion? ACI Mater. J. 96 (2), 173–180.

Hansen, E., Saouma, V., 1999b. Numerical simulation of concrete deterioration: Part II. Steel corrosion and concrete fracture? ACI Mater. J. 96 (3), 331–339.

Hillerborg, A., Modéer, M., Petersson, P., 1976. Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements? Cement Concrete Res. 6 (6), 773–782.

Hilsdorf, H., Kropp, J., Koch, H., 1978. The Effects of Nuclear Radiation on the Mechanical Properties of Concrete. Technical Report SP 55-10. American Concrete Institute.

Hoover, C.G., Bažant, Ž, Vorel, J., Wendner, R., Hubler, M., 2013. Comprehensive concrete fracture tests: description and results. Eng. Fract. Mech. 114, 92–103.

Hydrofrac Inc., 2012. http://www.hydrofrac.com/deformation_gage.pdf (retrieved: 01.11.12).

Ichikawa, T., Kimura, T., 2002. Effect of nuclear radiation on alkali–silica reaction? J. Nucl. Sci. Technol. 44 (10), 1281–1284.

Ichikawa, T., Koizumi, H., 2002. Possibility of radiation-induced degradation of concrete by alkali–silica reaction of aggregates? J. Nucl. Sci. Technol. 39 (8), 880–884.

Ichikawa, T., Miura, M., 2007. Modified model of alkali-silica reaction. Cement and Concrete Research 37, 1291–1297.

Kobayashi, K., Fukushima, T., Rokugo, K., 2013. Shear strength of ASR-deteriorated RC members and shear reinforcing effect of repair by adding rebar. In: Proceedigs of the 8th International Conference on the Fracture Mechanics of Concrete and Structures, Toledo, Spain.

Kupfer, B., Gerstle, K., 1973. Behavior of concrete under biaxial stresses? ASCE J. Eng. Mech. Div. 99 (4), 853–866.

Larive, C., 1998. Apports Combinés de l'Experimentation et de la Modélisation àla Comprehension del'Alcali-Réaction et de ses Effets Mécaniques. Laboratoire Central des Ponts et Chaussées, Paris (PhD thesis).

Leśnicki, K., Kim, J., Kurtis, K., Jacobs, L., 2013. Assessment of alkali–silica reaction damage through quantification of concrete nonlinearity. Mater. Struct. 46, 497L 509.

Matest Inc., 2012. http://www.matest.com/products/concrete/flat-jacks-tests-on-brickworks-0.aspx (retrieved: October 2012).

Mikata, Y., Shimazu, Y., Hatano, Y., Inoue, S., 2012. Flexural and shear capacity of PRC beams damaged by combined deterioration due to ASR and corrosion. In: Drimalas, T., Ideker, T., Fournier, B. (Eds.), Proceedings of the 14th Engineering Mechanics Conference. Austin, TX, USA.

Miki, T., Matsutani, K., Miyagawa, Y., 2013. Evaluation of crack propagation in ASR damaged concrete based on image analysis. In: Proceedigs of the 8th International Conference on the Fracture Mechanics of Concrete and Structures, Toledo, Spain.

ML121160349, 2012. Structural Assessment of Seabrook Station. Technical Report ML121160349. University of Texas, Austin, Prepared by Prof. O. Bayrak.

ML121160422, 2012. Impact of Alkali Silica Reaction on Seabrook Concrete Structure. Technical Report ML121160422. NextEra.

ML121220109, 2012. Meeting Summary Regarding Concrete Degradation Held on April 23, 2012. Technical Report ML121220109. United States Nuclear Regulatory Commission.

ML121250588, 2012. Seabrook Alkali-Silica Reaction Issue Technical Team Charter. Technical Report ML121250588. United States Nuclear Regulatory Commission.

ML12160A374, 2012. Safety Evaluation Report with Open Items Related to the License Renewal of Seabrook Station. Technical Report ML1160A374. United States Nuclear Regulatory Commission.

ML12199A295, 2012. Presentation by NextEra. Technical Report. United States Nuclear Regulatory Commission.

ML12199A300, 2012. Seabrook advisory committee on reactor safeguards presentation slides. Technical Report ML12199A300. United States Nuclear Regulatory Commission.

ML13151A328, 2013. Response to Confirmatory Action Letter. Technical Report ML13151A328. NextEra.

ML13221A172, 2013. Seabrook Station, Unit No. 1 – Confirmatory Action Letter Follow-Up Inspection – NRC Inspection Report 05000443/2012010. Technical Report ML13221A172. United States Nuclear Regulatory Commission.

Multon, S., 2004. Evaluation expérimentale et th’eorique des effets mécaniques de l'alcali-réaction sur des structures modèles. Université de Marne la Vallée, France (PhD thesis).

Multon, S., Seignol, J., Toutlemonde, F., 2005. Structural behavior of concrete beams affected by alkali–silica reaction? ACI Mater. J. 102 (2), 67–76.

Multon, S., Toutlemonde, F., 2006. Effect of applied stresses on alkali–silica reaction induced expansions? Cement Concrete Res. 36 (5), 912–920.

Murazumi, Y., Hosokawa, T., Matsumoto, N., Mitsugi, S., Takiguchi, K., Masuda, Y., 2005a. Study of the influence of alkali-silica reaction on mechanical properties of reinforced concrete members. In: 18th International Conference on Structural Mechanics in Reactor Technology (SMIRT 18), Beijing, China, pp. 2043–2048, SMIRT18-H03-3.

Murazumi, Y., Watanabe, Y., Matsumoto, N., Mitsugi, S., Takiguchi, K., Masuda, Y., 2005b. Study of the influence of alkali-silica reaction on structural behavior of reinforced concrete members. In: 18th International Conference on Structural Mechanics in Reactor Technology (SMIRT 18), Beijing, China, pp. 2036–2042, SMIRT18-H03-2.

Naus, D., 2007. Primer on Durability of Nuclear Power Plant Reinforced Concrete Structures - A Review of Pertinent Factors. Technical Report NUREG/CR-6927 ORNL/TM-2006/529. US Nuclear Regulatory Commission.

Northwestern, 2014. Infrastructure Technology Institute. http://www.iti.northwestern.edu/research/completed/safetea-lu/index.html

NUREG-0980, 2013. Nuclear Regulatory Legislation; 112th Congress, 2D Session. Technical REPORT NUREG-0980. United States Nuclear Regulatory Commission.

Orbovic, N., 2011. Personal communication. Canadian Nuclear Safety Commission.

Poole, A., 1992. Introduction to alkali-aggregate reaction in concrete. In: Swamy, R. (Ed.), The Alkali-silica Reaction in Concrete. Van Nostrand Reinhold, New York, pp. 1–28.

Poyet, S., Sellier, A., Capra, B., Thevenin-Foray, G., Torrenti, J.-M., Tournier-Cognon, H., Bourdarot, E., 2006. Influence of water on alkali-silica reaction: Experimental study and numerical simulations? Journal of Materials in Civil Engineering 18 (4), 588–596.

Puatatsananon, W., Saouma, V., 2005. Nonlinear coupling of carbonation and chloride diffusion in concrete? J. Mater. Civil Eng. 17 (3), 264–275.

Puatatsananon, W., Saouma, V., 2013. Chemo-mechanical micro model for alkali–silica reaction. ACI Mater. J. 110, 67L 78.

Puntel, E., Saouma, V., 2008. Experimental behavior of concrete joints under cyclic loading? ASCE J. Struct. Eng. 134 (9), 1558–1568.

RILEM TC, 2014. Prognosis of Deterioration and Loss of Serviceability in Structures Affected by Alkali–Silica Reactions, http://rilem.org/gene/main.php?base=8750&gp_id=323 (retrieved: April 2014).

Rivard, P., Ballivy, F., 2000. Quantitative assessment of concrete damage due to alkali–silica reactions(ASR) by petrographic analysis. In: 11th International Conference on Alkali Aggregate Reaction, pp. 889–898.

Saint-Pierre, F., Rivard, P., Ballivy, G., 2007. Measurement of alkali-silica reaction progression by ultrasonic waves attenuation. Cement Concrete Res. 37, 948L 956.

Saouma, V., 2013. Numerical Modeling of Alkali Aggregate Reaction. CRC Press, pp. 320.

Saouma, V., Martin, R., Hariri-Ardebili, M., 2014. A mathematical model for the kinetics of the alkali–silica chemical reaction. Cement Concrete Res. (submitted for publication).

Saouma, V., Perotti, L., 2006. Constitutive model for alkali aggregate reactions? ACI Mater. J. 103 (3), 194–202.

Saouma, V., Perotti, L., Shimpo, T., 2007. Stress analysis of concrete structures subjected to alkali-aggregate reactions? ACI Mater. J. 104 (5), 532–541.

Saouma, V., Sellier, A., 2010. Numerical Benchmark for the Finite Element Simulation of Expansive Concrete. http://civil.colorado.edu/saouma/AAR

Sargolzahi, M., Rivard, P., Rhazi, J., 2009. Evaluation of residual reactivity of concrete cores from ASR-affected structures by non-destructive tests. In: NDTCE'09, Non-Destructive Testing in Civil Engineering.

Sellier, A., Bourdarot, E., Multon, S., Cyr, M., Grimal, E., 2009. Combination of structural monitoring and laboratory tests for assessment of alkali aggregate reaction swelling: application to gate structure dam. ACI Mater. J., 281–290.

Serata Geomechanics, 2005. In-situ Stress/Property Measurements for Quantitative Design and Construction. Technical Report. Serata Geomechanics Inc.

Shimizu, H., Asai, Y., Sekimoto, H., Sato, K., amd Oshima, R., Takiguchi, K., Masuda, Y., Nishiguchi, I., 2005a. Investigaiton of safety margin for turbine generator foundation affected by alkali-silica reaction based on non-linear structural analysis. In: 18th International Conference on Structural Mechanics in Reactor Technology (SMIRT 18), Beijing, China, pp. 2049–2059, SMIRT18-H03-4.

Shimizu, H., Watanabe, Y., Sekimoto, H., Oshima, R., Takiguchi, K., Masuda, Y., Nishiguchi, I., 2005b. Study on material properties in order to apply for structural analysis of turbine generator foundation affected by alkali-silica reaction. In: 18th International Conference on Structural Mechanics in Reactor Technology (SMIRT 18), Beijing, China, pp. 2055–2060, SMIRT18-H03-5.

Slowik, V., Chandra, J., Saouma, V., 1998. Mixed mode fracture of cementitious bimaterial interfaces: Part I. Experimental results? Eng. Fract. Mech. 60 (1), 83–94.

Stanton, T., 1940. Expansion of concrete through reaction between cement and aggregate. Proc. of ASCE 66, 1781L 1811.

Swamy, R., 1997. Assessment and rehabilitation of AAR-affected structures. Cement Concrete Compos. 19, 427L 440.

Swamy, R., Al-Asali, M., 1988. Influence of alkali–silica reaction on the engineering properties of concrete. In: Dodson, V. (Ed.), Alkalies in Concrete. ASTM STP 930, Philadelphia, PA, pp. 69–86.

Takagkura, T., Masuda, H., Murazumi, Y., Takiguchi, K., Masuda, Y., Nishiguchi, I., 2005. Structural soundness for turbine-generator foundation affected by alkali-silica reaction and its maintenance plans. In: 18th International Conference on Structural Mechanics in Reactor Technology (SMIRT 18), Beijing, China, pp. 2055–2060, SMIRT18-H03-5.

Takatura, T., Ishikawa, T., Matsumoto, N., Mitsuki, S., Takiguchi, K., Masuda, Y., 2005a. Investigation of the expanded value of turbine generator foundation affected by alkali–silica reaction. In: 18th International Conference on Structural Mechanics in Reactor Technology (SMIRT 18), Beijing, China, pp. 2061–2068, SMIRT18-H03-7.

Takatura, T., Watanabe, Y., Hosokawa, T., Ishii, T., Takiguchi, K., Masuda, Y., 2005b. Vibration measurement and simulation analysis on a reinforced concrete structure with alkali–silica reaction. In: 18th International Conference on Structural Mechanics in Reactor Technology (SMIRT 18), Beijing, China, pp. 2026–2035, SMIRT18-H03-1.

Tcherner, J., Aziz, T., 2009. Effects of AAR on seismic assessment of nuclear power plants for life extensions. In: 20th International Conference on Structural Mechanics in Reactor Technology (SMIRT 20), Espoo, Finland, SMIRT20-Division 7 Paper 1789.

US Energy Information Administration, 2013. Frequently Asked Questions, http://www.eia.gov/tools/faqs/faq.cfm?id=228&t=21 (retrieved: 19.06.13).

Vodák, F., Trtík, K., Sopko, V., Kapičková, O., Demo, P., 2004. Effect of *gamma*-irradiation on strength of concrete for nuclear safety-related structures. Cement Concrete Res. 35, 1447–1451.

Xie, Z., Xiang, W., Xi, Y., 2002. Asr potentials of glass aggregates in water-glass activated fly ash and portland cement mortars. J. Mater. Civil Eng. 15, 67–74.