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Final Report on the Phase 1 of the Assessment of Structures Subjected to Concrete Pathologies (ASCET)

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English text only

NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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Final Report on Phase 1 of the Assessment of Structures Subjected to Concrete Pathologies

Appendices 3 & 4 only available in PDF format on the NEA documents webpage.

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 35 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, Chile, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Latvia, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Korea, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission takes part in the work of the OECD.

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 31 countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Korea, Russia, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission and the International Atomic Energy Agency also take part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;
- to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of senior scientists and engineers with broad responsibilities for safety technology and research programmes, as well as representatives from regulatory authorities. It was created in 1973 to develop and co-ordinate the activities of the NEA concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations.

The committee’s purpose is to foster international co-operation in nuclear safety among NEA member countries. The main tasks of the CSNI are to exchange technical information and to promote collaboration between research, development, engineering and regulatory organisations; to review operating experience and the state of knowledge on selected topics of nuclear safety technology and safety assessment; to initiate and conduct programmes to overcome discrepancies, develop improvements and reach consensus on technical issues; and to promote the co-ordination of work that serves to maintain competence in nuclear safety matters, including the establishment of joint undertakings.

The priority of the CSNI is on the safety of nuclear installations and the design and construction of new reactors and installations. For advanced reactor designs, the committee provides a forum for improving safety-related knowledge and a vehicle for joint research.

In implementing its programme, the CSNI establishes co-operative mechanisms with the NEA Committee on Nuclear Regulatory Activities (CNRA), which is responsible for issues concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with other NEA Standing Technical Committees, as well as with key international organisations such as the International Atomic Energy Agency (IAEA), on matters of common interest.

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Gratitude is expressed to Neb Orbovic for his great effort in implementing and managing the ASCET programme and for managing the workshop with the help of Jacob Philip; to Canadian Nuclear Safety Commission (CNSC) for organising the ASCET workshop; to Joannie Chin and National Institute of Standards and Technology (NIST) for hosting the workshop; to Steve West for the support and to the Organising Committee of ASCET.

ORGANISING COMMITTEE

Neb Orbovic	Canadian Nuclear Safety Commission
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Andrei Blahoianu	Canadian Nuclear Safety Commission
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LIST OF ABBREVIATIONS AND ACRONYMS

AAR	Alkali-aggregate reaction
ACC	Accelerated carbonation test
ASCET	Assessment of structures subjected to concrete pathologies
ASR	Alkali-silica reaction
CAPS	CSNI activity proposal sheet
CNSC	Canadian Nuclear Safety Commission
CONMOD	Concrete model in the Swedish concrete testing project
CSNI	Committee on the Safety of Nuclear Installations
DEF	Delayed ettringite formation
DiD	Defence in depth
DRI	Damage rating index
EDF	Électricité de France
EPRI	Electricity Power Research Institute (United States)
FE	Finite element
GPR	Ground penetrating radar
HECR	High energy computed radiography
IAEA	International Atomic Energy Agency
IFSTTAR	French Transports and Public Works Research Institute
IRSN	Institut de radioprotection et de sûreté nucléaire (France)
LTO	Long-term operation
MASW	Multi-channel analysis of surface waves
NDE	Non-destructive examination
NDT	Non-destructive test
NEA	Nuclear Energy Agency
NIST	National Institute of Standards and Technology
NPP	Nuclear power plant
ODOBA	Observatoire de la durabilité des ouvrages en béton armé
OECD	Organisation for Economic Co-operation and Development

RGIB	RGIB-modulus of the finite element programmme
RILEM	International union of laboratories and experts in construction materials, systems and structures
RIVE	Radiation-induced volumetric expansion
SLS	Serviceability limit state
TSO	Technical Support Organization
ULS	Utimate limit state
UPV	Ultrasonic pulse velocity
USNRC	US Nuclear Regulatory Commission
WGIAGE	Working Group on Integrity and Ageing of Components and Structures

EXECUTIVE SUMMARY

Taking into account life extension, concrete degradation becomes one of the main issues for long-term operation (LTO). Concrete pathologies/degradation mechanisms – alkali-aggregate reaction (AAR), delayed ettringite formation (DEF), irradiated concrete, sulfate attack, reinforcing steel corrosion, freezing and thawing cycles – have been detected in concrete nuclear facilities in several NEA member countries which might very likely affect their performance and the residual lifetime.

The workshop on assessment of structures subjected to concrete pathologies (ASCET) was held at National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, from 29 June to 1 July 2015. The objective of the CSNI activity proposal sheet (CAPS) and the workshop was to assess the possibilities to define general international recommendations for ageing managements of concrete nuclear facilities subjected to different concrete pathologies/degradation mechanisms. This report describes the results of the ASCET work for assessing the recent requirements and related working methods in countries and looking for the possibilities to harmonise them.

Based on the discussions in the workshop and the work done in ASCET Phase 1, the following conclusions and recommendations were provided:

- There is a need to create an open international database to bring together information on concrete degradation mechanisms. Collaboration with the International Atomic Energy Agency (IAEA) in the development process of a new NEA database would be beneficial for all member countries. All information from nuclear facilities of NEA member countries and, if possible also from decommissioned non-reactor nuclear facilities worldwide, is useful for database development in the Working Group on Integrity and Ageing of Components and Structures (WGIAGE). The report presents information on examples and methods on the detailed assessment of concrete degradation mechanisms of bridges.
- In the case of concrete with pathologies/degradation mechanisms, the strength predictions based on the design equations in the current codes will likely not agree with the results of structural element testing. Therefore, numerical models should be developed and validated using structural testing with quantification of uncertainties in input data and the results. In some cases, the tests on reduced scale structures cured in laboratory conditions cannot provide the correct information related to the performance of full scale heterogeneous structures in normal environmental conditions. Nevertheless, tests of reduced scale models in laboratory conditions, where it is possible to focus on limited parameters with precise control during the test, provide valuable information for assessing the ultimate capacity of a full-scale structure.
- The proposal of the ASCET Phase II is to organise a blind numerical simulation benchmark of a representative AAR-affected structure, the evolution of which has been well-controlled and documented, and the final capacity checked. During the benchmark, a shear wall with advanced AAR will be tested under cyclic loading (simulating seismic loading) up to the wall failure. In parallel, a shear wall with the same geometry and reinforcement under the same loading but built with sound aggregate will be simulated in order to compare the ultimate capacity, displacements and failure modes.

1. INTRODUCTION

Public acceptance of existing nuclear facilities depends on demonstrating adequate structural performance of these facilities during their entire lifetime. The goal of the CAPS on assessment of structures subjected to concrete pathologies (ASCET) is to organise and implement a research activity that can be publicly vetted as a means of establishing and validating evaluation techniques for structures with degraded concrete.

2. OBJECTIVE

The objective of the CAPS and the workshop was to assess the possibilities to define general international recommendations for management of concrete nuclear facilities subjected to different concrete pathologies/degradation ageing mechanisms.

3. BACKGROUND

The CAPS on assessment of structures subjected to concrete pathologies (ASCET) was initiated, planned and executed by the Organising Committee: Neb Orbovic, CNSC; Jacob Philip, USNRC; Andrei Blahoianu, CNSC; and Olli Nevander, NEA, within the Working Group on Integrity and Ageing of Structures and Components (WGIAGE).

The Organising Committee received technical support from the members of the Scientific Committee: Prof Alain Sellier, University of Toulouse, France; Prof Erik Schlangen, Delft University of Technology, The Netherlands; Prof Patrice Rivard, University of Sherbrooke, Canada; Dr Francois Toutlemonde IFSTTAR, France.

The kick-off meeting for Phase I of ASCET was held on 30 June 2014 at the EPRI offices in Washington DC and the final workshop at the National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, from 29 June to 1 July 2015.

Taking into account life extension, concrete degradation becomes one of the main issues for long-term operation. Concrete pathologies/degradation mechanisms – AAR, DEF, irradiated concrete, sulfate attack, rebar steel corrosion, freezing and thawing cycles – have been detected in concrete nuclear facilities in several NEA countries which might very likely affect their performance and the residual lifetime. It is necessary to analyse their performance and to assess whether it is still within acceptable thresholds.

In this regard, one of the biggest challenges in dealing with ageing/deteriorating concrete structures is to identify the cause of possible distress, to establish the correlation between the modification in the mechanical/physical properties and the chemical reaction behind, to define structural ultimate limit state (physical integrity) and serviceability limit state (structural performance and durability), to evaluate possible implications of the pathology/degradation and also their potential for further deterioration. It is necessary as well to have simulation means to predict the structural behaviour, the residual safety as a function of time, and the effect of repair strategies, if needed. Those are critical steps in the selection of management actions on the structures with concrete pathologies and deterioration mechanisms.

Independently of the type of degradation mechanism, the work was articulated among the following directions: 1) material testing; 2) material modelling; 3) structural component testing/destructive testing; 4) structural component modelling, 5) In situ structural condition assessment/non-destructive testing; 6) structural acceptance criteria for structures with concrete pathologies/degradation mechanisms; and 7) structural repair.

The types of investigations to understand and evaluate concrete pathologies are discussed by each member state on its needs and sensitivities. Some NEA member countries have already developed and put in place methodologies to deal with concrete pathologies/degradation mechanisms and some licensees already included theses phenomena in their ageing management programmes.

Twenty two high quality presentations from eight countries (Canada, Finland, France, Germany, Japan, the Netherlands, Sweden and the United States) were made during the final workshop followed by very animated discussions.

4. ASCET WORKSHOP SUBJECTS

4.1 Development of general methodologies for ageing management and addressing concrete pathologies/degradations

At Électricité de France (EDF) (Gallitre et al. 2015), a general policy of the ageing management of nuclear power plants (NPPs), which covers concrete pathologies/degradations has been under development since 1990s. It is described in three documents: 1) a document regarding safety-related structures other than containment; 2) a document related to containment structures with a steel liner; and 3) a document related to double wall containment structures without liner. The doctrine presents the feedback collected from operated plants and provides safety requirements.

The derivation of these fundamental documents has led to ageing management programmes for all safety-related buildings. In these ageing management programmes, all ageing mechanisms are addressed on the basis of a generic inspection document dedicated to civil structure. This generic inspection document contains typical sheets depending on the related mechanism.

In the frame of NPP life extension EDF has built a set of ageing management sheets which present every key point by answering to the following questions:

- Which component or structure is affected by the degradation mechanism?
- Which are the potential damages due to this mechanism?
- What is the assumed design life of the component?
- Is the mechanism potential or already encountered?
- Did we encounter difficulties that could have affected a safety function?
- Is the degradation mechanism taken into account in design documents?
- Is the maintenance programme adapted?
- Is the repair easy or difficult?
- Is there any risk of obsolescence of the system and is the replacement easy or difficult?

Sixty six ageing sheets have been written on this basis. A detailed procedure is derived for every plant, consistent with the general International Atomic Energy Agency (IAEA) guide NS-G 2.12 (ageing management for NPP). Since 2015, EDF has under preparation a long-term operation (LTO) programme as a continuity of existing ageing management programme (operating lifetime over 40 years) with additional questions:

- Is there any regulation or qualification requirement against accidental condition that can affect the lifetime?
- Is there any additional inspection or maintenance to perform for LTO?
- What is the expected lifetime of the items and what is the assessment basis?

The French Transports and Public Works Research Institute (IFSTTAR) has developed a methodology (Toutlemonde et al. 2015) for dealing with concrete swelling degradation mechanisms (AAR, and DEF) based on the experience with French infrastructure (mainly bridges and dams) but this approach appears applicable to nuclear facilities. The methodology is presented in two documents: Handbook for identifying reaction of internal degradation of concrete structures and guide for bridge management. The five steps of the methodology are:

- prioritisation (classification of structures);
- initial assessment:
  - characterisation of cracking;
  - sensor installation for monitoring of deformations;
  - programming of measurements.
- monitoring (Significant and evolving deformations? Presence and evolution of cracks?);
- search for the causes of disorders:
  - sampling;
  - laboratory analysis of samples and diagnosis.
- forecast of the evolution:
  - residual expansion tests;
  - specific recalculations (chemo-mechanical model);
  - optimisation of retrofitting technique.

The application of the methodology has turned out effective in the prevention of degradation mechanisms. Significant experience has been gained in diagnosis, residual expansion tests, structural monitoring and modelling. Non-destructive techniques are still under development for less accessible structures.

However, the quantity of affected structures is still growing (the latency time for AAR is typically 15-25 years).

4.2 Material testing

Material testing was presented by all participants and for all degradation mechanisms. Material testing is performed on samples extracted from structures or manufactured for specific tests. The material testing can be subdivided in (Mueller et al. 2015):

- durability-related material properties;
- structural-physical material properties and;
- deformation and strength properties.

Realistic assessment of concrete durability must consider complex interactions when multiple mechanisms interact during the deterioration process of reinforced concrete structures under field conditions. Recent research has drawn attention to the interaction of degradation mechanisms occurring in the harsh environmental conditions, the possible synergy between deterioration mechanisms and transport mechanisms (Ferreira and Bohner, 2015). This approach will lead to more realistic understanding of the in situ performance of concrete, and will result in an improved service life assessment of existing structures, and design of new ones.

Concerning durability-related material properties basically the quantification of concrete cover, carbonation depth, chloride content and frost resistance can be performed and the results can be rated. In addition to the quantification of the carbonation depth and the chloride content in selected concrete samples taken on-site, it can be done on test specimens that have been specially prepared or produced. Different acceleration procedures are used for the different deterioration mechanisms. These are, for example:

- accelerated carbonation test (ACC-test method) for the determination of the inverse;
- carbonation resistance;
- rapid chloride migration test for the determination of the chloride migration coefficient.

As the durability of concrete structures is primarily influenced by the Hygrothermal behaviour of the concrete the interaction between external and internal moisture conditions of the concrete structure has to be determined. The material laws concerning the moisture behaviour of concrete require different material constants which describe the physical material properties of:

- capillary suction;
- vapour diffusion resistance;
- water absorption;
- porosity;
- sorption isotherm;
- pore size distribution.

For the purpose of evaluating the structural capacity against the different loading and environmental conditions, the code equations require:

- compressive and tensile strength;
- static modulus of elasticity;
- dynamic modulus of elasticity.

Material test used to define the extent of concrete free swelling (e.g. AAR, DEF) and its consequences on material properties are (Orbovic et al. 2015):

- concrete prism tests, or performance tests (on prisms or cylinders) or residual expansion tests to characterise the reaction:
    - expansion (longitudinal and transversal);
    - dynamic modulus of elasticity;
    - damage rating index (DRI);
    - modulus of rupture;
    - water absorption;
    - resistivity.
- concrete cylinder test (unconfined compressive strength);
- dog bone specimen tests (tensile strength);
- cube specimen test to characterise expansion and degradation in mechanical properties for under different types of restrains (1D, 2D, 3D).

Material tests on irradiated concrete show radiation-induced volumetric expansion (RIVE) as a first order mechanism, along with decrease in mechanical properties (Le Pape et al. 2015). The difference between the concrete swelling under AAR and DEF comparing to RIVE is that RIVE has higher level of expansion (>1%) but limited to the relatively narrow concrete layer directly exposed to radiation.

4.3 Material modelling

The gradual loss of durability due to service conditions and environmental exposures has to be described by means of appropriate material constitutive laws, which generally depend on an internal irreversibly evolving variable associated with the ageing mechanism (chemical reaction degree, etc.). Such laws should take into account real physical and chemical mechanisms. This holds true, e.g. for the degradation processes caused by carbonation, chloride ingress or by frost attack. Some models used for the description of the mentioned phenomena are described in Mueller et al. (2015).

The process of carbonation is considered in the models comprising a material constitutive law. In order to calculate the carbonation depth at a defined time (or concrete age) various parameters take into account curing effects, environmental conditions (relative humidity) and CO_2-concentration in the air as well as the rewetting of surfaces due to rain events and the inverse effective carbonation resistance of concrete. This model bases on the fib (International Federation for Structural Concrete) Model Code for Service Life Design (Mueller et al. 2015).

The service life design of reinforced concrete structures requires material models capable of reliably describing both mechanisms of damage and the general progression of damage over time. However, most models that are currently being used only capture the process of carbonation and chloride penetration into the uncracked concrete that is at the initial phase of degradation. Typically, these models disregard the actual damage, i.e. the corrosion of the reinforcing steel. As a result, the service life design established to date only considers the end of the initiation phase of the degradation process, i.e. the onset of damage (time of de-passivation or onset of corrosion) as a critical limit state. The corrosion of the reinforcement and its consequences, i.e. the crack formation and spalling of concrete, are not considered, which may lead to a substantially shorter estimated service life of the structures.

Time-dependent reliability analyses provides valuable support to the decision making process, whether for design, or for defining maintenance and repair strategies. The service life prediction of deteriorating structures is affected by the uncertainties associated with material properties, mechanical and environmental loads as well as damage occurrence and propagation models. Therefore, the service life estimation requires probabilistic models and methods to account for the uncertainties that govern the deterioration processes.

Designers must define the criteria for which the limit state is evaluated. There is still considerable debate as to what are the appropriate values for durability-related limit states. Values based on experience or set by conventions are required. When defining the requirement for probability of failure (or reliability index) the criteria that should be taken into account are: the type of limit state (initiation of deterioration, SLS or ULS; the service life for new structures or reference period for existing structures; the consequences of failure; and, the cost of safety measures. Considerable work is still needed on this topic to enable a robust application procedure in the future (Ferreira and Bohner, 2015).

4.3.1 Most presented models were addressing concrete swelling typical for AAR and DEF

For the evaluation of AAR expansion, several distinct alternative models were implemented in existing software (e.g. VecTor2). One option is to consider the expansion equally distributed in the principal directions, similar to the procedure used for handling shrinkage strains (Orbovic et al. 2015)

This option yields the highest strains, out of the five models available, as the effect of confining stresses to reduce the expansion is not considered. The other four options represent constitutive models reported in the literature, two of which include a kinetics component for simulating AAR growth in time. The Charlwood (1992) model evaluates AAR strains independently in each direction, limited by the effect of confinement. The Curtis (2014) model is an extension to the Charlwood model, with a refined growth law for concrete in tension. In the Saouma and Perotti (2005) model, which incorporates a kinetics feature, the induced expansion is treated as a volumetric strain redistributed to each principal direction based on weight factors. Provided that sufficient laboratory data are available to describe the free expansion law, the model simulates the expansion as a function of time. The Sellier (2009) model evaluates AAR strains as a consequence of the gel pressure, which in turn is determined as a function of various parameters describing the gel formation. The models must be able to consider progressive filling of porosity by gel, and anisotropic cracking in case of gel pressure in pores connected to reactive aggregate. The most important aspect to consider is the swelling anisotropy induced by stresses; the second one is the creep. If anisotropic swelling is evaluated incorrectly the error on the stress state can reach 500%. The anisotropic swelling error is attenuated by creep (Sellier et al. 2015).

In a tool, called RGIB-modulus of the finite element programme (Toutlemonde et al. 2015), developed at the French Transports and Public Works Research Institute (IFSTTAR), the time evolution of expansion is characterised by only a few parameters. It has not been attempted to derive the parameters from the concrete mix-design or similar material *a priori* information, or form a micro-meso approach, due to the number of parameters involved and the frequency of operational situations where detailed information are missing (Toutlemonde et al. 2015). Conversely, input determination relies on residual expansion data from cores drilled out of the affected structure. And the physically-based coupling laws allow adapting the chemically-induced prescribed strains to the precise physical or mechanical environment of the structure considered.

One of the comments (Gocevski, 2015) was that majority of the early numerical models were developed for the simulation of material tests only (concrete cylinders or blocks). Within the framework, developed by Hydro-Quebec, which represents a phenomenological approach, the tests on the cylinders and blocks are perceived as material tests that define the rate of free expansion under different conditions. These tests provide a valuable information that may be employed to identify the parameters entering the law of reaction kinetics; they cannot, however, be simulated as initial boundary-value problems. The latter requires a multi-scale approach (i.e. micro/mesoscale) that, even though conceptually attractive, cannot be employed in the context of analysis of large-scale structures (V. Gocevski, 2015).

However, models developed by Sellier et al. (2015) and RGIB-modulus of the finite element programme “CESAR-LCPC” developed by IFSTTAR have been applied to real complex and large-scale structures: Temple sur Lot dam, Salanfe and Songloulou dams, Veytaux hydraulic power plant, Térénez and Bourgogne Bridges. Even though progress in their qualification is expected (e.g. with the benchmark organised within RILEM TC ISR) and even though further advanced capacities are still under implementation and validation, these tools already represent in France (and has represented for the owners of these large structures also in Switzerland and Africa) an important and necessary support to engineering judgement and AAR/DEF-affected structures management.

4.4 Structural component destructive testing

The only structural component tests results presented during the ASCET workshop were the tests performed at the University of Toronto on squat shear walls (Orbovic et al. 2015). The structural aspect focuses on destructive and non-destructive testing of squat shear walls, as the most common structural elements in nuclear facilities. The wall design (1.54 m long, 0.75 m high, 0.1 m thick) with barbells, as boundary elements, and strong horizontal beams was chosen based on previously performed tests in order to obtain a known failure mechanism. The walls are designed using code equations for shear-friction in order to obtain the failure through the wall and to avoid the failure on the contact of the wall with the beam. Six walls are cast and, similar to the specimens for material testing; they are subjected to accelerated ageing in an environmental chamber with 50°C and 95%-100% humidity.

The goal of destructive examinations is to determine mechanical characteristics such as: ultimate resistance, ultimate displacement, ductility, residual strength of walls with AAR (compared to sound walls) as well as to correlate the level of damage in terms of crack spacing and crack width with the structural drift.

The concrete compressive strength of the sound wall was 75 MPa and of the wall with AAR 62 MPa (-17.3%). The concrete tensile strength (direct tensile tests) of the sound wall was 4.76 MPa and of the wall with AAR 3.24 MPa (-31.9%). The elastic modulus of the sound wall was 47 150 GPa and of the wall with AAR 35 750 GPa (-24.2%). Despite the lower level of all concrete properties used in the design, the maximum capacity of the regular shear wall was recorded as 1 180 kN and the maximum capacity of the AAR shear wall was recorded as 1 355 kN. Therefore, the AAR shear wall showed 14.8% higher capacity than regular shear wall.

The next set of two tests is scheduled to be performed in April 2016 and it is expected that the reaction will be exhausted at that time (approximately after 50 months of accelerated ageing). The damaged walls with exhausted reaction will then be then retrofitted using carbon fibres and tested again using destructive and non-destructive examinations to assess the effectiveness of the retrofit measures.

Other tests performed on structural elements were mentioned during the workshop (Toutlemonde et al. 2015) and available in the literature, such as those carried out jointly by EDF and IFSTTAR.

Two series of structural destructive tests on degraded concrete are planned for the future: IRSN and US NRC/NIST tests.

IRSN has a plan for a large structure testing that should take place from 2016 to 2026: the *Observatoire de la durabilité des ouvrages en béton armé* (ODOBA) project. The evolution and coupling between pathologies (mainly AAR and DEF) would be studied with accelerated process. It would be completed with laboratory experimentation. Assessment of detection of pathology (early stage and evolution) by non-destructive examination (NDE) methods would also be investigated.

It was proposed to organise, as the next phase of ASCET, a blind simulation benchmark of the tests scheduled for April 2016 at the University of Toronto. In order to serve as a benchmark for validation of models adapted to AAR/DEF structures affected assessment, structural tests should be accompanied by precise information on humidity and temperature, expansion potential of the material, expansion survey of the structure, possible concomitant shrinkage, etc.

4.5 Structural modelling

During the 1980s and early 1990s a significant amount of research has been devoted to physicochemical aspects of AAR in concrete. The primary focus was on experimental studies examining the kinetics of the reaction. At the same time, the research on the development of constitutive models describing the chemo-mechanical interaction has been quite limited. More general continuum approaches, involving the framework of chemo-plasticity/elasticity, started to appear in the mid-1990 (V. Gocevski, 2015). The initial work of Hydro-Quebec follows the general approach proposed in the article by Pietruszczak (1996), albeit with significant revisions that pertain to the description of the reaction kinetics, modelling of crack path propagation and the incorporation of heavy reinforcement (Pietruszczak and Winnicki 2003; Gocevski and Pietruszczak, 2004). Simultaneously other non-linear models coupling poro-mechanis and anisotropic damage or plasticity were developed in Europe (Ulm, Coussy, Kefei and Larive, 2000; Capra and Sellier, 2002). Later, several derivative concepts were proposed that included both the macroscale models (e.g. Multon and Toutlemonde, 2006; Saouma and Perotti, 2006; Grimal et al. 2008) as well as micromechanical descriptions of AAR-induced deformation. The predictive ability of these models is still advancing and to be validated, not only at the scale of laboratory specimens, but to address engineering issues of large-scale affected structures (where damage may frequently be localised). One of the main issues corresponds to the simultaneous accounting for AAR/DEF reaction(s) and creep, in three-dimensional problems.

Over the last fourteen years Hydro-Quebec has carried out extensive numerical studies for the containment structure of G-2 NPP and for the other concrete structures affected by AAR in the plant (Gocevski, 2015). These numerical simulations included the implementation of a transient thermal analysis for the period of construction and for the freeze-thaw cycles occurring during a fifty-year period.

Generally speaking, the currently available commercial finite element programmes are not prepared to adequately address some complex problems involving AAR-related swelling. In particular, most of these programmes lack material models with constitutive relations that are suitable for the description and the evolution of complex material properties related to AAR.

Based on Hydro-Quebec’s experience in simulating the behaviour of Hydroelectric and NPP structures affected by AAR swelling, the essential requirements of the concrete/reinforced concrete constitutive model accounting for the chemo-mechanical interaction, which should be incorporated in advanced finite element (FE) codes, are as follow:

- adequate description of the kinetics of the reaction;
- general failure criterion, provision for the development of irreversible deformations, general criterion for the onset of macro cracking in both compression and tension regimes;
- degradation law for strength and deformation characteristics;
- proper description of propagation of damage in both tension and compression regimes;
- constitutive relation for the interface material relating the velocity discontinuity to the traction vector.

Based on Hydro-Quebec’s experience, pursuing an appropriate analytical procedure, that includes calibration steps, is of great importance in any non-linear static or dynamic analysis as it is a basic requirement for obtaining reliable and accurate results. The procedure is outlined in the following:

Step 1:

- evaluate material properties;
- evaluate the rate of free expansion;
- define the parameters used in the numerical formulation;
- define the time step to be used.

Step 2:

- Run preliminary analysis; runs for 20, 30, 40...years, calibration with the in situ observations and measurements.

Step 3:

- Run final structural analysis for present time evaluation: from the end of the construction until present time.

Step 4:

- Run final structural analysis for future time evaluation: evaluation of the structural behavior in the future.

A similar description of the successive steps of affected structures assessment has been detailed by IFSTTAR (guide for the management of AAR/DEF-affected structures, 2003 – Li, Coussy and Larive, 2004) and applied to dams, bridges and a hydraulic plant for expert investigation of the residual operability/safety and assessment of mitigation/retrofitting procedures.

4.6 In situ condition assessment and non-destructive testing

In situ monitoring provides the first data for prioritisation and management decisions related to further survey and deeper investigations as presented in Sub-section 4.1. It is mainly based on visual inspection, distance and deflection measurements as well as crack monitoring. Crack monitoring is performed either for localised widely open cracks, or for cracked zones (determination of cracking index and evolution).

Distance and deflection measurements as well as cracking survey appear as directly related to the output of the structural modelling, which appears as a mandatory step for effective condition assessment (Toutlemonde et al. 2015).

One possible application of non-destructive tests (NDT) on structural elements was presented in Orbovic et al. (2015) Acoustic techniques and vibration response are also used: 1) to determine the extent of damage due to AAR using linear and non-linear acoustic techniques; 2) to determine the walls’ dynamic characteristics using modal analysis (Eigen frequency, operational mode shapes and damping characteristics) and to correlate them with the results from the destructive material and structural tests (Orbovic et al. 2015)

4.6.1 Acoustic methods, linear and non-linear, which produce stress waves propagation throughout a solid, are used to monitor the integrity of concrete against damage mechanisms

Linear acoustic methods commonly used to monitor AAR damage are:

- linear wave attenuation;
- impact echo;
- ultrasonic pulse velocity (UPV).

Non-linear approaches appear to be more sensitive to AAR damage at early stage. Non-linear acoustic technique used in this project is called Ultrasonic Travel Time Shift method (Orbovic et al. 2015). The technique uses high frequency ultrasonic waves to probe the medium, while a low-frequency high-amplitude wave generated by an impact (typically a hammer) is applied on the surface of the medium. The impact disturbs the medium locally, and temporarily modifies its elastic properties. The technique benefits from the strong non-linear elastic behaviour of micro-cracked concrete when subjected to stress. This non-linear behaviour is essentially associated with the opening and/or closing of micro-cracks in the concrete material. Non-linear acoustic methods are presented in details in Cusatis et al. (2015).

In general, acoustic methods applied for AAR/DEF diagnosis have to be used with much care, due to possible artefacts related to other sources of cracking and effects of the evolution in the moisture field within the structure.

4.6.2 For modal analyses two different methods are performed

- frequency response function method;
- basic frequency domain method.

The frequency response function method deals with the analysis of the output acceleration and the input excitation force, which in this case is a hammer blow. This method is generally implemented in a laboratory environment because measuring the force input on a specimen is not always easy to do during on-site tests. The second method is an output only method that does not take the force measurement into account. This type of method is better suited for field testing. A frequency decrease of 8.1% for AAR wall was recorded. This result is consistent with the decrease in Young's modulus of elasticity obtained from destructive tests. The same results are obtained using basic frequency method. In terms of damping ratios, the damping ratio for regular wall was 0.336% and for AAR wall was 0.653%, or an increase of 94%.

However, the performed NDT were not able to predict the increase of structural capacity of the wall with AAR which was seen in the destructive test.

In Thunell et al. (2015) is presented the concrete model (CONMOD) based on Swedish CONMOD material testing project at the Barsebäck NPP is presented in reference 7 of Appendix 2 by Thunell et al. (2015). CONMOD, a Swedish project put in place during the years 2002-2005, in order to establish a methodology for a subset of what today is called a generic AMP, for the ageing reactor containments of the Swedish nuclear fleet. As a demonstrator, the decommissioned NPP Barsebäck was used in the structural assessments. Non-destructive test methods include: high energy computed radiography (HECR), ground penetrating radar (GPR), multi-channel analysis of surface waves (MASW).

A few series of measurements had been made during the CONMOD project, using various non-destructive techniques on the containment wall of Barsebäck unit 1 and 2. The objectives of these tests were to: 1) test the capability and performance of selected NDT techniques; and 2) obtain information about typical structure characteristics. Information sought for included:

- visibility (positioning) of reinforcement and pre-stressing tendon ducts;
- visibility of steel liner;
- concrete properties (elastic material properties, or rather wave velocities) and homogeneity;
- condition of concrete around pipe penetrations (detection of voids);
- condition of pre-stressing tendon ducts and filler grout.

There is a need to continue investigations (Le Pape et al. 2015) on decommissioned nuclear facilities as Zion NPP Units 1 and 2, Milsetone 1, Indian Point Unit 1, Crystal River 3 (all in United States), Zorita (Spain), and Krunnel (Germany). Harvesting of concrete cores from decommissioned nuclear power plants (NPPs) will provide an opportunity to generate data from concrete that has experienced typical radiation fields, while also providing guidance to accelerated irradiation studies. The coupling of accelerated or laboratory-irradiated concrete with harvested nuclear power plant cores is expected to facilitate the effort to develop an understanding of the damage mechanisms in irradiated concrete, including understanding potential effects of accelerated testing (Le Pape, 2015).

4.7 Structural acceptance criteria

As presented in Sub-section 4.4, the code relations between the concrete compressive strength, tensile strength and modulus of elasticity are not valid anymore for AAR or DEF-affected concrete. The design equations based on concrete compressive strength may not be valid either. Therefore there is a need of a cases-by-case assessment of ULS taking into account all degradation mechanisms.

The criteria associated with structural management decisions are often related to the serviceability limit state (SLS): opening of visible cracks or cracking index with defined thresholds, strains in rebars and/or tendons, as well as thresholds related to the variation of global dimensions and shape of the structure (and significant trend over years as compared to seasonal variations). Some examples follow:

- Even though the global structural safety is not immediately engaged, important cracking combined with freeze-thaw degradations and re-bars corrosion may cause deterioration of structural ULS.
- Non-compatibility of concrete deformations, with respect to equipment or active components, may correspond to loss of SLS and require immediate corrective actions.
- Excessive crack can lead to the loss of leak-tightness and again correspond to loss of SLS.

As a conclusion on this aspect, important decisions on structural acceptance related to concrete degradation affected structures have been (and should be) taken based on advice of technical committees comprising material experts, structural engineers, operators and regulators with due consideration of careful structural assessment (Toutlemonde et al. 2015).

4.8 Repair

Management decisions, including repair/retrofitting, should be based on a risk informed approach, which integrates the information gained on the structure itself, significance of the present and evolving damage, cause and prognosis of the disorders etc. (Toutlemonde et al. 2015).

Hydro-Quebec’s significant repair experience is presented (Gocevski, 2015). In a NPP with affected concrete, it is the uninterrupted production which is often challenged. Some of the problems and inconveniences which may arise in these circumstances as well as proposed repair solutions are as follows:

- An extensive micro/macro cracking observed in some areas, is the main cause of water or air leakage. Cracking in areas like the Spent Fuel Storage Pool, Spent Fuel Exchange Room and the tunnel connecting them, is likely to cause leakage. An appropriate repair is usually made by lining the inside surfaces of the affected areas with a flexible membrane. As for the air tightness, it can be restored by adding layer of a flexible liner on the concrete surfaces on the same side on which the high air pressure take action. These interventions are relatively easy to do and their cost is relatively low. However, the cost of the production loss during repairs may be substantial. Therefore, the optimal solution is the one which requires minimum time of execution.
- Structural deformation as a result of concrete swelling will likely require adjustment for certain equipment, particularly: (a) the turbo-generator requires the addition or the removal of steel shims with different thicknesses placed under the base plates. This represents an easy and fast-to-do solution; however, it may require careful planning to provide margin for further levelling due to future expansion. Similar adjustment procedure was successfully applied for the superstructure and crane runway repetitive adjustments of the Beauharnais hydroelectric power plant; (b) accommodating concrete deformation by making adjustments

to the anchorage and the base plates of important equipment to ensure accurate levelling or plumbness; (c) adjustments for the main pipe supports attached to the concrete; (d) grinding of the rising concrete floors at the containment building entrance; (e) grinding of deformed door frames and other wall and slabs openings; (f) adjustments of the pipes which are anchored to the Reactor Vault in order to insure safe operation of the CALANDRIA (CANDU reactor vessel).

- Degradation of the mechanical properties of AAR-affected concrete requires careful evaluation and – when necessary – providing additional reinforcement. The replacement of select concrete anchor bolts may be needed in order to compensate the reduction in concrete shear strength if the strength of pull-out resistance of the concrete cone governs the ultimate strength capacity.
- Splitting (delamination) of concrete in the areas of high two-directional pre-stressing: this problem may require pinning the concrete wall or element using concrete steel anchors.

5. CONCLUSIONS AND RECOMMENDATIONS

Based on very animated discussions during the assessment of structures subjected to concrete pathologies (ASCET) Workshop at National Institute of Standards and Technology (NIST), Germany, from 29 June to 1 July 2015, a consensus among participants was reached regarding several points.

5.1 International database

There is a need to create an open international database to bring together information on concrete degradation mechanisms from nuclear community worldwide (also taking into account relevant information acquired in non-nuclear civil engineering).

Decommissioned nuclear facilities present an excellent opportunity to use in parallel destructive and non-destructive tests (NDT) in order to validate non-destructive examination (NDE) techniques as well as numerical models. Some decommissioned nuclear power plants (NPP) as mentioned in Sub-section 4.6 were already tested and it would be useful to make the results available to the NEA member countries. The list of facilities presented in Sub-section 4.6: Zion NPP Units 1 and 2, Milestone 1, Indian Point Unit 1, Crystal River 3 (all in United States); Zorita (Spain); and Krümmel NPP (Germany) can be extended to Douglas Point and Gentilly 1 (Canada). Gentilly 1 is an example of a nuclear power plant with AAR.

ASCET is open to all suggestions from NEA member countries and decommissioned non-reactor nuclear facilities worldwide. Collaboration with the International Atomic Energy Agency (IAEA) when building the new Nuclear Energy Agency (NEA) database would be beneficial for both IAEA and NEA member states.

5.2 Combined approach: Material and structural level

As discussed in Sub-sections 4.4 and 4.6, the information gained on concrete prisms, cubic or cylindrical samples regarding material properties is not sufficient and can be misleading regarding the overall capacity. Then code equation using material properties based on concrete samples are not in accordance with structural element testing. Concrete restraint due to the presence of reinforcement and/or boundary conditions in the case of concrete expansion, as well as effects of temperature and moisture gradients having led to differential expansions; modify significantly the behaviour in terms of ultimate capacity and displacements. Moreover, the use of correlations between chemical or petrographic analysis of reactive aggregate recovered in core samples, residual swelling tests, in situ conditions (temperature and humidity), and structural measures, should be exploited to improve the predictive capability of this combined approach.

Validation of numerical models should be performed using structural testing.

5.3 Data from structural tests, both full-scale and reduced scale tests

A discussion during the workshop was related to the use of reduced scale specimens cured in chambers under accelerated ageing conditions using uniformly applied elevated temperature and humidity. The comment was that the real structures are not in such conditions: the degradation mechanism is not uniformly distributed and the temperature and humidity vary inside and outside of the structure as well as on different portions of the structure. For example, in real structures, the swelling amplitude is often heterogeneous due to humidity, temperature and reinforcement ratios, leading to cracks and rebar's loading in sound zones induced by swelling gradient. As a consequence, the tests on reduced scale structures, if not addressing gradients of moisture, chemical-induced strains and swelling, cannot provide the correct information related to the full-scale structures in normal conditions. The answer to this comment was that in research tests we should focus on one parameter at a time and even in simplified conditions it is difficult to find the answers to the questions. What is needed is to understand the physics of the phenomena first and with this understanding more challenging questions can be faced. Another problem is that with full-scale structures it is difficult and in most cases impossible to assess their ultimate capacity. The ultimate capacity as well as the failure mode is essential information to understand the physics of the phenomenon. Therefore it is necessary to continue with both reduced and full-scale testing.

5.4 Development of performance based criteria

Concrete degradation mechanisms are challenging from both ultimate limit state (ULS) and serviceability limit states (SLS). In some case structural integrity is not an issue but the structure can have serious serviceability problems. Current codes and standards do not include degradation mechanisms. As presented in Sub-section 4.7, some NEA member countries have developed specific acceptance criteria for the structures with concrete swelling (AAR and DEF). There is a need for case studies and feedback of affected structures management in order to discuss the acceptance criteria for USL and SLS.

5.5 Assessment of the impact of one degradation mechanism on other mechanisms and coupling of degradation mechanisms

The effect of one degradation mechanism on other degradation mechanisms was very widely discussed during the workshop. Structural condition is rarely the consequence of a single degradation mechanism as it is often the case in a laboratory environment. Real structures are exposed to simultaneous action of several degradation mechanisms and it is not an easy task to assess their contributions in the overall structural condition. Especially, the effect of concrete cracking due to swelling (AAR of DEF) coupled with freeze-thaw cycles and rebar corrosion can have important effects. The AAR-induced concrete cracking can significantly affect the capacity of the structure if it leads to corrosion of the rebars. Freeze-thaw cycles can increase the speed of this coupled degradation mechanism.

5.6 Ageing management and long-term operation

The ASCET participants agreed that the Électricité de France (EDF) comprehensive ageing management and long-term operation (LTO) programme presented in Sub-section 4.1 can be used as the basis of a standardised approach for worldwide applications. This is a risk informed approach which can be tailored to the specificities of NEA member countries.

The ASCET participants expressed a need for the development of a standard risk assessment for durability in order to answer the question: "Where do I need to worry and where should management of the structure be focused?" in order to optimise the action plan and maximise the outcome. The IFSTTAR five step methodology presented in Sub-section 4.1: prioritisation, initial assessment, monitoring, search for the causes of disorders, forecast and evolution, can be standardised for the applications worldwide.

5.7 Development and validation of non-destructive tests

Due to difficulties to perform core drilling and other destructive methods in nuclear facilities, non-destructive tests (NDT) should be developed in order to identify the damaged zones, the damage magnitude and the impact on the overall structural behaviour. The techniques should allow the identification of degradation, especially when the damaged zones are not accessible. From the present experience, non-destructive techniques provide alerts, but due to artefacts and sensitivity to various parameters (especially moisture) they should be used with care. NDTs should address these difficulties. It is necessary to develop a set of NDTs in order to perform cross examination of both local areas and global structural response. They should be coupled with reference methods as deformation monitoring, crack survey, and residual expansion tests.

5.8 Simulation tools

At the present time simulation is the only effective tool to predict the structural behaviour. There is a need for model validation and quantification of uncertainties in input data and the results. Collaboration on simulation is needed in order to validate research models as well as industrial numerical models which simplify phenomena developed in mesoscale models. ASCET Phase II is proposed to develop and to benchmark the simulation tools. It should take advantage of parallel initiatives in the non-nuclear civil engineering community, also keeping in mind the differences between nuclear and non-nuclear structures.

5.9 Proposal ASCET Phase II

The proposal of the ASCET Phase II is to organise a blind numerical simulation benchmark of a representative AAR-affected structure, the evolution of which has been well-controlled and documented, and the final capacity checked.

In a first step, the shear wall with advanced AAR, manufactured and cured at the University of Toronto, scheduled to be tested in April 2016, under cyclic loading (simulating seismic loading) up to the wall failure will be modelled and simulated. In parallel will be simulated the shear wall with same geometry and reinforcement under the same loading but built with sound aggregate, in order to compare the ultimate capacity, displacements and failure modes. The tests will be performed at the University of Toronto as a part of the CNSC research programme presented in Sub-section 4.4. Provided the experimental data satisfy the necessary conditions of relevance and comprehensiveness for the benchmark of ASR/DEF assessment tools. The benchmark is to be launched and input data provided to participants in April 2016.

In parallel, alternative documented data on AAR-affected structures will be searched for complementing useful and relevant case studies.

The final workshop of ASCET Phase II could be organised in May 2017 tentatively in Ottawa, Ontario, Canada.

APPENDIX 1: PROGRAMME OF CONFERENCE

Day 1: 29 June 2015	
9:00-9:10	**Welcome** *by Joannie Chin, Deputy Director of Engineering Laboratory, NIST*
9:10-9:20	**Welcome** *by Steve West, Deputy Director, Office of Research, US NRC*
9:20-9:30	**Opening Address,** *Olli Nevander OECD/NEA*
9.30-10.00	**ASCET Introduction,** *Neb Orbovic (CNSC), Jacob Philip (US NRC)*
10:30–11:00	**Performance of Concrete Structures Affected by ASR and NDE Testing,** *Neb Orbovic, CNSC/University of Toronto*
11:00-11:30	**Structural Performance of Concrete Structures Affected by ASR**, Jacob Philip, *NIST/US NRC*
11:30-12:00	**Irradiation Effects on Concrete Structures Performance,** *Yann Le Pape, Oak Ridge National Laboratory*
13:30–14:00	**Concrete Barriers Partnership: Short and Long-Term Performance of Nuclear Waste and NPP Structures**, *Kevin Brown, Vanderbilt University, United States*
14:00-14:30	**Delayed Ettringite Formation (DEF), Structural Acceptance Criteria**, *Olivier Loiseau, IRSN, France*
14:30-15:00	**Presentation of a member of the Scientific Committee,** *Victor Saouma, University of Colorado, United States*
15:30-16:00	**EDF Presentation**, *Etienne Gallitre, EDF, France*
16:00-16:30	**Durability research at VTT on freeze-thaw/chloride ingress interaction and Service Life Design,** *Miguel Ferreira, STUK/VTT, Finland*
16:30-17:00	**Summary of the day and Discussion**
Day 2: 30 June 2015	
8:30-9:00	**Invited speaker: Francois Toutlemonde,** *IFSTAR, France* **Assessment of structures subject to concrete pathologies**
9:00-9:30	**Concrete Degradation and Structural Concrete Studies at the Federal Highway Administration**, *Richard Meninger, FHWA, United States*
9:30-10:00	**Service Life Modeling of Concrete Structures, Repair,** *Eric Samson, SIMCO TECHNOLOGIES, Canada*
10:30-11:00	**Mesoscale Simulation of Alkali-Silica Reaction (ASR) Deterioration of Concrete and Interpretation of Nonlinear Ultrasound Measurements,** *Gianluca Cusatis, Northwestern university, United States*
11:00-11:30	**EPRI Presentation,** *Maria Guimaraes, EPRI*
11:30-12:00	**Presentation of a member of the Scientific Committee,** *Erik Schlangen, Delft University of Technology, The Netherlands*
13:30-14:00	**Irradiation and ASR Effects on Concrete**, *Makio Nakano, NRA, Japan*
14:00-14:30	**Scanscot Presentation**, *Bjorn Thunell, RSA/Scanscot, Sweden*
14:30-15:00	**Presentation of a member of the Scientific Committee,** *Alain Sellier, INSA Toulouse, France*

15:30-16:00	**Investigations of Concrete Degradation (AAR, sulfides, shrinkage, corrosion), Repair Techniques,** *Vladimir Gocevski, Hydro-Quebec, Canada*
16:00-16:30	***Concrete Materials testing, Modeling, Structural Performance, NDE and Repair Technologies,*** *Brian Green, US Army Corps of Engineers, United States*
16:30-17:00	**Summary of the day and Discussion**
Day 3 – 1 July 2015	
8:30-9:00	**Presentation of a member of the Scientific Committee,** *Patrice Rivard, University of Sherbooke, Canada*
9:00-9:30	**Concrete Materials and NDE Research,** *Julia Tcherner, Candu Energy, Canada*
9:30-10:00	**Presentation of Karlsruhe Institute of Technology,** *Michael Vogel and Detlef Eckhardt*
10:30 -11:00	**Conclusions and Recommendations,** *Presentation Neb Orbovic, Jacob Philip and Discussion*
11:30-12:00	**Presentation of ODOBA Project,** *Christophe MARQUIE, IRSN, France*

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APPENDIX 3

Appendix 3 - Conference papers (follow this link)

1. N. Orbovic, CNSC, Alkali Aggregate Reaction in Nuclear Concrete Structures: A Holistic Approach
2. J. Philip, US NRC, Alkali-Silica Reaction (ASR) Degradation of Nuclear Power Plant Concrete Structure
3. Y. Le Pape, Irradiation Effects on Concrete; Contribution from Oak Ridge National Laboratory (ORNL) to the OECD ASCET project
4. E. Gallitre, Assessment of Structures subject to Concrete Pathologies, EDF contribution
5. F. Toutlemonde, Assessment of Structures subject to Concrete Pathologies; Contribution of IFSTTAR (Transports and Public Works Research Institute), France
6. G. Cusatis, North-western University Mesoscale Simulation of Alkali-Silica Reaction (ASR) Deterioration of Concrete and Interpretation of Nonlinear Ultrasound Measurements
7. B. Thunell, ASCET participant initial survey report Ed. 2 by Scanscot Technology (Sweden)
8. V. Gocevski, Pathologies/Degradation Mechanisms Experienced by Hydro-Quebec During the Evaluation of GENTILLY-2 NPP
9. Leandro Sanchez, Report: Assessment of Structures Subject to Concrete Degradation: works developed and under development at Université Laval & McGill University, Quebec, Canada.
10. M. Ferreira, E. Bohner, VTT Report on Research on concrete deterioration mechanisms – Assessment of structures with concrete pathologies
11. J. Tcherner, SNC-Lavalin Experiences on Assessment and Repair of Nuclear Concrete Structures Subject to Degradation
12. R. Meininger, Concrete Degradation and structural Concrete Studies by the FHWA
13. M. Guimaraes, EPRI Concrete Program
14. H. Mueller, Assessment of Structures Subject to Concrete Pathologies, MPA Karlsruhe
15. Ch. Marqui,G. Nahas, IRSN ODOBA Research Project

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Ferreira, M. and E. Bohner (2015), *Research on concrete deterioration mechanisms – Assessment of structures with concrete pathologies*, VTT Technical Research Centre of Finland Ltd, Espoo, Finland.

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Meininger, R. (2015), *Concrete Degradation and structural Concrete Studies*, Turner-Fairbank Highway Research Center (TFHRC), Federal Highway Administration (FHWA), United States Department of Transport, McLean, VA, United States.

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Thunell, B. (2015), *ASCET participant initial survey report Ed. 2,* Scanscot Tech., Lund, Sweden.

Toutlemonde, F. (2015), *Assessment of Structures subject to Concrete Pathologies*, Transports and Public Works Research Institute (IFSTTAR), Guerville, France.

Appendix 4 - Key presentations in the conference (follow this link)

1. Stress state prediction in structures affected by AAR and DEF, A.Sellier
2. IS2C project in the Netherlands, E. Schlangen
3. Monitoring and Nondestructive evaluation of ASR, P. Rivard,
4. Experience of Assessment and Management of large non-nuclear ASR- and/or DEF-affected structures: Science, practice and questions, Francois Toutlemonde.