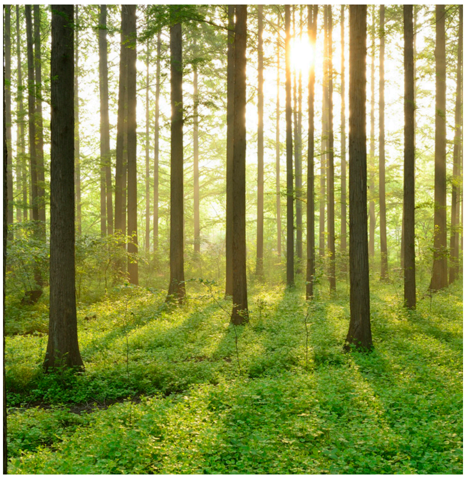
ACCEPTANCE CRITERIA FOR MAINTENANCE OF NUCLEAR CONCRETE STRUCTURES

REPORT 2017:358



NUCLEAR CONCRETE
R&D PROGRAM

Energiforsk

Acceptance Criteria for Maintenance of Nuclear Concrete Structures

Feasibility study

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ISBN 978-91-7673-358-5 | © ENERGIFORSK March 2017
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Foreword

The concrete infrastructure at the Nordic nuclear power plants has reached the age that it was originally designed for. Most important structures being rector containment and cooling waterways. To ensure a high level of safety and plant availability, established maintenance acceptance criteria are needed to verify the status and maintenance needs of the structures.

This is a feasibility study carried out to map acceptance criteria used in nuclear power plants in other countries, and in other concrete infrastructures like hydropower, wind power, bridges and shipping. The study has been carried out within the Energiforsk Nuclear Concrete research program out by senior scientists Miguel Ferreira, Edgar Bohner and Kim Calonius at VTT Technical Research Centre of Finland Ltd.

The aim of the Energiforsk Nuclear Concrete research program is to initiate research and development that will contribute to a safe and cost effective long term operation of Swedish and Finnish nuclear power. The program is financed by Vattenfall, Sydkraft Nuclear Power, Teollisuuden Voima Oy (TVO), Fortum, Skellefteå Kraft, Karlstads Energi and the Swedish Radiation Safety Authority.

Reported here are the results and conclusions from a project in a research program run by Energiforsk. The author / authors are responsible for the content and publication which does not mean that Energiforsk has taken a position.

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Sammanfattning

Syftet med denna studie är att identifiera och sammanställa information avseende befintliga acceptanskriterier som utlöser underhållsåtgärder av armerade betongkonstruktioner på kärntekniska anläggningar. Denna studie fokuserar på acceptanskriterier för alla aspekter av säker och pålitlig långtidsdrift, d.v.s. strukturell prestanda, beständighet och åldrande av armerade betongkonstruktioner.

Studien omfattar en litteraturgenomgång av gällande standarder och riktlinjer som används inom det betongtekniska området, erfarenhet från relevanta forskningsprojekt och egen praktisk erfarenhet samt erfarenheter från internationella tekniska kommittéer rörande alla aspekter av betongtekniska frågor.

För att kunna bedöma effekterna av åldersrelaterad degradering av armerade betongkonstruktioner måste det utföras en bedömning av betongkonstruktionernas strukturella status. Detta omfattar okulära besiktningar, mer detaljerade inspektioner och analysmetoder.

Studien visar att en betydande del av bedömningen av tillståndet hos en betongkonstruktion är begränsad till användning av okulära besiktningar. Eftersom en okulär inspektion är subjektiv, och bedömningen till stor del är kvalitativ, har stor ansträngning lagts ned på att utveckla acceptanskriterier för kvalitativ bedömning av armerade betongkonstruktioner. Detta har resulterat i omfattande beskrivningar av skador och defekter, inklusive bildbaserade/illustrerade riktlinjer.

Användandet av mer detaljerade inspektioner är i hög grad beroende av inspektörens erfarenhet och kvalifikation, och är av kvalitativ natur. Det finns inga övergripande riktlinjer med tillhörande procedurer för att specificera behovet av förstörande och icke-förstörande testmetoder. Dessutom finns det inga riktlinjer för hur resultaten av både förstörande och icke-förstörande undersökningar ska tolkas.

Betongens beständighet beror på dess beståndsdelar, dess kvalitet, konstruktionens placering och miljömässiga belastningsförhållanden. Detta gör att betongens beständighet måste utvärderas separat för varje konstruktion och t.o.m. för olika strukturella delar av samma konstruktion. Av denna anledning är det dagens expertis och kunskapsnivå som ligger till grund för bedömningen av en betongkonstruktions beständighet. Det går därför inte att fastställa allmänna acceptanskriterier för betongkonstruktioner som täcker in alla nivåer av en tillståndsbedömning.

Denna studie innehåller även en lista över forsknings- och utvecklingsbehov.

Summary

The aim of this preliminary study is to identify and compile information regarding existing acceptance criteria that trigger maintenance actions of reinforced concrete infrastructure of nuclear facilities. This study focuses on the acceptance criteria for all aspects of safe and reliable long-term operation, i.e. structural performance, durability and ageing of reinforced concrete structures.

The study covers a literature review of current standards and guidelines used in several fields of civil engineering concrete infrastructure, experience gained from relevant research projects and own practical experience, and shared expertise from international technical committees addressing all aspects of concrete structures.

In order to assess the effects of age-related deterioration of reinforced concrete structures, structural condition assessment of concrete structures must be performed. This includes visual inspections, special inspections and analytical methods.

The study reveals that a significant proportion of condition assessment is limited to the use of visual inspection. Since inspection based on observation is subjective, and the assessment is in great part qualitative, a lot of effort has been put into developing acceptance criteria for the assessment of reinforced concrete structures. This has resulted in extensive descriptions of condition damage and defects, including image/pictorial guides.

The use of special inspection is strongly dependant on the experience and qualification of the structural inspector, and is qualitative in nature. There are no comprehensive guides with procedures to specify the need for destructive and non-destructive testing methods. Furthermore, there are no guidelines how to interpret the results of both destructive and non-destructive tests.

Concrete durability performance is a function of its constituents, its quality, its location and environmental loading conditions. This makes concrete durability a unique evaluation for every structure, and even for the same structure for different structural elements. For this reason, it is based on nowadays expertise and knowledge level, and it is not possible to generalise acceptance criteria for all levels of condition assessment, and for all structures.

This study also includes a list of R&D needs.

Acknowledgment

The authors of this report would like to acknowledge the special contribution of Manouchehr Hassanzadeh (Sweco AB.), for providing relevant support material, generating pertinent discussions, and for the review of this report.

Abbreviations

AAR – alkali aggregate reaction

ACI – American Concrete Institute

BMS – bridge management systems

BWR – boiling water reactor

CC – condition class

DEF – delayed ettringite formation

IAEA – International Atomic Energy Agency

ISI – in-service inspection

KTA – German Nuclear Safety Standards Commission

LOCA – loss-of-coolant accident

LTO – long term operation

LWR – light water reactor

NDE – non-destructive evaluation

NPP – nuclear power plants

NRC – U.S. Nuclear Regulatory Commission

NSSS – nuclear steam supply system

OCC – overall condition class

PCCV – prestressed concrete containment vessel

PWR – pressurised water reactor

R&D – research and development

RCS – reinforced concrete structures

RIVE – radiation induced volumetric expansion

SSC – structures, systems, and components

SSM – Swedish Radiation Safety Authority

STUK – Radiation and Nuclear Safety Authority of Finland

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1 Introduction

1.1 OBJECTIVE

The aim of this preliminary study is to identify and compile information regarding existing acceptance criteria that trigger maintenance actions of reinforced concrete infrastructure of nuclear facilities, but due to the expected scarcity of information, criteria used in other concrete infrastructure related fields of civil engineering will also be considered.

This study focuses on the acceptance criteria for all aspects of safe and reliable long-term operation, i.e. structural performance, durability and ageing of reinforced concrete structures.

Furthermore, areas where further R&D (research and development) is required will be identified. The study is based mainly on literature review of current standards and guidelines used in several fields of civil engineering concrete infrastructure, experience gained from relevant research projects and own practical experience, and shared expertise from international technical committees addressing all aspects of concrete structures.

The performance of concrete is a direct consequence of the environmental loading (mechanical, physical and chemical), and the demands associated with the use of the structure. Different types of infrastructure (road bridges, tunnels, dams, nuclear power plants, etc.) are subject to varying severity of such loadings. As such, the compilation of information will not be as a function of the type of infrastructure, but the consequence of a reinforced concrete deterioration process during LTO (long-term operation).

1.2 BACKGROUND

Reinforced concrete structures (RCS) in the nuclear power plants (NPP) in Sweden and Finland have reached an age which exceeds the projected age which they were originally designed for. The main safety related concrete structures are the containments and the cooling water channels, both of which are vital to reactor safety. To ensure a stable operation and high safety acceptance criteria are needed for the assessment of concrete structures and to determine when maintenance work is needed. Currently, there are no commonly agreed acceptance criteria that trigger maintenance actions of concrete structures of NPP in the Nordic countries.

However, NPP RCS present a unique technical challenge for the development of acceptance criteria because of their large size, limited accessibility in certain locations, and the stochastic nature of past and future loads. Critical safety related NPP RCS infrastructure can be characterised by large wall thicknesses (typically >1.0 m); dense and complex reinforcement detailing; existence of penetrations or cast-in-place items; limited accessibility (i.e. due to liners or other components); severe functioning environmental conditions, and inaccessibility to RCS parts. Furthermore, both the effects of ageing and the qualitative nature of many non-destructive evaluation methods highlight the difficulty in determining

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performance characteristics (mechanical and durability) used for assessing concrete deterioration. Improved guidelines and acceptance criteria to assist the interpretation of condition assessment results, including development of performance-based degradation acceptance limits, considering the stochastic nature, are required [1].

Structures, systems, and components (SSC) have an important safety function in NPP. They play a key role in mitigating the impact of extreme environmental/ loading events such as earthquakes, winds, fire and floods on NPP safety. Moreover, the importance of SSC in accident mitigation is amplified by common-cause effects, such as ageing. Concrete ages due to changes in its properties as a result of continuous microstructural changes (e.g., cement hydration, crystallisation of amorphous constituents, and reactions between cement paste and aggregates), as well as environmental influences. Ageing leads to time-dependent changes in mechanical and durability characteristics that may impact the RCS ability to withstand various actions during their service lives from operation, the environment and accidents. Time-dependent changes in structural properties as well as challenges to the system are random in nature. Structural condition assessments supporting a decision regarding continued service or intervention is necessary.

Extending the operation period of a NPP past its initial operating license period is not expected to be limited by environmentally related deterioration of the concrete structures. However, age-related deterioration of RCS has been observed, such as [2-4]: the corrosion of steel reinforcement in water intake structures, corrosion of post-tensioning tendon wires, greater-than-anticipated loss of prestressing force, water infiltration, cracking and spalling of the containment dome concrete weathering, corrosion of concrete containment liners (interior areas as well as backside areas adjacent to concrete). In the USA, experience to ageing related deterioration shows that the most common visible manifestations are in the form of cracking/spalling/loss of material due to aggressive chemical attack [5].

The ageing management of NPP RCS relies on accurate and up to date knowledge about its condition and performance, with the main objective of ensuring that the RCS have sufficient structural margins to continue to perform in a reliable and safe manner. This requires the need to inspect and assess RCS performance, which is undertaken within the in-service inspection (ISI) programs (based on visual inspection, non-destructive evaluation (NDE) and monitoring). A secondary goal for the ageing management of NPP RCS, is to identify environmental stressors or ageing factor effects before they reach sufficient intensity to potentially degrade structural components.

1.3 STRUCTURE OF REPORT

This report is divided into four main sections. The first is the introduction where the scope of the study is defined.

In the second sections, the relationship between safety related SSC, environmental/loading conditions, and deterioration processes of reinforced concrete is established. The typical safety related SSC of NPP RCS are defined. The environmental/ loading conditions expected to occur for each SSC are identified, and related to one or several environmental/loading conditions with each safety related SSC. Deterioration processes of reinforced concrete are briefly described, and the corresponding environmental/loading conditions under which they potentially occur are identified.

The third section reviews current standards and guidelines for concrete, both nuclear related and not. Relevant research projects are highlighted. The review is conducted critically addressing the current state of acceptance criteria that trigger maintenance actions of reinforced concrete infrastructure.

The last section is dedicated to presenting final considerations of the study. This is complemented with an overview of R&D needs.

2 NPP concrete infrastructure

2.1 NPP STRUCTURES, SYSTEMS AND COMPONENTS

NPP are very complex infrastructures with many different building and functions which demand different solutions. NPPs can vary according to the technology they use (in Finland and Sweden pressurised or boiling water reactor types are used – PWR or BWR). Even between similar technology types there are differences in the design concepts resulting in some different solutions. However, it is generally possible to group typical safety related concrete structures for both PWR and BWR into several categories. Table 1 presents a description of the accessibility for visual examination of the typical safety-related concrete structures in PWR/BWR plants.

Table 1. Typical safety-related concrete structures in LWR (light water reactors) plants and their accessibility for visual examination [6].

Concrete structure	Accessibility
Primary containment	
Containment dome/roof	Internal liner/complete external
Containment foundation/basemat	Internal liner (not embedded) or top surface
Slabs and walls	Internal liner/external above grade
Containment internal structures	
Slabs and walls	Generally accessible
Reactor vessel support structure (or pedestal)	Typically lined or hard to access
Crane support structures	Generally accessible
Reactor shield wall (biological)	Typically lined
Ice condenser dividing wall (ice condenser plants)	Lined or hard to access
NSSS equipment supports/vault structures	Generally accessible
Weir and vent walls	Lined with limited access
Pool structures (reactor, fuel, condensation)	Lined with limited access
Diaphragm floor	Lined with limited access
Drywell/wetwell slabs and walls	Internal liner/partial external access
Secondary containment/Reactor buildings	
Slabs, columns, and walls	Accessible on multiple surfaces
Foundations	Top surface
Sacrificial shield wall (metallic containments)	Internal lined/external accessible
Emergency cooling water structures	
Cooling water channels	External surfaces above waterline
Water wells/pools	Limited accessibility
Turbine building	Generally accessible

Table 2. (Continuation). Typical safety-related concrete structures in LWR plants and their accessibility for visual examination [6].

Concrete structure	Accessibility
Fuel/Equipment storage pools	
Walls, slabs, and canals	Internal lined/partial external
Auxiliary building	Generally accessible
Fuel storage building	Generally accessible
Control room (or building)	Generally accessible
Diesel generator building	Generally accessible
Piping or electrical cable ducts or tunnels	Limited accessibility
Radioactive waste storage building	Generally accessible
Intake structures (including concrete water intake piping and canal embankments)	Partial internal/external above grade
Pumping stations	Internal accessible/external above grade and waterline
Plant discharge structures	Internal accessible/external above grade and waterline

2.2 ENVIRONMENTAL/LOADING CONDITIONS

Most of the NPPs in Sweden and Finland are built so that the primary containment structure is housed within the reactor building. In this way, this primary containment structure is protected directly from the aggressive Nordic environment, where winter temperature can often descend below – 20 °C. Ringhal's NPPs are the exception where the containment structure is exposed directly to the environment. All existing Nordic NPPs are located along the coast depending on sea water as a means of cooling. Another particularity of the Nordic NPPs is the use of water pools for the interim storage of spent fuel.

When designing a RCS, to ensure the fulfilment of the design service life, accurate definition of the working environmental/loading condition is required so as to define the appropriate concrete performance parameters necessary for design (structural and durability). This conditions the choice of the characteristics of the mix design and basic concrete properties.

The main exposure and loading conditions (internal and external) that can be expected to occur at NPPs are:

- E1: High/low temperature (environments where temperature is constantly at high /low values in relation to ambient temperature, or where high temperature gradients can occur);
- E2: High humidity (environments where humidity levels are constantly high, i.e. > 90 %);
- E3: Atmospheric conditions (environmental exposure to all elements of weather, such as rain, wind, freeze/thaw, sun radiation, etc.);
- E4: Submerged or in contact with sea/fresh water;
- E5: Underground (structural elements that are in contact with the ground, typically foundation structures, tunnels, etc.)
- E6: Radiation (environments where concrete is subject to a source of radiation);

- E7: Internal building conditions (environments occurring in office type buildings), or low humidity conditions;
- E8: Mechanical/Structural loading (dead weight, service load, pressure, vibration and other type of mechanical loads that are present);

Any combination of exposure environments can result in unique loading conditions for which the RCS are expected to withstand (if designed accordingly). While in theory this seems relatively straight forward, in reality the RCSs are subjected to local climatic conditions, micro climates, that can have synergetic effects on the deterioration process of concrete [7]. For example, a specific surface of a RCS beam or column subject to the atmosphere, can be loaded differently due to the existence of dominant winds/driving rain directions. The beams/column can become subject to differences in moisture content which can influence the rate of development of a specific deterioration mechanism, or influence the ingress rate of an aggressive species. For a specific scenario, common practice is to design for the most severe conditions. This ultimately can result in un-optimised design solutions, albeit a safe one.

Based on the division above, the environmental conditions expected for different SCCs are shown in Table 2. Note that, while some environmental conditions are common, others can occur periodically or as a result of unforeseen events.

All Nordic containments are also constantly under load due to the prestressing of the concrete, which is by far greater than the dead weight of the structures. The biological shield is also prestressed in some plants. This should be added

All RC structures are constantly under mechanical loading, i.e. under gravitational loading and due to the prestressing of the concrete. The latter is by far greater than the dead weight of the structures. The main purpose of the RC civil structures is to carry the dead weight of the structures and all types of service live loads. Since some of the RC structures also serve as a biological shield against radiation and as protective structures against external and internal accidental loads, they are unusually heavy. The RC containment also has to withstand high internal pressure in case of loss-of-coolant accidents (LOCA). The accidental loads are not considered in this report, since they are not related to the normal maintenance of the NPPs. Actually, it is a matter of choice if dead loads should be counted as an environmental load, since it is something that is always present in all structures.

2.3 DETERIORATION AND AGEING MECHANISMS

The ageing of structures starts immediately following construction and continues through its service life. For NPP infrastructures, it is also necessary to consider the effects of ageing up to the end of any decommissioning process.

In general, NPP RCS are subject to the same types of environmental loading as many common RCS infrastructure, with the exception of exposure to radiation. As a result of the safety requirements for radiation containment, NPP infrastructure have unique features and design solicitations. These requirements are stricter for performance and fall outside the scope of conventional RCS design codes.

Table 3. Typical exposure environment for safety-related concrete structures in LWR plants.

Concrete structure	**Environments**
Primary containment	
Containment dome/roof	E1, (E3), E7
Containment foundation/basemat	E5
Slabs and walls	E1, E7
Containment internal structures	
Slabs and walls	E1, E7
Reactor vessel support structure (or pedestal)	E1, E6, E7
Crane support structures	E1, E7
Reactor shield wall (biological)	E1, E6, E7
Ice condenser dividing wall (ice condenser plants)	E1, (E6) , E7
NSSS equipment supports/vault structures	E1, (E6), E7
Weir and vent walls	E1, E7
Pool structures (Reactor, fuel, condensation)	E1, E4, E7
Diaphragm floor	E1 , E7
Drywell/wetwell slabs and walls	E1, , E7
Secondary containment/Reactor buildings	
Slabs, columns, and walls	E3, E5
Foundation	E4, E5, E7
Fuel/Equipment storage pools	
Walls, slabs, and canals	E1, E2, E4, E5
Auxiliary building	E3, E7
Fuel storage building	E3, (E2), E6, E7
Control room (or building)	E7
Diesel generator building	E1, E3, E7
Piping or electrical cable ducts or tunnels	E1, E2, E7
Radioactive waste storage building	E2, E6, E7
Intake structures (including concrete water intake piping and canal embankments)	E1, E3, E4, E5
Pumping stations	E2, E3, E7
Plant discharge structures	E1, E3, E4, E5
Emergency cooling water structures	
Cooling water channels	E3, E4, E5
Water wells/pools	E3, E4, E5
Turbine building	E2, E3, E7

Concrete is a strong and durable building material. However, RCS are affected by a number of factors that can cause deterioration, which can result in reduction of its performance and unsafe conditions. As the RCS are structurally designed with a high safety factor, the common causes of deterioration are typically due to environmental conditions other than mechanical loading or it is directly linked with errors in the construction phase.

Table 4. Causes of concrete/reinforced concrete deterioration as a function of the exposure environment.

Mechanism/Environments	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**
Chemical & biological								
Aggressive water			●	●	●			
Acid attack (Boric acid *)		(●)	●	●	●		(●)†	
Leaching		(●)	●	●	●			
Alkali aggregate reaction (AAR)		●	●	●	●			
Carbonation		●	●				●†	
Chloride ingress			●	●††	●			
Sulphate and thaumasite			●	●	●			
Bacterial		(●)	●	●	●		(●)†	
Physical								
Freeze-thaw	(●)		●	(●)	(●)			
Elevated and high temperature	●					●		
Shrinkage (dry/plastic)	●					(●)	●	
Mechanical /Structural								
Abrasion/Erosion			●	●	(●)		(●)†	
Cavitation				●				
Creep and relaxation	(●)							●
Fatigue								●
Settlements and movements								●
Vibration (and seismic)								●
Thermal stresses	●					(●)		
Radiation *								
Radiolysis (in concrete)						●		
Radiation induced volumetric expansion (RIVE)						●		
Mechanical property change						●		
Corrosion (embedded metals, liners, etc.)								
Chloride ions - pitting		●	●	●††	●			
Carbonation - general			●				●†	
Other corrosion mechanisms	(●)	●	●	●	●			

* Unique to NPP concrete; (●) Possible indirect occurrence; ●† Internal building conditions; ●†† Does not occur in contact with fresh water.

Concrete deterioration typically occurs when the material is exposed to atmospheric conditions, water or chemicals over an extended period of time. In general, concrete can deteriorate for a variety of reasons, and often damage results due to a combination of factors. The main deterioration mechanisms of RCS may be divided into those affecting the concrete and those affecting the reinforcing steel materials (i.e., steel reinforcement or post-tensioning system).

The RCS are structurally designed with a high safety factor and in normal operating conditions the structural loading alone is not any major issue. In fact, the structural stiffness of the massive RCS only increases in time due to hydration. However, the drying shrinkage and creep in concrete are long-term effects which, in addition to the structural loading, will result in displacements and possible cracking. One type of cyclic mechanical load in normal operation is caused by the vibration of pipelines that are anchored to the surrounding civil structures.

In many NPP types, the containment wall is post-tensioned with high-strength steel tendons This kind of structure is at present mainly called as prestressed concrete containment vessel (PCCV). In PCCV, the concrete is in compression which enhances creep. High temperature due to the operation of the reactor enhances creep. Near the anchors, also high shear forces are present, which demands careful design of reinforcement. Furthermore, the tendons undergo prestress losses in time, which decreases the compression in concrete and lead to deformations of the structure. The behaviour of PCCV is complex and the state of the structure is slowly but constantly changing. Together with environmental loadings such as temperature and moisture gradients through the thick walls, this can lead to different deterioration mechanisms of the concrete material.

The deterioration of concrete can be caused by changes to the cement-paste matrix or aggregates under chemical or physical attack. Deterioration by chemical attack may occur due to: leaching, sulphate attack, acid/base attack, salt crystallization, alkali-aggregate reactions, among others. Deterioration by physical attack may include freeze/thaw cycling, thermal exposure/thermal cycling and abrasion due to mechanical attack [8]. A quick glance at Table 3 reveals that the majority of the chemical, biological and corrosion related problems of concrete are connected to the presence of water.

The deterioration of steel reinforcement due to electrochemical attack can occur due to the carbonation of the concrete cover layer, or due to the ingress of chlorides. Post-tensioning systems are susceptible to the same degradation mechanisms as mild steel reinforcement, plus loss of prestressing force, primarily due to tendon relaxation and concrete creep and shrinkage [8].

3 Review of acceptance criteria

Acceptance criteria in the context of this report are defined as an objective description of a specific deterioration or an anomaly for RCS. Inspection requirements vary according to the nature of the inspection. For visual inspections they are generally qualitative, and for special inspections using NDE and other testing means, they are generally quantitative. This report cover also the extrapolation of inspection results to assess future performance, based on models and service life engineering tools. This report does not cover the structural stability re-evaluation or re-design of deteriorated SCCs.

The review of assessment criteria is based on a literature review of current design codes, standards and guidelines. Both nuclear and non-nuclear documents are reviewed. It is not possible to be comprehensive in the review within the framework of this project, but focus has been on covering civil infrastructure other than nuclear, and looking at some of the current R&D in this field.

3.1 EUROPEAN STANDARDS FOR CONCRETE DESIGN

The design of RCS is covered by the Eurocodes, and supported by many additional standards/guidelines for concrete. The durability design of concrete is covered in several standards. In the Eurocode 0: Basis of structural design [9], indicative design working lives for design purposes for various types of structures are presented. In the Eurocode 2: Design of concrete structures - Part 2 [10], durability design concerning the determination of the exposure conditions and the required concrete quality and the concrete cover to the reinforcement are presented. More specific concrete material aspects are presented in the SFS EN 206 [11] where environmental exposure classes are described in more detail and prescriptive requirements for durability are presented as a function of these. The requirements given are for maximum water/cement ratio, minimum strength class, minimum cement content and minimum air content. The presented values are based on the assumption of an intended design service life of 50 years. The SFS EN 13670 [12] deals with concrete durability with regards to execution and curing practices. Finally, European standards also specify documents for the repair/rehabilitation of concrete (SFS EN 1504 standard series, for Products and Systems for Concrete Protection and Repair [13]), which state in part 9 that any repair should be preceded by condition assessment. However, there are no standards for the inspections and condition assessment.

Many European countries, in addition to the proposed prescriptive values (i.e., EN 206), present their National Annexes recommending limiting values for composition and properties of concrete, with requirements in accordance with the specific conditions of the country. In Finland, these are presented in the SFS 7002 [14], and in Sweden in the SS 137003 [15]. Attempts are made to improve the guidance for designers by providing more specific rules on the use of alternative binders and longer service life until 100 years. While these National documents improve the durability of the concrete, they are still prescriptive in nature and therefore cannot ultimately guarantee the expected design service life. The Finnish National Annex for the SFS-EN 13670 is the SFS 5975 [16].

In the Eurocode 2, the consequences of deformation due to temperature, creep and shrinkage shall be considered in design. The strength of the anchorage devices and zones shall be sufficient for the transfer of the tendon force to the concrete and the formation of cracks in the anchorage zone shall not impair the function of the anchorage. Cracks may be permitted to form without any attempt to control their width, provided they do not impair the functioning of the structure. A limiting calculated crack width, w_{max}, taking into account the proposed function and nature of the structure and the costs of limiting cracking, should be established. The recommended surface crack width values vary between 0.2 mm and 0.4 mm depending on the structural member and its exposure.

Additional limit states of cracking to the basic design are given. In the DD ENV 1992-1-5 [17] for structures with unbonded and external prestressing tendons. In the DD ENV 1992-4 [18], liquid retaining structures are classified based on the requirements for leakage. If leakage is not permitted, cracks which may be expected to pass through the full thickness of the section should be avoided.

Summary: European CEN standards are prescriptive with regard to durability. This means no specific criteria are used for durability design, and therefore it is not possible to use these standards for assessing deterioration. Structural design codes state extensive cracking as a serviceability limit state. Cracking shall be limited to an extent that will not impair the proper functioning or durability of the structure. The recommended limiting surface crack width values vary between 0.2 mm and 0.4 mm depending on the structural member and its exposure. Furthermore, there are no standards covering the inspection of RCS. *R&D needs:* Standardized approach to RCS inspection. Specification of performance based parameters for concrete durability, and definition of performance criteria for structural assessment.

3.2 NON-NUCLEAR RELATED DESIGN CODES

3.2.1 Swedish concrete standards and durability guidelines

The Eurocode 2 is the current standard in Sweden concerning concrete structures and replaced the previous Swedish handbook BBK 04 [19]. European regulation has been applied in Sweden since 2009 for bridges and 2010/11 for buildings concerning concrete and concrete structures. Relevant standards are referred to, in particular the standards SS-EN 206-1 (concrete), SS-EN 197-1 (cement), EN 12620 (aggregates) and Eurocodes. In addition, national application documents are published, among which the most important are the SS 137003 connected to EN 206, and the SS 137010 [20] about cover thickness. The SS 137003: 2015 defines concrete compositions allowed for different exposure classes, and the new concept of equivalent performance of the binder combinations. In addition, it has introduced classes for the characterization of the concrete environment with regard to the impact on the risk of alkali silica reactions. The limit for surface crack width which is sensitive for corrosion is 0.1 mm [21].

The Betongrapport 12:2007 - Guidance for service life design of concrete structures [22] is a guideline for the service life design. The report presents the principles for service life design, models for the most common degradation processes of reinforcement corrosion (carbonation and chlorides) and frost attack, and the environmental loading of RCS. In addition, practical guidelines and examples are presented for reinforcement corrosion.

As a tool for estimating the performance of RCS with time when subject to a specific deterioration mechanism, criteria for assessing the performance are defined and linked to the definition of "durability" limit states. Assessment of the limit state is done using a semi-probabilistic approach (partial safety factors), and durability performance parameter values are suggested taking into account the most common cement/concrete types used and the typical environmental loading conditions occurring in Sweden.

The limit states defined are: the initiation of corrosion due to carbonation of concrete (relationship between the depth of the reinforcement and the depth of the carbonation front, as a function of time); the initiation of corrosion due to chloride ingress of concrete (relationship between the depth of the reinforcement and the depth of the critical chloride concentration front, as a function of time); and, freeze-thaw attack without deicing slats (relationship between the critical degree of saturation and the actual degree of saturation, as a function of time).

Summary: The Swedish concrete codes follow closely European standards, with the addition of the National Annex to the SS EN 206-1 which presents prescriptive requirements for durability design. Furthermore, the approach for durability service life calculation of the Betongrapport n.12 clearly specifies the criteria for assessing deterioration leading to reinforcement corrosion, including durability indicator for concrete performance. *R&D needs:* Standardized approach to RCS inspection. Specification of performance based parameters for concrete durability (other than for corrosion initiation).

3.2.2 Swedish Transport Administration - Bridge and Tunnel Management System

The purpose of Bridge and Tunnel Management System (BMS) is to combine management, engineering and economic input in order to determine the best actions to take on a network of bridges over time. At the heart of the BMS is a database derived from the field inspections. The integrity of a BMS is directly related to the quality and accuracy of the bridge inventory and physical condition data obtained through field inspections [23].

The main purpose of the bridge inspections is to establish the physical and functional conditions of bridge individual structural elements and consequently the entire bridge. The physical condition is determined with reference to the development of previous or new damage and certain known deterioration processes. The functional condition is described by the bridge inspector in terms of condition class (CC). The CC describes to what extent a certain structural member satisfies the designed functional properties and requirements at the time of inspection. In contrast to other BMSs, The Swedish BMS does not contain deterioration models. The assessment of the condition classes is composed on previous and current measured values (the physical condition) and the inspector's judgement in the propagation of different deterioration processes. The CC for a structural member can be registered on a scale of four (0-3). Using this CC system, the functional conditions of the structural members will automatically be translated to numerical numbers that can easily be used in the LCC analysis. The overall condition class (OCC) is also used in the BMS, where it reflects the function of the entire structure with respect to the bearing capacity, traffic safety and durability. The OCC for a bridge is determined by the assigned CC for the different structural members. The assigned condition classes are given different weights [23].

Part of the development of the Swedish BMS was undertaken within the Nordic joint project ETSI [24], whose objective to develop a unified, reliable and usable Nordic methodology and an Internet-based computer tool for bridge life-cycle optimization.

Summary: The condition of RCS is based on the visual assessment of deterioration and the estimated development of the deterioration with time. The system does not contain material performance models that take into account the unique combination of material characteristic/environmental loading. The approach specified relies on the competence of the inspectors.

3.2.3 Finnish concrete standards/guides

The Finnish Concrete Code *by50* [25] includes instructions concerning concrete in the Part B4 of the Building Code of Finland, and normative parts of standard SFS-EN 206 and its National Annex (SFS 7002). The SFS 7002 provides additional Finnish instructions relating to the frost resistance of concrete and design of the working life of concrete structures up to an intended life of 200 years.

There are three limit states of cracking for structures: limit state of tensile stress, at which no tensile stresses may occur; limit state of crack formation, at which the cracking capacity of the structure is reached; and, limit state of crack width, at which the characteristic crack width may not exceed the specified limits.

The SFS 7002 present performance based requirements for freeze-thaw loading conditions. These are the RDM (relative dynamic modulus, %) and the scaling (g/m^2). No performance values are provided for carbonation or chloride ingress.

The *by50* presents in Appendix 4 (Design by calculation of the working life of concrete structures) a model for durability design based on the factor method described in the ISO 15686-1:2011 [26]. The assessment and evaluation of service life is based on the identification of the main factors influencing service life. The determination is semi-probabilistic because a safety factor for the design service life is used. The method has been developed as simple as possible for a practical designer still maintaining the theoretical background. In the *by50* method the active corrosion time is not included in the service life evaluation. Durability design is performed for the initiation time of corrosion (for carbonation), and for freeze-thaw performance based on the P-factor method [27]. The P-Factor method result from extensive laboratory and in situ testing, and is based on the composition and quality of the concrete and the environmental exposure.

Summary: Finnish concrete codes follow closely European standards, with the addition of the National Annex to the SFS EN 206-1 which presents prescriptive requirements for durability design, and specific performance-based criteria for freeze-thaw deterioration. Furthermore, the approach for durability service life calculation of the *by50*, while not directly specifying performance indicators of concrete, uses indirect limit state criteria in the form of depth of carbonation and depth of critical chloride front with regards to corrosion of reinforcement. *R&D needs:* Standardized approach to RCS inspection. Specification of performance based parameters for concrete durability, and definition of performance criteria for structural assessment.

3.2.4 Finnish Transport Agency – Bridge Management System

The repair and reconstruction programmes are the central concept of the Project Level Bridge Management Systems (BMS). The programmes are produced for a period of six years using condition indexes to determine the bridges in need of repair or reconstruction. The quality of this information is directly related to the amount of data in the BMS. It is therefore of major importance to carry out inspections at regular intervals and to document them carefully and in an appropriate manner [28].

The condition indicator must be stable and robust, well describing the structure condition but it must also be predictable. Condition predictions and efficiency analyses are needed for example, when combining repair and reconstruction needs in an annual work programme. Well qualified inspection and well-chosen condition indicator also serve and help to reach the policy targets.

The inspections and repair actions follow guidelines and handbooks to ensure as homogeneous and good quality output as possible. The damage severity and a structural part’s estimated condition are classified on a scale from 0 (no damage) to 4 (serious damage). The Finnish Bridge Inspection Manual [29] recommends repair measures for each damage class and each type of structure. The inspectors give their judgment to a repair measure recommendation regarding the observed damage on an individual bridge. Every repair measure recommendation is saved in the database together with its expected cost.

The BMS uses deterioration models based on the time dependant behaviour for individual bridges and developed using the information from the network level models and from investigations and inspection data from a group of 120 reference bridges. The models are implemented together with a life cycle cost-analysis. The BMS has a unique inspection process that tracks material defects in addition to elements. Each defect is classified by element, sub-element, and material. Each defect also has a location, which may consist of one or more spans longitudinally, and one or more positions laterally. The quantity and condition state of each defect is noted in each inspection and can be tracked over time [29].

The economic planning and maintaining of the national capital invested in engineering structures is also important. Hence, the inspection is an element of a well-organized engineering structure management system, which can be truly helpful for maintenance and repair work planning. For example, the system gives information about how to use resources optimally so that the desired condition level is reached with minimum costs.

Summary: The condition assessment of RCS is based on the visual assessment criteria and the development of the deterioration with time. No quantitative criteria are specified. The BMS relies on simple material performance models to estimate future development of deterioration mechanism. The approach depends heavily on the quality of the inspection.

3.2.5 German concrete standards/guides

The design codes and quality assurance procedures during construction are the basis to interpret the monitoring and inspection outcomes. On the other hand, inspection data are gathered and categorized systematically in Germany and the data banks are another source for interpretations. Interpretations in turn are the basis for the maintenance strategies. The standard DIN 1076 [30] is the basis for inspections of engineering structures.

Hydraulic construction. The framework of standards for construction of hydraulic structures in Germany and the relation of the complementary technical conditions for contracts Zusätzliche Technische Vertragsbedingungen und Richtlinien - Wasserbau (ZTV-W LB215), Wasserbauwerke aus Beton und Stahlbeton [31]. This standard is based on the European standards for concrete, and is prescriptive in the design approach. It includes mandatory supplementary regulations that need to be applied for the design and construction of public massive hydraulic structures. The design service life of these structures is expected to be 100 years. The standard provides acceptance criteria for the dimensional accuracy of the concrete surfaces, the concrete cover and the quality of the concrete. Depending on the demand classification of the structure, compressive strength, splitting tensile strength, water permeability, and frost resistance of the hardened concrete need to be tested. As an acceptance criterion at the initial inspection after construction, the cover thickness of the reinforcement must not differ more than 20 mm from the design cover depth. If the deviations exceed the limits, repair measures can be requested.

Maintenance inspections of road structures. The inspections for maintenance of road construction, in particular those for bridges, are conducted in accordance with DIN 1076 comprising regular studies and steering. Through systematic data collection, regulated by RI-EBW-PRÜF (Richtlinie zur einheitlichen Erfassung, Bewertung, Aufzeichnung und Auswertung von Ergebnissen der Bauwerksprüfung nach DIN 1076', 2007-11) [32], the understanding of damages develops accordingly. Documentation is based on ASB-ING ('Anweisung Straßeninformationsbank-

Teilsystem Bauwerksdaten', 2008-03) [33]. Tests on structures are divided to principal tests (each sixth year), simple tests (each third year after the principal tests) and tests for particular reasons.

According to RI-EBW-PRÜF, damages and deficiencies are categorized in the framework that includes structural safety, traffic safety and durability (S/V/D) and assessed to levels 0-4. The descriptions for each category and level are presented in RI-EBW-PRÜF. The assessment relies on the damage cases presented in the Appendix of RI-EBW-PRÜF. The cases include typical observations and tests aiming to detect early warnings of risks for serviceability and safety. The assessment according to structural and traffic safety takes into account the actual situation and long-term impacts of damages. Quantitative acceptance criteria are not given, but a catalogue with practical examples provides advice. Recommendations for actions need to be provided as a result of the inspection. They cover stability, serviceability and durability. Dependent on the severity of the damage, actions are either mandatory or non-binding.

Summary: In German standards for engineering structures, there are only few quantitative acceptance criteria given. Mostly, only conditions that are limiting the structural stability trigger action for repair or replacement. Deviations in serviceability and durability lead to recommendations, but not to binding measures. The German regulation relies on the contractual agreements between owner and contractor. Any deviations from the performance defined under the contract need to be agreed or declined at the initial acceptance of the construction work, or can be claimed during the warranty period. The German legislator does not provide distinct values or quantitative criteria.

3.2.6 American Concrete Institute

Condition assessment of reinforced concrete structures and service life prediction is addressed in several documents published by the American Concrete Institute (ACI). A brief overview of the most relevant document is given, focusing mainly on the ACI 349.3R-02 [34] and ACI 365.1R-00 [35].

• ACI 349.3R-02 (reapproved 2010), *Evaluation of Existing Nuclear Safety-Related Concrete Structures*, is a report that provides guidelines for the evaluation of existing nuclear safety-related concrete structures. Methods of examination including visual inspections and testing techniques, and their applications are cited. This document comprehensively addresses all safety-related parts of a NPP and provides details regarding the criteria for the evaluation of the structure. Focus is on commonly occurring deterioration conditions. These criteria mainly address the classification and treatment of visual inspection results, because this technique will have the greatest usage. The following three-level acceptance criteria have been developed. The level approach was adopted to allow simple and expeditious treatment of minor discontinuities, and to provide guidelines for further evaluation of more significant degradation.

Level 1- Acceptance without further evaluation - The result from a visual inspection or condition survey are considered acceptable without requiring any further evaluation. Criteria are given in five categories: i) concrete surfaces; ii) concrete surfaces lined with metal or plastic; iii) areas around embedments in concrete; iv) joints, coatings, and nonstructural components; and, v) prestressing-steel systems.

Level 2 - Acceptance after review - The result from a visual inspection or condition survey require review and interpretation by the inspection team in order to judge their acceptability. This involves determining the likely source, the activity level, and the net effect on the afflicted structure. If the cause and degree of damage is considered to be acceptable, possible treatment include: acceptance as-is, further evaluation with enhanced visual inspection, testing, and repair. The review should analytically examine the impact of existing deterioration on the performance characteristics. Also, the potential for propagation should be considered in the treatment selected. Criteria are given in the same five categories as in Level 1.

Level 3 – Condition requiring further evaluation - Any condition observed outside of the acceptance criteria of Levels 1 and 2 requires an evaluation to determine the appropriate treatment for the affected structure. This likely requires an enhanced employment of NDE and destructive testing and analytical methods to define the ability of the damaged structure to fulfil structural and other functional performance requirements. If the condition is found to be acceptable, future performance should be examined.

As an example of acceptance criteria for concrete surface - Level 1: Absence of leaching and chemical attack; Popouts and voids less than 20 mm in diameter or equivalent surface area; and for Level 2: Appearance of leaching and chemical attack; Popouts and voids less than 50 mm in diameter or equivalent surface area.

• ACI 365.1R-00, *Service-Life Prediction – State-of-the-Art Report*, provides a review of the state of the art of service life prediction theory and practice for concrete structures. The document presents a detailed review of service life criteria, factors that affect service life, condition assessment techniques, economic considerations, and service-life prediction models and methods. The latter is of interest, especially when attempting to determine the future performance of deteriorating concrete. Several approaches to predicting service-life of new (and existing) structures is given. Predictions methods based on experience, comparison of performance, accelerated testing, mathematical models and stochastic models are given.

• ACI 201.1R-08 [36], *Guide for Conducting a Visual Inspection of Concrete in Service*, this report provides terminology to perform and report on the visual condition of concrete in service.

• ACI 201.2R-08 [37], *Guide to Durable Concrete*, elaborates on factors related to durability of concrete. This document describes various deterioration mechanisms and various factors influencing durability. Consideration should be given to the climate and particularly microclimate to which the specific structural element is exposed.

• ACI 224.1R-07 [38], *Causes, Evaluation, and Repair of Cracks in Concrete Structures*, this report summarizes the causes of cracks in concrete structures. The procedures used to evaluate cracking in concrete and the principal techniques for the repair of cracks are presented.

• ACI 228.2R-98 [39], *Non-destructive Test Methods for Evaluation of Concrete in Structures*, this report provides detailed discussions of most non-destructive test methods that can be used for evaluating concrete conditions for both new and mature concrete.

• ACI 318-11 [40], *Building Code Requirements for Structural Concrete and Commentary*, is a 'code' level document that covers the materials, design, and construction of structural concrete used in buildings and other structures.

• ACI 349-06 [41], *Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary*, is a 'code' level document that covers the materials, design, and construction of structural concrete used in Safety-Related structures.

• ACI 364.1R-07 [42], *Guide for Evaluation of Concrete Structures before Rehabilitation,* this report presents general procedures for evaluation of concrete structures before rehabilitation.

• ACI 369R-11 [43], *Guide for Seismic Rehabilitation of Existing Concrete Frame Buildings and Commentary*, describes methods for estimating the seismic performance of both existing and new concrete components in an existing building.

• ACI 437R-03 [44], *Strength Evaluation of Existing Concrete Buildings*, is a report that includes recommendations to establish the loads that can be sustained safely by the structural elements of an existing concrete building. The report covers conventionally reinforced cast-in-place concrete, precast-prestressed concrete, and post-tensioned concrete.

• ACI 437-12 [45], *Code Requirements for Load Testing of Existing Concrete Structures*, The purpose of this Code is to establish the minimum requirements for the test load magnitudes, load test procedures, and acceptance criteria applied to existing concrete structures as part of an evaluation of safety and serviceability.

Summary: ACI present a comprehensive array of documents related to the condition assessment and testing of concrete, in particular ACI 349.3R-02 that provides guidelines for the evaluation of existing nuclear safety-related concrete structures. Methods of examination including visual inspections and testing techniques, and their applications are cited. This document comprehensively addresses all safety-related portions of a NPP and provides details regarding the criteria for the evaluation of the structure. Focus is on commonly occurring deterioration conditions. These criteria mainly address the classification and treatment of visual inspection results. *R&D needs*: Changes are needed to make these guides more specific to the environments and conditions expected to be encountered for nuclear facilities. These include heat, radiation, and potentially limited access to exposed surfaces. End-of-service criteria for nuclear structures should be established in terms of the types of attack that have more influence on their deterioration. Prediction models, whether physics-based or empirical, require onsite measurements at different ages for model parameters to be updated with respect to the current condition of the structure [46].

3.2.7 FIB - International Concrete Federation

The Model Code for Service Life Design (2006) [47] introduced the probabilistic approach to service life design. Use of such a model requires that it must be sufficiently validated in order to provide realistic and representative results. The parameters can be defined by probability distribution functions with uncertainties being measurable by tests, observations and experience. Even the uncertainties associated with the model and the tests used should be considered [48]. Conformity is checked by verifying that the specified reliability (i.e., reliability index or probability of limit state failure), defined by codes or the owner of the infrastructure, is not exceeded in the verification of the limit state function over the service life of the structure. The code presents conceptually defined limit state equations for deterioration mechanism, acknowledged that more research is needed to bring these models to the same level as those presented for corrosion. In fact, only the models with regards to corrosion initiation of reinforcement have developed limit state functions. The code present recommended values for the durability indicators to be used, and functions for the characterization of the environmental loading of the structures.

The limit state functions defined in the code are (for uncracked concrete): the initiation of corrosion due to carbonation of concrete (relationship between the depth of the reinforcement and the depth of the carbonation front, as a function of time); the initiation of corrosion due to chloride ingress of concrete (relationship between the depth of the reinforcement and the depth of the critical chloride concentration front, as a function of time) - A single value is recommended for the critical chloride content, independent of cement type, concrete quality and exposure conditions: 0.6 wt.-%/cement.

The *fib* Model Code 2010 [49] presents a new and comprehensive approach to concrete durability, supplying design equations for the most common deterioration mechanism. This code has implemented the framework developed in the Model Code for Service Life Design (2006) [47].

Summary: Performance criteria are defined for the initiation phase of the corrosion process for both carbonation (depth of carbonation) and chloride ingress (depth of critical chloride front). Durability indicators are provided as guidance. The models have certain parameters that are very sensitive and can dominate the outcome of a service life calculation. *R&D needs*: Comprehensive review of performance parameters and time dependency effects. Realistic environmental conditions (effect of cold winters), and consequences of coupled deterioration should be addressed.

3.3 NUCLEAR RELATED DESIGN CODES & GUIDES

3.3.1 Swedish Radiation Safety Authority

The Swedish Radiation Safety Authority (SSM) publishes both regulation and research documents to be applied to construction, operation, maintaining and decommissioning of nuclear power plants. For design of concrete structures, Boverkets konstruktionsregler (BKR) were applied until 2011. For conventional application areas, Eurocodes are followed nowadays. General rules for design of buildings in nuclear power plants are presented in the industrial standard DRB:2001 (industristandarden Dimensioneringsregler för byggnader vid kärntekniska anläggningar) [50]. In addition, SSM has given rules for design of structures. The SSM rules and guidelines on safety in NPPs states that building structures, components and systems and related installations with relevance to safety need to be inspected regularly in accordance with a programme that clearly identifies all such building parts. In assessment of inspection results, experiences from similar facilities may be used. The publication refers also to IAEA's safety standard on maintenance, control and testing of NPP facilities.

Review of design basis is on regulatory body's (SSM) responsibility in SC1, SC2 and SC3 (and SC4/NNS). Reviews of the detailed component design documentation are delegated to IOs. SSM inspects commissioning tests of components/steel structures after major plant modifications in SC1 and SC2, IO in SC3. In minor component replacements or modifications IO supervises manufacturing, installation and commissioning of pressure equipment, components and steel structures in SC1, SC2 and SC3. (See a special section dealing with the Swedish situation.)

A brief overview of the most relevant document SSM reports is given:

• 2010:37 *Utvärdering av regler och normer för betongkonstruktioner i svenska kärnkraftsanläggningar* [51]. This report is the final delivery to the Swedish Radiation Safety Authority (SSM) for the work undertaken within the Commission, "Evaluation of rules and standards for concrete structures in Swedish nuclear power plants". The relevant codes, standards, guidelines etc. for load-bearing concrete structures in different countries are compared and evaluated.

• 2014:31 *Degradering i betong och armering med avseende på bestrålning och korrosion* [52]. This is a literature review on radiation induced degradation in concrete and especially its effect on the strength of concrete. The acceptance criteria are not directly considered here.

• 2015:24 *Dimensionering av nukleära byggnadskonstruktioner (DNB)* [53]. This Design Guide reports design rules for concrete structures at nuclear power plants in Sweden. The scope of DNB includes instructions regarding design and analysis of loadbearing concrete structures covering reactor containments as well as other safety-related structures. According to this report, the acceptance criteria are mainly based on Eurocodes such as SS-EN 1992-1-1, but complementary criteria are based on other codes such as ASME Sect III Div 2. The design rules for the concrete structure of the containment imply that verification for effects of actions or other effects in many cases must be carried out according to both the Eurocodes and ASME Sect III Div 2. In this situation the regulation that prescribes the most conservative design solution is used. Leak-tightness requirements for the containment follow, for all limit states, the provisions given in ASME Sect III Div 2. The Eurocodes have no applicable provisions for this requirement. For highly improbable design situations additional acceptance criteria have been introduced. The acceptance criteria used shall be consistent with the analytical model and the evaluation methods, as well as the result that are used. All possible failure modes should be identified and evaluated. This replaces the first edition that was issued by SSM in January 2014 (Report No. 2014:06). There is also an English version document (Report No. 2015:25).

• 2015:28 Utvärdering av materialdata för befintliga betongkonstruktioner - med inriktning på verifiering av förankringar vid kärntekniska anläggningar [54]. This report provides an overview of various factors which are important to consider in testing and evaluation of concrete strength parameters. Standards for testing and evaluation considering in-situ testing of concrete structures are available and should be considered. The acceptance criteria are not directly considered here.

• 2015:44 *Krav på funktion, konstruktion och provning av reaktorinneslutningar* [55]. The purpose of this report is to highlight the important reactor containment issues for existing plants as well as for new construction. The report addresses reactor containments in light water reactors (BWRs as well as PWRs). Focus is also on concrete reactor containments with an internal steel liner, especially prestressed structures. One chapter deals with the design of reactor containments. Regarding acceptance criteria, other SSM reports such as 2014:06 are being referred to. Another chapter deals with testing, mainly monitoring. The acceptance criteria regarding the leakage test are considered in more detail.

• 2015:50 *Bedömning av degraderade betongkonstruktioner - Assessment of structures subject to concrete pathologies (ASCET)* [56]. The ASCET (Assessment of Nuclear Structures Subject to Concrete Pathologies) program was initiated by the OECD/NEA/CSNI in 2013 and is an international research program targeted at degradation of concrete in nuclear facilities. The project aims to create a basis for general recommendations regarding management of ageing issues in nuclear facilities exposed to concrete pathologies (material degradation mechanisms). This report provides an overview of some of the recent research activities carried out by the independent Swedish consultancy company Scanscot Technology, related to various types of assessments of concrete structures (numerical, destructive, non-destructive). The acceptance criteria are not directly considered in this report.

• 2016:13 *Spännarmerade betongkonstruktioner vid kärntekniska anläggningar* [57]. The main purpose of this report is to, based on public information, highlight different aspects regarding function and risk factors for the prestressing system at Swedish nuclear facilities. Regulatory Guide 1.35 [58] describes guidelines for testing prestressed structures including acceptance criteria and procedures in case the criteria are not met. ASME Section III, Division 2 [59] describes complete criteria for inspections. The Standard Regulatory Guide 1.35.1 [60] complements 1.35.

Summary: Until 2010, the National Swedish Building Code (BKR, BBK) has been applied for the design and analysis of civil structures. In 2011, the National Swedish Building Code was replaced by the European Building Code, Eurocodes. To ensure that the reactor containment function in the event of an accident is not compromised or that its operational life time is not significantly reduced due to normal operation events, additional requirements are provided for the reactor containment based on ASME Sect III Div 2. The design with respect to seismic actions is primarily based on ASCE 4-98. The SSM documents mainly refer to the above mentioned codes and standards.

3.3.2 Radiation and Nuclear Safety Authority of Finland

The Radiation and Nuclear Safety Authority of Finland (STUK) publishes regulatory guides describing the requirements for the safe use of radiation and nuclear energy. The regulatory guide most closely related to concrete materials and structures is YVL E.6 Buildings and structures of a nuclear facility [61], published in 2013. It covers the control of construction and service life of the buildings and structures of nuclear facilities. More specific aging management guidance is in YVL A.8 [62] YVL E.6 sets forth requirements and instructions for the design and execution of safety-classified concrete, steel and composite structures of nuclear facilities, and for the inspections performed during operation. In addition to the requirements in YVL E.6 steel, concrete and composite structures shall also adhere to the laws, regulations, building codes and standards in force in Finland. The execution of concrete structures shall follow the requirements set forth in YVL E.6 and standard SFS-EN 13670 and its national application standard SFS 5975.

Review of design basis and commissioning inspections are on STUK's responsibility in SC1 (safety class 1), SC2 and SC3. In SC1 also other inspections and reviews are solely on STUK's responsibility.

The regulatory body STUK publishes regulations and regulatory guidelines for ensuring safety of installations and facilities of nuclear power plants. In its series 'Regulatory Guides' the Group E is dedicated for structures and equipment of a nuclear facility. The guidelines concerning concrete and steel and steel-concrete composite structures were revised in 2013 [63].

Oversight of ageing management starts from the procurement and construction phases. During operation the licensee is required to plan activities during the outages and perform periodic plant level inspections. These procedures are supported by a comprehensive ageing management plan and program. Follow-up reporting should identify long-term trends concerning critical structural ageing issues.

Summary: STUK's regulatory guides do not cover specific aspects such as the inspection and condition assessment of NPP RCS. These are mentioned within the context of ageing management plan and program.

3.3.3 German Nuclear Safety Standards Commission

The German Nuclear Safety Standards Commission (KTA) is responsible for elaborating nuclear safety standards in the realm of the public law. For the ageing management of NPPs, the KTA 1403 (2010) [64] specifies provisions for a systematic and comprehensive ageing management in NPPs. For tests and controls at NPPs, the supervisory authority of the respective Land performs on-site inspections at regular intervals, in part also with the consultation of authorised experts. Such inspections may be directed to the clarification of specific issues or be performed with the objective of a general plant walk-down. Section 4.3. explains the requirements for structures as follows:

4.3.1 Classification of structural facilities - Within the framework of ageing-management the structural facilities shall be classified as follows: a) buildings or partial buildings, b) structural systems, and c) structural components.

4.3.2 Extent of ageing-related observation and classification - Within the framework of ageing-management, all safety related structural facilities shall be taken into consideration. The classification criteria for the SSCs are the respective safety requirements specified, e.g., in the licensing documents.

4.3.3 Identification of the relevant damage mechanisms - The potential relevant damage mechanisms shall be compiled within the framework of the Basis Report (cf. Section 6) for all safety-related structural components. The relevance of these damage mechanisms shall be determined individually for each structural component part, taking the respective boundary conditions into account.

4.3.4 Determining the condition of the (safety-related) SSCs - The condition of the (safety-related) SSCs as documented during assembly shall be updated within the framework of modification measures. Whenever new relevant damage mechanisms are made known, the condition of the structural systems and component parts shall be newly established and assessed with respect to their meeting the existing safety requirements.

4.3.5 Procedure for the mitigation of relevant damage mechanisms - The measures including surveillance procedures for the mitigation of relevant damage mechanisms shall be specified for the individual level of the structural component part. These measures may be: a) preventive maintenance, b) in-service inspections, c) special examinations, d) repair tasks, and e) structural modifications. The frequency and intensity of the examination measures shall be adjusted to the relevant damage mechanisms that can occur in the individual structural component parts and to the anticipated damage development. The point in time for performing the required repair tasks or structural modifications shall be chosen such that the anticipated damage development is taken into consideration.

Summary: The German KTA 1403 does set forward specific criteria for the inspection and condition assessment of NPP RCS. Rather, it provides guidance for the condition assessment, whether visual or special inspection, and defines generically the approach for mitigation deterioration.

3.3.4 Nuclear Regulatory Commission

The Nuclear Regulatory Commission (NRC) has issued three types of documents on repair Inspection Procedures (IP), NUREGs, and Regulatory guides (RG). The NUREG are reports on regulatory decisions, results of research, results of incident investigations, and other technical and administrative information. The RG is a series which provides guidance to licensees and applicants on implementing specific parts of the NRC's regulations. Documents pertaining to ageing management have not been reviewed here. The main documents found related to inspection and repair of existing NPP are:

• RG 1.127-78, *Inspection of Water-Control Structures Associated with Nuclear Power Plants* [65], collection and evaluation of plant degradation occurrences, an assessment of the available technical information on age-related degradation, and a scoping study to identify which structures and components should be studied in the subsequent phases of the research program.

• IP 46051-1983: *NRC Inspection Manual - Structural Concrete* [66], The scope of this document is to "determine whether the technical requirements detailed and referenced in SAR associated with structural concrete have been adequately addressed in the construction specifications". This document cites an extensive list of standards documents from: ACI, ASTM, American Welding Society, AASHTO, Corps of Engineers- US Army, National Ready Mixed Concrete Association (NRMCA).

• NUREG-1522/1995 *Assessment of In-service Conditions of Safety-Related Nuclear Plant Structures* [67], summarizes the results of inspection and survey conducted on several NPP to determine the type of deterioration observed. It provides some information on how to conduct the inspection and what documents would be useful to the NPP operators.

• NUREG/CR-6424-96 [6], *Report on Aging of Nuclear Power Plant RCS*, summary of program results in the form of information related to longevity of nuclear power plant reinforced concrete structures.

• IP62002-1996: *Inspection of Structures, passive components, and civil engineering features at Nuclear Power plants* [68], evaluate the licensee maintenance and monitoring program to ensure compliance with Federal Regulations. The document uses as reference ACI 349-10, ACI 207-94 and ASCE 11-90.

• NUREG/CR-6679-00, *Assessment of Age-Related Degradation of Structures and Passive Components for U.S. Nuclear Power Plants* [69], describes the results of the first phase of a multi-year research program to assess age-related degradation of structures and passive components for U.S. NPPs.

• IP71002-2005: *NRC Inspection Manual - License Renewal Inspection* [70], ensure that all components have a maintenance program and that documentation is available to ensure that procedures are followed.

• NUREG/CR-6927/2007 (ORNL/TM-2006/529) *Primer on Durability of Nuclear Power Plant Reinforced Concrete – A Review of Pertinent Factors* [5], overview of the concrete deterioration process and the possible causes of such deterioration with time. It has some chapters directly related to NPP as it addresses elevated temperature and irradiation.

• IP71003-2008: *NRC Inspection Manual - Post Approval Site Inspection for License Renewal* [71], provides guidelines to conduct an inspection after the NPP was renewal license was granted.

• NUREG/CR-7153/2014 Vol.4 (ORNL/TM-2013/532) *Expanded Materials Degradation Assessment (EMDA) – Vol.4: Ageing of Concrete and Civil Structures* [6], describes an EMDA for an expanded analytical timeframe to 80 years to encompass a potential second 20-year license-renewal operating-period. Further, a broader range of SSCs was evaluated.

Summary: The NRC provides extensive guidance for all aspects related to the condition assessment of the structural safety of NPP RCSs. Information on the time variation of concrete materials under the influence of environmental stressors and ageing factors is reviewed. Guidance is given for in-service inspection and condition assessments techniques (including qualitative acceptance approach – See ACI 3.2.6), use of repair materials and methods.

3.3.5 Oak Ridge National Laboratory

A review of documents published by 1.1.1 Oak Ridge National Laboratory (ORNL) has shown that the ORNL/NRC/LTR-95/14, *In-service inspection guidelines for concrete structures in Nuclear power plants* [72], is most relevant within the scope of this report. However, this document was drafted in conjunction with the initial version of the ACI 349.3R-96. (See ACI section for short summary). Other documents of interest are:

• ORNL/TM-2012/360, *Light Water Reactor Sustainability Non-Destructive Evaluation for Concrete Research and Development Roadmap* [73], define R&D actions to address gaps between available NDE concrete techniques and the technology needed to make quantitative measurements to determine the durability and performance of concrete structures on the current US NPP fleet.

• ORNL/TM-2007/191, *Inspection of Nuclear Power Plant Structures - Overview of Methods and Related Applications* [74], overview of the methods that are available for inspection of nuclear power plant reinforced concrete and metallic structures, and to provide an assessment of the status of methods that address inspection of thick, heavily-reinforced concrete and inaccessible areas of the containment metallic pressure boundary.

• ORNL/TM-2008/170, *Materials Degradation in Light Water Reactors: Life After 60* [75], present an overview of current materials issues in the existing reactor fleet and a brief analysis of the potential impact of extending life beyond 60 years.

• ORNL/TM-2006/529, *Primer on Durability of Nuclear Power Plant Reinforced Concrete Structures - A Review of Pertinent Factors* [76], provides a primer on the environmental effects that can affect the durability of nuclear power plant concrete structures. It includes, a discussion on concrete durability and the relationship between durability and performance, a review of the historical perspective related to concrete and longevity, a description of the basic materials that comprise reinforced concrete, and information on the environmental factors that can affect the performance of nuclear power plant concrete structures.

• ORNL/TM-2005/520, *Final Report Inspection of Aged/Degraded Containments Program* [77], main objective is to understand the significant factors relating corrosion occurrence, efficacy of inspection, and structural capacity reduction of steel containments and liners of reinforced concrete containments.

Summary: Many ORNL document are developed under NRC grants. Other reports cover basic science, but address the identical issues: time variation of concrete materials under the influence of environmental stressors and ageing factors, in-service inspection and condition assessment techniques, use of repair materials and methods.

3.3.6 Other documents

In this section, two International Atomic Energy Agency (IAEA) documents, and an American Society of Mechanical Engineers (ASME) code are summarized:

• IAEA-EBP-LTO-23, *Long term operation – structures and structural components. Final working group 4 report* [78]. This already 10 years old document reports that all countries have established in-service inspection systems (ISI) for building structures and structural components based on national regulations and guidance, procedures supplied by vendors, or utility programmes developed on the basis of industrial experience. It states that lack of design basis information and acceptance criteria is a real issue in some countries. An acceptable ISI programme should include the method of monitoring for each degradation factor important for long term operation (LTO) including information on frequency of performed measurements and/or inspections.

Chapter 5 deals with in-service inspection, regarding to what the International Atomic Energy Agency (IAEA) sees as several future challenges and has some recommendations concerning the challenges. Regarding especially the acceptance criteria, the following basic issue was seen as one of the main future challenges (in 2006): It is important that appropriate criteria are developed to allow proper judgment about the condition of structures. As a basic recommendation, IAEA sees that a systematic approach should be proposed for all countries, where acceptance criteria that address all the expected ageing/degradation mechanisms are pre-established.

According to the experience of the countries, the methods for assessing the acceptance of ageing, i.e. strength, depth of carbonation, corrosion of concrete rebar, width of cracks, strength of anchoring elements, condition of hermetic liners and concrete water-tightness, need further development. For the evaluation of trends and time-limits due to ageing, both deterministic and probabilistic approaches should be applied. Many problems are related to the uncertainties in the behaviour of massive concrete structures especially under the effect of relatively high temperature and changing moisture fields.

• IAEA Draft Safety Guide DS 482, *Design of reactor containment structure and systems for nuclear power plants* [79]. This is a revision of the earlier safety guide (Safety Series No. NS-G-1.10, 2004), which is now superseded. The objective of this Safety Guide is to make recommendations on the implementation and fulfilment of SS-R 2/1 Revision 1 requirements relevant for the containment structures and systems primarily targeted to new nuclear power plants. Design limits and engineering criteria are specific to the design and are therefore outside the scope of this safety guide. No specific acceptance criteria are given.

According to this document, engineering criteria for leak-tightness and integrity of the containment should be established on the basis of stress and deformation limits for different load combinations and with an adequate margin. Concrete should have characteristics of quality and performance consistent with its use.

• ASME code Section III Division 2 - *Rules for Construction of Nuclear Facility Components* (ACI 359-04) [80]. The acceptance criteria of RC containments are given. Loads are categorized into service loads and factored loads. Only service loads are considered in this report. They are divided into normal loads, construction loads and test loads. Normal loads are loads which are encountered during normal plant operation and shutdown such as:

- dead loads, including hydrostatic and permanent loads;
- live loads, including any movable equipment loads and other loads which vary with intensity and occurrence, such as soil pressures;
- loads resulting from the application of prestress;
- loads resulting from relief valve or other high energy device actuation;
- thermal effects and loads during normal operating and shutdown conditions, based on the most critical transient or steady state condition;
- pipe reactions during normal operating or shut-down conditions, based on the most critical transient or steady state condition;
- external pressure loads resulting from pressure variation either inside or outside the containment.

Construction loads are loads which are applied to the containment from start to completion of construction. Test loads are loads which are applied during structural integrity or leak rate testing.

The structural test requirements state that the patterns of cracks that exceed 0.01 in. (0.25 mm) in width and 6 in. (150 mm) in length shall be mapped at specified locations before the test, at maximum pressure, and after the test. Displacements shall also be recorded. The acceptance criteria in such tests are following:

- Yielding of conventional reinforcement does not develop as determined from analysis of crack width, strain, or displacement data.
- No visible signs of permanent damage to either the concrete structure or the steel liner are detected. Evidence, resulting from the test, of spalling, laminations, or voids behind the liner are to be considered. Special care shall be exercised in the post-test examination to detect evidence of localized distress which may not be revealed by strain or displacement data. The significance of such distress, if detected, must be determined by the Designer and be acceptable to the Owner.

- Residual displacements at the points of maximum predicted radial and vertical displacement at the completion of depressurization or up to 24 hr later shall not exceed the following:
  - × For conventional reinforced containments or conventionally reinforced directions of partially prestressed containments: 30% of measured of predicted displacement at maximum test pressure, whichever is greater, plus 0.01 in. (0.25 mm) plus measurement tolerance.
  - × For prestressed containments or prestressed directions of partially prestressed containments: 20% of measured of predicted displacement at maximum test pressure, whichever is greater, plus 0.01 in. (0.25 mm) plus measurement tolerance.
  - × The above criteria shall be applied to the average of radial displacements measured at the same elevation.
- The measured displacements at the test pressure at points of predicted maximum radial and vertical displacements do not exceed predicted values by more than 30% plus measurement tolerance. This criterion shall apply to the average of radial displacement measured at the same elevation. This requirement may be waived if the residual displacements within 24 hr are not greater than 10% for prestressed structures or 20% for conventionally reinforced concrete structures.

Surface cracks and strain measurements shall be reviewed by the Designer for evaluation of overall test results.

3.4 Research projects and scientific technical committees

In this section, the experience from active participation in international and national technical committees is summarised. The working groups are defined, and the objectives and the relationship to assessment criteria described (outcome).

• OECD NEA/CSNI - WGIAGE (Working Group on Integrity and Ageing of Components and Structures) ASCETS CAPS - Assessment of structures subject to concrete pathologies. *Objective*: Assess the possibilities to define general international recommendations for management of concrete nuclear facilities subjected to different concrete pathologies/degradation ageing mechanisms [81]. *Outcome*: There is a need to create an open international database to bring together information on concrete degradation mechanisms from nuclear community worldwide (also not ignoring relevant information acquired in non-nuclear civil engineering). Furthermore, there is a clear need for the development of performance based criteria - there is a need for case studies and feedback of affected structures management in order to discuss the acceptances criteria for Ultimate and Serviceability Limit state. Emphasis should come from the development of comprehensive Ageing Management Programs addressing Long Term Operation. Finally, there is also a clear need for development and validation of NDT in NPP RCS.

• COST Action TU 1406 BridgeSpec - Quality specifications for roadway bridges, standardization at a European level. *Objectives*: To develop a guideline for the establishment of Quality Control plans in roadway bridges, by integrating the most recent knowledge on performance assessment procedures. Systematize knowledge on QC plans for bridges – achieve state-of-art report that includes performance indicators (PI). Collect and contribute to up-to-date knowledge on PI, including not only technical indicators but also environmental, economic and social ones, and, establish a wide set of quality specifications through the definition of performance goals, aiming to assure an expected performance level. Create a data base from COST countries with PI values and respective PG. *Outcome*: Cost Action in initial year where data from member countries on their respective Bridge Management and Inspection systems is being compiled.

• RILEM - International Union of Laboratories and Experts in Construction Materials. TC 230-PSC - Performance-based specifications and control of concrete durability. *Objective*: Develop test methods to characterize the behaviour of concrete under combined actions such as mechanical load, freeze-thaw cycles, carbonation, and chloride penetration. The validity of the recommended test methods shall be checked by comparative test series carried out in a number of selected laboratories in different countries [82]. *Outcome*: A RILEM recommendation for test methods to characterize durability under combined actions, i.e., chloride ingress and compressive/tensile stress (under final review). Furthermore, priorities and orientations for future research work on the effect of combined loads are addressed.

TC 246-TDC - Test methods to determine durability of concrete under combined environmental actions and mechanical load. *Objective*: Establish guidelines for the specification of the penetrability and thickness of the concrete cover, as function of the exposure conditions and service life design, and for its compliance control through suitable site and/or core testing [83]. *Outcome*: A RILEM draft recommendations on suitable 'durability indicators' and their application in performance-based specifications for durability, including recommendations on: sampling criteria, application of site test methods to evaluate the penetrability (NDT and cores) and thickness of the concrete cover, interpretation of results and principles of compliance control based on site tests.

• FIB - The International Federation for Structural Concrete. TG 8.6 - Calibration of code deemed to satisfy durability provisions. *Objective*: To benchmark rules for chloride-induced corrosion as given in national codes, e.g. European, US and Australian standards. In this benchmark it is determined which reliability ranges regarding chloride-induced depassivation of rebar can be expected if the deemed-to-satisfy rules of different countries. The calculated reliability ranges thus determined are compared with the target reliabilities proposed by current specifications and, based on the above comparison, a proposal for improvement of deemed-to-satisfy rules and specifications is made [84]. *Outcome*: A reliable database for a performance-based probabilistic service life design of concrete structures exposed to chlorides (either exposed to salt fog, sea water or de-icing salts).

TG 8.3 - Operational documents to support Service Life Design. *Objective*: To provide guidance on use of the durability models and the full probabilistic approach, in addition to relate it to the deterministic approach, based on the traditional definition of limits in the concrete mix proportions [85]. *Outcome*: A technical guide that addresses the practical application of service life design, with description of the approaches current limits and, validated with real practice.

• NUGENIA ACCEPPT Project - Aging of concrete and civil structures in nuclear power plants. *Objective*: A study on containment liners with regard to functionality, i.e. the liner's ability to fulfil the required tightness. A study on the pre-stressed containment including the concrete structure of the containment, conventional reinforcement and post-tensioned reinforcement. The focus was on functionality requirements, i.e. whether or not the structure and its constituents fulfil as designed, or eventually new, requirements. *Outcome*: Structural and material properties of nuclear reactor containments in European NPPs were compiled. A containment was numerically modelled for an analysis of stress concentrations and crack risks. Also moisture and temperature conditions and their development were determined. The general mechanical features of steel liners used in European NPPs were gathered. Liner's repair techniques and non-destructive monitoring techniques were reviewed. Experimental liner tests were conducted to reproduce the liners' damage mechanisms under LOCA and update the numerical models.

• OECD NEA/CSNI - WGIAGE (Working Group on Integrity and Ageing of Components and Structures) TENDON CAPS - Post Tensioning Methodologies for Containment Building: Greased or Cement Grouted Tendons - Consequences on Monitoring, Periodic Testing and Modelling Activities. Objective: One objective is to clearly identify the technical considerations of both technologies (bonded versus unbonded), not in order to rank one before the other, which would be useless due to reliability of both, but in order to properly address the drawbacks. The objective of this CAPS is to produce a guideline obviously to help every country for the technology choice but mainly to clarify the consequences of their choice in terms of design basis, in term of behaviour during severe accident, in term of construction requirements, in term of monitoring and in-service inspection of containment. *Outcome*: To clarify the consequences of the chosen containment tension technology in terms of design basis, in term of behaviour during severe accident, in term of construction requirements, in term of monitoring and in-service inspection of containment in various operating conditions due to the high importance of the tendons for the containment capacity.

• VeRCoRs Project - Vérification réaliste du confinement des réacteurs. *Objective*: An ongoing research program focusing on civil work numerical models, organized by Électricité de France (EDF). *Objective*: To study the behaviour at early age, the evolution of the leak tightness under the effect of aging (drying effects are about 9 times faster on the mock up because of scale effects) and the behaviour under severe accident conditions for which the thermo-mechanical loading is maintained for several days. *Outcome*: The project is ongoing and the first experiments have been successful. The numerical workshop held in March 2016 gave an insight to the calculation methods and models used for analysing the above-mentioned phenomena.

• IRSN ODOBA Project - Observatoire de la durabilité des ouvrages en béton armé. *Objectives*: Experimentation both at large and small scale blocks; Parametric experimentation exploring coupling between phenomena; Realistic materials (granulates, cement) and model materials (for comprehension); On-line instrumentation, periodic NDE and destructive examinations; Accelerated aging process. *Outcome*: Project has just started, but already technical challenges are identified to guide the progress of work: develop and validate innovative NDE, define and qualify accelerated aging processes modelling multi-scale and multi-physic issues.

• SAFIR 2018 WANDA Project - Non-destructive examination of NPP primary circuit components and concrete infrastructure. *Objective*: To raise expertise of NDE of concrete infrastructure. Includes critically assessing the NDE techniques and monitoring systems currently in use to fulfil the needs of NPP infrastructure, and to develop guidelines for the use of NDE techniques in design and condition assessment, for the implementation of monitoring systems, and for performance based design and ageing management of the concrete infrastructure [86]. *Outcome*: Project is still ongoing, but will end with the construction a mock-up of a full-scale NPP concrete cross section with artificial defects and QC issues. With this mock-up, it will allow continuous long term testing and monitoring, and provide basis for teaching of young professionals, calibration of NDE methods, and accreditation of experts.

• SAFIR 2014 MANAGE Project - Ageing management of concrete structures in NPP. *Objective*: To develop an Ageing Management Systems for Finnish NPP to avoid premature degradation of their facilities and to be able to extend their operating service life. Harmonise the inspection practices of concrete structures in NPPs by defining in-service inspection methods and data registering practices [87]. *Outcome*: The MANAGE Platform for Ageing management of concrete infrastructure, including the ServiceMan application [88] for estimation of concrete service life based on known deterioration processes.

• TEKES/VTT DURAINT project - Deterioration Parameters on Service Life of Concrete Structures in Cold Environments. *Objective*: Conduct preliminary study into the effect of coupled deterioration and transport mechanisms on the durability performance of concrete – carbonation, chloride ingress and freeze-thaw (internal cracking and surface scaling [89]. *Outcome*: New knowledge on the synergetic effect of coupled deterioration mechanism. Preliminary models for the combined effects of degradation mechanisms based on the results of laboratory and in situ exposure tests on frost attack, and its effects on the rate of carbonation and chloride penetration.

• TEKES/VTT CSLA project - Concrete Service Life Assessment - Modelling frost attack degradation in the presence of chlorides. *Objective*: Study of the effect of coupled deterioration mechanisms on the performance of concrete, with special focus on chloride ingress and freeze-thaw action [90]. *Outcome*: Modelling of the interaction between transport mechanisms and freeze-thaw loading conditions. Coupled effects result in synergic effect on chloride ingress. Development of Duracon FT (a software for SLD of RCS in de-icing road environment) and the VTT Concrete Performance Modelling Platform (CPMP – 3D-FEM model for concrete performance).

• VTT Research Project - New limit-states for concrete service life determination. *Objective*: Study of new methodology for service life design considering a single limit state of concrete cracking [91]. *Outcome*: The benefit of using a coupled limit state analysis until the time to first corrosion induced crack to appear is shown. Joint consideration of corrosion initiation and propagation describes the damaging mechanism more realistically and facilitates an extension of the service life of the structures.

• Elforsk Report - Evaluation of NDT methods with possible applications in nuclear engineering concrete structures. *Objective*: To give recommendations regarding which NDT methods are suitable for practical application and which should be selected for further development, provided that the results are intended to be used in calculations, that will result in the remaining service-life of the plant. [92] *Outcome*: However, only the methods based on mechanical wave propagation has a physical phenomenology that connects to the strength of concrete. Because of that and promising early results, it is recommended to develop the following methods further: Shear wave reflection (geometry, cavities), Contact less surface wave measurements (strength), Nonlinearity detector (fissures), Impedance measurements (delamination) and the use of tendons as wave guides.

• Elforsk rapport - Literature studies and testing of non-destructive test (NDT) with possible applications of nuclear concrete structures. *Objective*: The present report details a survey of methods suitable for detecting delamination in nuclear power-plant cooling-water channels. It is also a close-up study of the russian instrument A1220 Monolith manufactured by ACSYS [93].

• Elforsk rapport - Impulse Response measurements dependent on crack - delamination. *Objective*: The purpose of the project is to investigate the impulse-response method’s ability to detect delamination at different depths. This method is of particular interest, since some of its realizations strongly resemble established methods like instrumented hammering (“bomknackning”) [94].

• Elforsk rapport - Impulse response measurement dependence on crack depth. *Objective*: Those test-methods that have been developed in a laboratory setting within the ELFORSK-project BET 012 ”Impulse response measurement dependence on crack depth”, and have potential for measurements in real delamination situations, have been tested during a visit to the Ringhals Nuclear Power Plant 2011-04-20. [95].

• Elforsk rapport - Study of the water line corrosion liner embedded in concrete at the condensation pool. *Objective*: The first part of the report is a survey of published information regarding waterline corrosion and the effect of wholly or partly liquid-filled voids at a steel surface cast in concrete. The second part is a report on the investigations of the corrosion status of the steel liner on the inside of the reactor containment at the Barsebäckverket I plant and of the laboratory investigations of the concrete samples that were taken from the reactor containment wall [96].

• Elforsk rapport - Corrosion of steel in concrete in the cooling water paths Report 1 - Literature Review. *Objective*: The aim of the present literature study has been to collect knowledge about reported concentrations of chloride in concrete exposed to brackish water and also to get an overview of whether a critical threshold chloride concentration for chloride induced corrosion on steel embedded in concrete has been reported and/or accepted [97].

• Elforsk rapport - Stainless steel's resistance to corrosion and galvanic effect on carbon steel in concrete with high moisture and chloride content. *Objective*: The present report concludes the R&D project Corrosion properties of stainless steels in concrete with a high content of moisture and chloride. The report includes results from four interim reports previously published within the project. The report also includes recent results from two years of outdoor exposure in sea water and in urban atmosphere of stainless steel test bars (ribbed bars) cast in concrete, as well as of test bars of carbon steel electrically coupled to stainless steel test bars for investigation of the risk of galvanic corrosion on the carbon steel [98].

• Energiforsk rapport - Corrosion of steel in concrete at various moisture and chloride levels. *Objective*: In the present study, samples made of steel cast in chloride containing mortar were exposed to different moisture conditions. The moisture condition was either static at a certain relative humidity or dynamic where the relative humidity was cycling between 75% and 100%. *Outcome:* The lowest chloride concentration which caused initiation of corrosion was 1% Cl by mass of cement and was measured for samples exposed to 97% RH. At higher or lower moisture conditions than 97% RH, the corrosion rate was lower. For samples exposed to dynamic moisture conditions, the lowest chloride concentration which initiates corrosion was measured to be 0.6% Cl by mass of cement [99].

• Energiforsk rapport - Climatic conditions inside nuclear reactor containments. *Objective*: The work concerns the moisture condition within nuclear reactor containment inner walls in addition to other concrete structures within the containments. The study aims to describe earlier, ongoing and future moisture contributions, and redistribution of moisture within and from the concrete structures within the containments. *Outcome:* The measurements and simulations done in this study show that the concrete structures within the reactor containment are still drying after approximately 30 years of operation, and will continue to dry and contribute with moisture to the ambient compartment for the remaining part of the service life for the reactors. The simulations present that 35–45 % of the initial evaporable water had dried out, until this study, and that the amount for 60 years of operation is 45–55 %. The main drying has already occurred, and the moisture contribution to the ambient compartments will continue to decrease, thus contributing less moisture to the air in the containment in the future [100].

3.5 DETERIORATION MECHANISMS

Only the most common deterioration mechanisms are covered in this section. The deterioration mechanisms are reviewed based on existing performance criteria and how they might be assessed, a critical review of the criteria, and possible R&D needs. In this section, the focus is on criteria for special inspections where NDE/testing is required, and the input for service life calculations.

3.5.1 Carbonation

Existing performance criteria: The main criterion is based on the depth of the carbonation front. This is relevant as a precursor for the corrosion of the reinforcement. According to common service life design and performance assessment models [20, 47], a serviceability limit state is defined by the relationship between the depth of the carbonation front and the cover depth of the reinforcement. When the carbonation front surpasses the cover depth, it is considered that the limit state has been exceeded and corrosion of the reinforcement has initiated.

The parameter being measured is the carbonation front, which is measured on a concrete sample removed from the structure, either by colorimetric methods (phenolphthalein indicator), or by thin section analysis. The use of service life models implies the conversion of the carbonation depth into a carbonation coefficient that defines the rate of carbonation as a function of time. In research, concrete samples can be subject to accelerated carbonation testing which determines an accelerated carbonation rate. For service life determinations, in addition to other model parameters, known concrete cover and environmental loading conditions are required (concentration of CO_2 in the atmosphere).

Critical review of criteria: The use of the carbonation front is a relatively easy procedure to assess the current performance of concrete, but provides little information as to the future trend, unless several measurements have been obtained in time. Despite concrete intrinsically vary one type to another, and being subject to different local environmental conditions, the same criterion is still valid: depth of carbonation front > cover depth.

There are many models for estimating the remaining service life, with varying need for input. From simple square root of time models to sophisticated numerical models that start modelling performance at the time of concrete placement, can be used. Most common approach is currently the use of engineering models (based on analytical expressions) that can be calibrated for the performance of a specific concrete/environmental exposure.

R&D needs: NDE methods are needed. Models are sensitive to certain parameters which are not always well defined, or are calibrated for specific concretes/testing scenarios. Need for robust models that are widely applicable. Coupling deterioration mechanisms. Typical modelling SLD refers to state where no damage has occurred, which could be considered unrealistic and uneconomical. Verification of the usability of modelling results from accelerated testing method for carbonation. Verification of moisture dependence of carbonation on structural orientation.

3.5.2 Chloride ingress

Existing performance criteria: The main criterion is based on the depth of the critical chloride content front. As for carbonation, this is relevant as a precursor for the corrosion of the reinforcement. According to common service life design and performance assessment models [20, 47], a serviceability limit state is defined by the relationship between the chloride content at the depth of the reinforcement and the critical chloride content necessary to initiate reinforcement corrosion. When the chloride content at the depth of the reinforcement surpasses the critical chloride content, it is considered that the limit state has been exceeded and corrosion of the reinforcement has initiated.

The parameter being measured is the chloride content (at the depth of the reinforcement), which is measured on a concrete sample removed from the structure. Typically, a chloride profile showing the variation of chloride content as a function of concrete depth is determined because additional information can be extracted from this data, such as the apparent diffusion coefficient and the surface chloride concentration, which are needed input for service life models. In addition, concrete samples can be subject to accelerated chloride diffusion/migration testing which determines a diffusion/migration coefficient. For service life determinations, in addition to other model parameters, known concrete cover and environmental loading conditions are required (chloride surface concentration).

Another approach is based on electric-chemical techniques used to determine the initiation of corrosion. These vary in approach, and whether they need connectivity to the reinforcement.

Critical review of criteria: The use of the chloride profile is a relatively easy procedure to assess the current performance of concrete, but provides little information as to the future trend, unless several measurements in time are obtained. This allows for the determination of the ageing factor which defines how the concrete transport properties change with time. Despite concrete intrinsically vary one type to another, and being subject to different local environmental conditions, the same criterion is still valid: chloride content at the depth of the reinforcement > critical chloride content. While simple in principle, current research does not converge on values for the critical chloride content at the depth of the reinforcement [101]. It is strongly influenced by the environment (submerged, tidal, atmospheric, etc.), by the concrete quality (w/b ratio) and the cement and use of SCM.

The measurement of the chloride profile to estimate the critical chloride content assumes that this value clearly defines the transition between passive, and corroding reinforcement. Electrochemical monitoring of reinforcement condition in concrete shows that the transition between initiation phase and propagation is not a clear one. It can be observed that the steel stays in a passive state, although the critical chloride content is clearly exceeded, or vice versa. The causes of this behaviour are still unknown, but it is evident that the processes in the passivation layer at the steel surface are highly complex and far from being understood.

As for carbonation, there are many models for estimating the remaining service life, with varying need for input. Also from basic square root of time models to sophisticated numerical models can be used. The most common approach is currently the use of engineering models (based on analytical expressions) that can be calibrated for the performance of a specific concrete/environmental exposure.

R&D needs: NDE methods are needed. Models are sensitive to certain parameters which are not always well defined, or are calibrated for specific concretes/testing scenarios. Need for robust models that are widely applicable. Coupling deterioration mechanisms. Typical modelling SLD refers to state where no damage has occurred, which could be considered unrealistic and uneconomical. Phenomenological explanation for the apparent chloride diffusion decrease with time. Long-time verification of chloride ingress, including the impact of cracks. Standard test method for Thresholds values. How temperature and moisture affect the transport of chloride in the concrete.

3.5.3 Alkali aggregate reaction

Existing performance criteria: Currently international research is focusing on developing a performance based testing concept for the prevention of deleterious alkali aggregate reaction (AAR) in concrete. Such is the focus of RILEM TC-258 AAA. There are more than a dozen test methods currently in use to assess AAR. The laboratory test methods have two objectives: to determine the alkali reactivity of an aggregate in a reasonable short time, and to evaluate and set acceptable expansion limits of a reactive aggregate/cement combination (performance criteria). Most test methods can be described as being either a mortar bar method, an accelerated mortar bar method, a concrete prism method, or an accelerated concrete prism method. The general conclusion to be derived from all of these tests is that it is inherent in the nature of AAR, and the numerous factors that influence the reaction, that no single test, wherever its nature, can be completely relied upon [102]. It is important to assess the role of laboratory testing, its aims and objectives, and bear these in mind when specifying acceptable limits of expansion for practical design.

R&D needs: An important additional tool in validation of the performance testing concept is to make an assessment of the link between the use of accelerated testing in the laboratory with the behaviour *in situ*.

3.5.4 Sulphate

Existing performance criteria: No direct rapid test procedure has yet been devised and fully tested for use on the structure or on concrete test specimens for assessing the durability of aggressive ground or water bearing sulfates. The recommendations for protection of concrete are based on many years of long-term testing as illustrated in this report.

Appropriate test methods are needed to determine the resistance of concrete under sulfate exposure. Accelerated test methods are most suitable since sulfate attack is typically a long term process. However, it is still questioned if accelerated test methods still reflect field conditions [103].

Critical review of criteria: Some test methods obtain results after 2 weeks, but the attack mechanism no longer represents field conditions in a realistic way. Another problem relates to the way of quantifying the degree of deterioration. Different test methods measure different as parameters to quantify deterioration: length change, decrease in flexural strength, change in mass, change in radius, reduction in sound velocity, electrochemical potential, change in pH, etc. are used. Depending on the selected degradation measure, different conclusions can be drawn regarding the performance of concrete under sulfate attack. Tests typically cannot mimic all relevant boundary conditions and in-situ scenarios.

R&D needs: To develop a comprehensive performance testing concept (multiple test approach) that addresses all relevant aspects in performance assessment. Development of accepted models of deterioration and conversion of these models into design tools. Calibration of the models with experience of real structures.

3.5.5 Leaching – Acid/Pure water attack

Existing performance criteria: There are no specific performance parameters for either leaching and acid attack. In the attack of concrete by strong acids or by pure water, the deterioration is due to the leaching of cementitious materials, responsible for higher porosity and loss of strength. Leaching tests are conducted to examine mass transfer of "leachate" from the solid to the liquid, termed the "leachant".

There are a large number of standard and non-standard leaching tests, which results in a limited comparability of the results, the problem being even bigger when using accelerated tests [104].

Critical review of criteria: As the different tests are defined by different experimental variables, the choice of the method has an effect on the results. It is recommended to perform a range of leaching tests in order to completely understand the leaching behaviour of a material and/or try to reproduce the mechanisms of the expected specific scenarios of the concrete degradation. Classification of leaching tests is a complex issue due to the high number of variables involved.

R&D needs: To develop a comprehensive performance testing concept (multiple test approach) that addresses all relevant aspects in performance assessment. Development of accepted models of deterioration and conversion of these models into design tools. Calibration of the models with experience of real structures.

3.5.6 Freeze-thaw

Existing performance criteria: Direct performance can be measure by volume change, mass change or change in dynamic modulus of elasticity (related to internal cracking) is often used as a descriptor of durability.

How can the criteria be assessed: Traditional freeze-thaw test methods for assessing the frost resistance of concrete vary and are well described in literature [90].

Critical review of criteria: These characteristics are of significant practical value but they do not provide any clear direct evidence for a particular mechanism of freeze-thaw action. They are not applicable *in situ*. No single laboratory test method can fully reproduce the conditions in the field in all individual cases. A good enough testing method should at least correlate to the practical situation and give consistent results. There is no "right" freezing and thawing resistance test method. Most of the standardized test methods have been prepared for quality control purposes, not for durability performance assessment. For this reason, a comprehensive analytical model for freeze-thaw durability has not yet been developed.

R&D needs: Establish correlation between laboratory test methods and field experience. To develop testing methods for assessing performance indicators that can be used in service life models. Effect of coupled deterioration mechanisms. Equivalent absorption in different environments and different orientations of concrete surfaces. Explanation of the salt scaling deterioration mechanism. Model for scaling development with time (function of exposure). Model for real-freezing temperatures of concrete structures in different environments with surfaces with different orientations.

3.5.7 Reinforcement corrosion

Existing performance criteria: A direct way to assess the corrosion condition of the reinforcement is the determination of loss of reinforcement bar cross section. This is usually only possible after partial removal of the concrete cover, or where the reinforcement bars are exposed due to spalling of the cover concrete. Other methods that can be applied locally or over wider areas of the concrete surface can be applied non-destructively or require not more than a temporary electrical connection to the assessed reinforcement.

These methods are based on the local determination of the polarisation resistance, or the spatial potential mapping. The potential mapping provides information, in which areas corrosion is likely, unlikely or undefined. A direct evaluation of the intensity or rate of corrosion is not possible with this method. There are measuring setups that allow the determination of the polarisation resistance, which is the basis of deriving the corrosion rate if additional measurements or assumptions of the electrical resistance and the dimensions of the polarised steel surfaces are available.

Commercially available equipment exists. Its application requires experience and a broad knowledge of corrosion phenomena. Another indirect parameter that can provide information about the likelihood of corrosion is the electrical resistance of the concrete. Distinct values that allow conclusions about the existence and intensity of reinforcement corrosion due not exist and are highly dependent on the temperature, concrete composition and quality.

Critical review of criteria: The nature of reinforcement corrosion in concrete structures is usually very complex. The locations of active corrosion can change over time and the intensity of the corrosion process is highly dependent on the ambient conditions and the properties of the concrete. Therefore, intermittent and localised measurements of corrosion indicators provide only an incomplete basis for an assessment. For a better evaluation of the corrosion state of the reinforcement, spatially extended and permanent corrosion monitoring would be necessary. This can be done for instance with a monitoring system based on embedded sensors. Such a system can provide valuable information for the use in deterioration models and subsequently for the condition and ageing assessment of the concrete structures.

R&D needs: Commercially available equipment and systems to directly or indirectly determine corrosion indicators need further developments which allow an easier application and increase the reliability of the measured data. Further developments in the field of autonomous wireless embedded sensor seem to be promising and might lead to a widespread integration of corrosion assessment systems in the building stock.

3.5.8 Radiation effects

Critical review of research on topic: As a result of LTO and anticipated subsequent license renewal, a renewed interest in radiation damage assessment of concrete in nuclear faculties has risen. The current status of understanding of radiation effects on concrete and its components specifically addresses drying and temperature effects and radiolysis of hydrated cement paste (HCP), and radiation induced volumetric expansion (RIVE) of aggregates [104]. HCP shrinks under drying conditions, the decrease in volume being only partially covered by the thermal expansion due to increased temperatures associated with radiation heat. Shrinkage of the cement paste is explained by water hydrolysis and water evaporation occurring under gamma-ray irradiation. RIVE of aggregates results from the accumulation of defects in their crystal structures generated mainly by neutron collisions. This conflicting volume expansion between HCP and aggregates has been indicated as the main cause of damage in irradiated concrete.

R&D needs: The need for long-term predictions of irradiated concrete performance has pushed the effort towards the modelling of the related deterioration mechanisms, both theoretically and numerically.

3.5.9 Prestress losses in the tendons

Critical review of research on topic: The main purpose of the prestressing system in the reactor containment is to maintain the structural integrity of the containment in the event of an internal accident, which, for instance, can be initiated by a pipe rupture in the cooling system. This will increase the pressure inside the containment, thus inducing tensile stresses in the concrete. The prestressing system is designed to withstand these tensile forces and maintain the concrete in a compressed state, thus the safety of the containment depends on the induced compressive stresses in the concrete. Due to long term effects in the materials, i.e. creep and shrinkage of concrete and relaxation of the prestressing steel the tendon forces will decrease with time. Shrinkage is the development of strain with time in an unloaded and unrestrained specimen at constant ambient temperature and is mainly due to the drying of the concrete. Creep is the time dependent increase of strain under constant load. Several factors influence the creep and shrinkage behaviour of concrete, for example the stress levels, duration of the load, the composition of the concrete, age at loading, ambient temperature and humidity. Relaxation is defined as the time dependent loss of stress in the tendon at constant strain. The most important factors which influence the relaxation of the steel are the stress level, duration of the load and the temperature.

Since the integrity of the containment is directly related to the forces in the tendons the tendon forces are monitored at certain in-service inspections (ISI) in containments with unbonded tendons. During the ISIs the remaining tendon forces are measured in a number of tendons using hydraulic jacks. The acceptance criteria for the tendon forces are the tendon forces from design that is sufficient to maintain the integrity of the structure, i.e. counterbalance the tensile stresses in the concrete. The failure of a number of tendons is included when calculating the lowest acceptable force levels, this allows for maintenance and replacements of tendons during operation of the reactor without compromising the safety of the structure.

R&D needs: One aspect of importance when considering the long term performance of NPPs is the need for better understanding of concrete creep at elevated temperatures.

3.5.10 Corrosion of steel liner

Critical review of research on topic: Corrosion of the containment liner has been observed and corrosion penetration of the liner associated with foreign materials embedded in the concrete from original construction has occurred [105,106]. Containment liner inspections are intended to identify damage to protective coating and liner corrosion initiated on the interior surface. However, the exterior liner surface in contact with the concrete cannot be visually inspected under normal circumstances. Because these steel containment liners are typically 6 to 10 mm thick, the frequency of inspections is designed to detect corrosion prior to significant damage to the liner. Corrosion of the exterior of the steel liner would be expected to proceed at a very slow rate due to the stabilization of a passive oxide film on the steel in the alkaline concrete environment.

Published operating experience has shown that the most common deteriorations found are through-wall corrosion of the containment liner initiating at the concrete interface, containment liner damage from corrosion initiated at the liner/concrete interface, damage initiated by embedded foreign material in concrete without liner corrosion, blistering, and cracking of welds [105,106]. As an example, through-wall corrosion of the embedded steel liner was discovered at Barsebäck Unit 2 in 1993 as a results of a failed integrated leak rate test. The Barsebäck design has a containment liner of 6 mm in contact with a 900 mm thick layer of concrete on the outside and a 200 mm thick layer of concrete on the inside. Corrosion was thought to have initiated at an area of poorly consolidated concrete around a penetration into containment where water had accumulated. No foreign material in the concrete was identified. [105,107]. Based on the age of the plants and the thickness of the liner, the average corrosion rate can be determined to be in the range of 0.29 to 0.50 mm/yr. The average corrosion rate for the liner corrosion penetration incidents can be compared to both measured atmospheric corrosion rates (0.005 to 0.02 mm/yr in rural atmospheres to 0.03 to 0.08 mm/year in marine environments) and the range of observed localized corrosion rates for steel (differential aeration or differential pH can be in excess of 3 mm/yr). [106].

R&D needs: A workshop addressing the corrosion of containment liners [107] concluded that, a NDE technique is desired that can be applied remotely to inspect and determine the overall condition of large areas of the containment liner in a cost- and performance-effective manner. Limited research indicates that several techniques (e.g., electromagnetic acoustic transducers, magnetostrictive sensors, and multimode guide waves) exhibit potential for detection of liner corrosion. Further investigation of these techniques could be pursued with respect to detection capability and signal processing (e.g., defect sizing). Furthermore, detailed modelling of containment liner corrosion initiation and propagation could be conducted to capture the complexity of the system. The model should at a minimum include accurate accounting for polarization at the anodic and cathodic regions and include the effect of oxygen transport and availability. The model should be able to quantify alternative scenarios where the effect of parameters describing concrete quality, water content, wall dimensions, rebar placement, temperature and its fluctuations and related variables, are evaluated.

3.5.11 Summary

Based on the descriptions given in the previous sub-chapter, a summary is presented in Table 5 for the listed deterioration mechanism and assessment criteria.

Table 5. Causes of concrete/reinforced concrete deterioration as a function of the exposure environment.

Deterioration mechanism	Assessment criteria
Carbonation (corrosion initiation)	Depth of the carbonation front in concrete < Reinforcement concrete cover depth
Chloride ingress (corrosion initiation)	Chloride content at depth of reinforcement < Critical chloride content need to initiate corrosion
Alkali aggregate reaction	(none)
Sulphate attack	(none)
Leaching – Acid/Pure water attack	(none)
Freeze-thaw - Scaling	Depth of scale surface < accepted value
Freeze-thaw – Internal damage	Relative dynamic modulus of elasticity > accepted value
Reinforcement corrosion	(none)
Radiation effects (reduction in compressive strength)	Radiation exposure < $1x10^{20}$ n/cm^2 for fast neutrons and $2x10^{10}$ rad for gamma rays
Prestress losses in the tendons	Current tendon forces > design tendon forces
Corrosion of the steel liner	(none)

4 Final considerations & future work

4.1 SUMMARY

This report presents the findings of a preliminary study that provides background information on existing acceptance criteria that trigger maintenance actions of nuclear power plant safety-related concrete structures. The long-term performance of reinforced concrete structures (RCS) depends on the characteristics of the materials of construction, and the deterioration mechanisms and processes that could potentially affect the functional and performance requirements of these structures.

This study has attempted to focus on the acceptance criteria for all aspects of safe and reliable long-term operation, i.e. structural performance, durability and ageing of reinforced concrete structures.

The ACI 365.1 [35] clearly states that the detection and assessment of the magnitude and rate of occurrence of environmental factor-related degradation are essential for estimating service life and in guaranteeing that RCS meet their operational requirements. The manifestation of ageing is individual, usually localised, and induced by errors in design, the construction and change in the operating regime.

Chapter 1 of this report provides a short introduction, whereas in Chapter 2, the main safety-related concrete structures of NPPs are linked to the expected environmental/loading conditions that the main structures, systems and components (SSC) are exposed to, which in turn are linked to the possibly occurring deterioration and ageing mechanisms for reinforced concrete. This allows for a quick preliminary assessment of what potential deterioration mechanisms a specific SSC could be subject to. This knowledge is the basis for all kind of condition assessment, starting with the initial visual inspection.

In Chapter 3 a review of acceptance criteria is addressed. A summary is provided for each sub-chapter:

- European standards for concrete design: European concrete standards do not cover or provide any guidance for the inspection of RCS. European concrete standards are prescriptive with regards to durability. This means no specific criteria is defined for durability design, therefore it is not possible to assess deterioration. Currently a new generation of performance based durability design standards are being prepared within the CEN technical committee. Corrosion induced deterioration and possibly freeze-thaw damage will be addressed. Structural design codes state extensive cracking as a serviceability limit state. Cracking shall be limited to an extent that will not impair the proper functioning or durability of the structure. The recommended limiting surface crack width values vary between 0.2 mm and 0.4 mm depending on the structural member and its exposure.
- Non-nuclear related design codes: The Swedish and Finnish concrete codes follow closely European standards, including the use of National Annexes to present often stricter durability requirements. These are generally prescriptive,

and when performance based, they are not linked to specific service life criteria, but based on experience and expert opinion.
Both Swedish and Finnish road authorities have in place bridge management systems that describe the condition assessment procedure. These systems are based mainly on the visual inspection, and the assessment of the development of the deterioration with time. Acceptance criteria are provided for visual material for comparison (photos of deterioration/grading systems). Special inspections are also used, but are defined by the inspectors and the assessment is based on their experience. No assessment criteria are presented for this type of inspection. The Finnish system contains simple material performance models that allow for estimation for future deterioration. Both the Swedish and Finnish bridge management system relies heavily on the competence of the inspectors, hence the great effort in their education and accreditation.

- ACI presents a comprehensive array of documents related to the condition assessment and testing of concrete. In particular, the ACI 349.3R-02 [34] that provides guidelines for the evaluation of existing nuclear safety-related concrete structures. Methods of examination including visual inspections and testing techniques, and their applications are cited. This document addresses all safety-related portions of a NPP and provides details regarding the criteria for the evaluation of the structure. Focus is on commonly occurring deterioration conditions. These acceptance criteria mainly address the classification and treatment of visual inspection results.
- Guideline documents are available for durability service life calculation fib - Model Code for Service Life Design [47] and the Swedish Betongrapport n.12 [20]. Performance criteria are defined for the initiation phase of the corrosion process for carbonation (depth of carbonation) and chloride ingress (depth of critical chloride front). Guidance is provided for the model parameter values considering typical concrete mix design and environmental conditions. This approach can also be used for assessing the residual service life, i.e., the evolution of deterioration with time. The models have certain parameters that are very sensitive and can dominate the outcome of a service life calculation.
- Nuclear related design codes & Guides: The Swedish, Finnish and German regulatory codes & guides provide the main design criteria for safety related concrete structures. They also specify the need for ageing management programs. Reference is made to other documents where ageing management approaches are described and how they should be implemented. General condition assessment is not specifically addressed; hence no criteria are available. The only exception is when the containment structure is periodically tested for tightness.
  On the other hand, the U.S. NRC (often in conjunction with National Laboratories such as ORNL, and with the American Concrete Institute) present a comprehensive array of documents providing guidelines for the evaluation of existing nuclear safety-related concrete structures. Since these are prepared in collaboration with ORNL and ACI, they are often identical. Included in this documentation are methods of examination including visual inspections and testing techniques (material characterization, non-destructive evaluation). Acceptance criteria that address the classification and treatment of visual

inspection results is given. No acceptance criteria are provided for the use of testing and NDE.

- Research projects and scientific technical committees: Currently, there is research addressing all the major deterioration mechanism affecting concrete. The advancement of knowledge is the common goal, trying to provide comprehensive mechanistic explanations for the deterioration mechanisms, their consequences on materials and structural behaviour, and models to predict their appearance and development. The applicability of current knowledge to engineering design and assessment principals varies according to the deterioration mechanism. Mechanisms such as chloride and carbonation induced corrosion are well documented and have been described in models useful for design purposes. Other mechanisms have not yet reached this level.
- Deterioration mechanisms: the most common (in the NPP context) were described based on the existing performance criteria and how they might be assessed, a critical review of the criteria, and R&D needs. The mechanisms considered were carbonation and chloride ingress induced corrosion initiation, alkali aggregate reaction, sulphate, leaching, freeze-thaw, corrosion and radiation effects. It can be seen that the availability of criteria, test methods, etc. varies according to the deterioration mechanism.

4.2 FINAL CONSIDERATIONS

In order to assess the effects of age-related deterioration of RCS, condition assessment of concrete structures must be performed. This includes visual inspections, special inspections and analytical methods. Special inspections include the use of both destructive and non-destructive testing. Analytical methods require use of models to either estimate the evolution of deterioration with time, or to re-assess the structural safety of the affects RCS.

A significant proportion of condition assessment is limited to the use of visual inspection. Since inspection based on observation is subjective, and the assessment is in great part qualitative, a lot of effort has been put into developing criteria for the assessment of the condition of RCS. This has resulted in extensive descriptions of damage and defects, including image/pictorial guides. The outcome of a visual inspection is: no need for action; accompany progress with time; or, need for special inspection/intervention. As a result of implementing ageing management programs, NPPs should have in place a comprehensive visual based condition assessment for their concrete infrastructure.

The use of special inspection is strongly dependant on the experience and quality of the structural inspector, and is quantitative in nature. There are no comprehensive guides with procedures to specify the need for destructive and non-destructive testing methods. While destructive testing is standardized to a certain extent, non-destructive examination is not. Furthermore, there are no guidelines how to interpret the results of both destructive and non-destructive tests.

There is a tendency to simplify processes in complicated decision making procedures. This applies particularly to the use of special inspections. An experienced engineer faces the following challenge: to assess the type(s) of deterioration mechanisms in action, identify the environmental stress affecting the deterioration process, specify the necessary additional testing (destructive or not), and evaluate the progress with time of the deterioration and the structural safety as a consequence of doing nothing (waiting), or planning an intervention. Furthermore, the economic consequence of such a decision also bare on the process.

Concrete durability performance is a function of its constituents, its quality, its location and environmental loading conditions. This makes concrete durability a unique evaluation for every structure, and even for the same structure for different structural elements. For this reason, it is - based on nowadays expertise and knowledge level - not possible to generalise acceptance criteria for all levels of condition assessment, and for all structures.

However, there are aspects where improvements can be made and development is needed to increase the reliability of condition assessments especially for RCS. As mentioned previously, there is a need for comprehensive guides with procedures to specify the need for non-destructive testing methods, and guidelines for interpretation of results of both destructive and non-destructive tests, when possible.

With the exception of radiation exposure of concrete, all other deterioration mechanisms reviewed (most common in the NPP context) occur on all types of reinforced concrete infrastructure. The effects of both carbonation and chloride ingress are relevant for the initiation of reinforcement corrosion. This is extensively covered by research and common acceptance criteria are related to the events that promote the initiation of corrosion. Expansive reactions such as alkali aggregate reaction and sulphate attack are difficult to assess, and model, reducing the possibility of defining specific criteria for performance assessment. Typically, these deterioration mechanisms rely on the presence of moisture and reactive composition, which is usually the focus of condition assessments (determining the aggressiveness of the environment and the potential for reactive expansion of the concrete). With regards to the prestressed tendons, the acceptance criteria for the tendon forces are the tendon forces from design that are sufficient to maintain the integrity of the structure.

4.3 FUTURE WORK

As a result of the literature review summarized in this report, a list of R&D needs has been prepared.

General R&D needs:

- Compilation of Nordic NPP Ageing Management approach for RCS, including approach to condition assessment of RCS;
- Standardized/Guideline approach to RCS condition assessment, and for repair of RCS, specific for nuclear structures (Nordic level);
- There are no comprehensive guides with procedures to specify the need for destructive and non-destructive testing methods. While destructive testing is

standardized to a certain extent, non-destructive examination is not. Furthermore, there are no guidelines how to interpret the results of both destructive and non-destructive tests.

- Guidelines must be more specific to the environments and conditions expected to be encountered for nuclear facilities. These include heat, radiation, and potentially limited access to exposed surfaces;
- Comprehensive review of performance parameters for concrete durability and time dependency effects;
- Establish end-of-service criteria specifically for nuclear structures (function of the types of attack that have more influence on their deterioration);
- Development of criteria for the assessment of ISI and monitoring findings to allow proper judgement about the condition of SSC;
- Developing and improving analytical methods (performance models) to assess the effects of age-related degradation of SSC (probabilistic approach);
- Performance models for service-life estimation should include not only chloride ingress, but also oxygen diffusion, moisture transport, electrical potential distribution, corrosion kinetics, heat transfer and carbonation rates, as well as interaction and coupled appearances of these processes;
- Development of inspection and monitoring techniques and methodologies especially for the assessment of the ageing process in inaccessible locations (e.g.: behind liners, reinforcement in massive structures);
- Service-life prediction models based on non-destructive evaluation parameters. Relationship between model parameters and NDE measurements needs to be developed;
- Establishing an open international database to collect data on concrete degradation mechanisms from nuclear industry.

In addition, deterioration mechanism specific R&D needs:

- Carbonation - Study effectiveness of re-alkalization procedures of carbonated concrete; Testing of non-carcinogenic indicators for replacement of phenolphthalein solutions currently used.
- Chloride ingress - Realistic critical chloride contents as a function of concrete composition/quality,exposure and steel surface properties; Chloride binding models that account for effects of binder, additions, temperature fluctuations, pH variations, and ion gradients.
- Alkali aggregate reaction and sulphate attack - Study relationship between performance testing (lab) and field performance under outdoor exposure conditions; Effect of coupling exposure conditions on the gel development; Efficient neutralization of concrete alkaline content in depth;
- Freeze-thaw – Scaling/Internal damage; Compatibility between air entrainment agents and new cement blends; Effective NDE for early age damage detection due to internal damage; Development of prediction models for internal cracking;
- Reinforcement corrosion - Modelling propagation phase in chloride environment - time to crack opening; Models for corrosion rate prediction and NDE methods for corrosion rate detection;
- Radiation effects - Detection of RIVE using NDE; Remote NDE for comprehensive containment assessment.

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ACCEPTANCE CRITERIA FOR MAINTENANCE OF NUCLEAR CONCRETE STRUCTURES

The aim of this preliminary study is to identify and compile information regarding existing acceptance criteria that trigger maintenance actions of reinforced concrete infrastructure of nuclear facilities. In order to assess the effects of age-related deterioration of reinforced concrete structures, structural condition assessment of concrete structures must be performed. This includes visual inspections, special inspections and analytical methods.

This study reveals that a significant proportion of condition assessment is limited to the use of visual inspection. Since inspection based on observation is subjective, and the assessment is in great part qualitative, a lot of effort has been put into developing acceptance criteria for the assessment of reinforced concrete structures. This has resulted in extensive descriptions of condition damage and defects, including image/pictorial guides.

Using special inspection is strongly dependant on the experience and qualification of the structural inspector, and is qualitative in nature. There are no comprehensive guides with procedures to specify the need for destructive and non-destructive testing methods. Furthermore, there are no guidelines how to interpret the results of both destructive and non-destructive tests.

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