ACCEPPT – AGEING OF CONCRETE AND CIVIL STRUCTURES IN NUCLEAR POWER PLANTS

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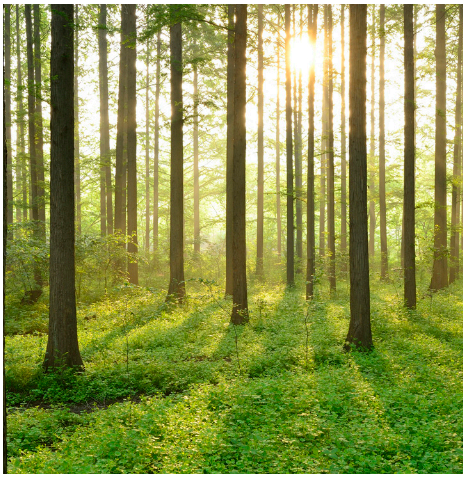

BETONGTEKNISKT PROGRAM
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ACCEPPT – Ageing of civil and concrete structures in nuclear power plants

Project summary

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Foreword

The nuclear power plant containments are designed to protect the outside environment in case of accidents. Regardless the age and the stage of the production of the NPPs, the owners of the NPPs have to guarantee their safety and serviceability. The owners have to show that their structures meet all requirements made by the authorities and other legislators. The owners have to assess the condition of the structures and provide reliable information about the current and future condition of the structures

In the project ACCEPPT (Ageing of Concrete and Civil structures in nuclEar Power PlanTs) several European nuclear power producing companies co-operated in developing the knowledge regarding the aging of pre-stressed containments with an internal steel liner. ACCEPPT regarded the ageing of prestressed nuclear reactor containments with an internal steel liner and was divided into two major parts.

The project had two focus areas; whether or not the pre-stressed structure and its constituents fulfil as designed/according to new requirements and the liner's ability to fulfil the required tightness.

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

Sammanfattning

ACCEPPT (ageing of civil and concrete structures in nuclear power plants) var ett europeiskt projekt som utfördes i samarbete mellan flera europeiska kärnkraftsproducenter. Projektet hanterade olika åldersrelaterade frågeställningar för spännarmerade reaktorinneslutningar försedda med en tätplåt. Arbetet inom projektet var indelat i två huvuddelar.

Den första delen fokuserade på olika frågeställningar rörande tätplåten och dess integritet. Denna del omfattade en genomgång av observerade skador och använda reparationsmetoder, en studie avseende olika oförstörande provningsmetoder (OFP) för att detektera skador på tätplåten samt både laboratorieförsök och modellering av samverkan mellan tätplåt och betong. Genomgången av observerade skador visade att de främsta skadeorsakerna på tätplåten är korrosionsskador samt sprickor i svetsar. Resultaten från genomgången av olika OFP-metoder visade att för global detektering av skador är sensorer av Microflown typ alternativt så kallade akustiska kameror mest lämpliga. För lokal detektering visade sig handhållna ultraljudsinstrument av typen Rotoarray vara effektiva för att detektera bland annat delamineringar och simulerade korrosionsskador mellan tätplåt och betong. Samverkan mellan tätplåt och betong undersöktes genom både försök på en laboratoriemodell samt med modellering av modellens beteende. Modellen bestod av en betongplatta med förankrad tätplåt, under försöket utsattes modellen för liknande belastningar som under en LOCA (loss of coolant accident). Resultaten visade att uppmätta töjningar var långt under töjningsgränsen för materialet och att ingen separation mellan tätplåt och betong kunde observeras. Modellering av samverkan mellan tätplåt och betong visade på god överensstämmelse med uppmätt beteende. Resultatet blev en modell som inkluderar effekterna av krypning och krympning i betongen för att beskriva tätplåtens beteende under LOCA belastning. Rekommendationen var att använda denna modell vid analyser av tätplåtens funktion över lång tid.

Den andra delen av projektet fokuserade på reaktorinneslutningen och åldringsfrågor relaterade till betongen. Detta inkluderade skador och degraderingsmekanismer samt långtidseffekter i materialen och klimatet och hur det påverkar spännings- och töjningstillstånden i en reaktorinneslutning. En sammanställning visade att väldigt få skador rapporterats på betongkonstruktionerna i reaktorinneslutningar. De skador som rapporterats beror till största delen på misstag under byggtiden och inte på degradering av materialen över tid. Beteendet hos en inneslutning till en tryckvattenreaktor modellerades under hela inneslutningens livslängd och resultateten jämfördes med mätningar. Resultaten visade att både axisymmetriska och modellering i 3D kan beskriva töjnings- och spänningsförändringar i inneslutningen över lång tid. Detta inkluderar effekterna av krympning och krypning hos betongen, relaxation av spännstålet samt inverkan av fukt- och temperaturförändringar. Resultaten visade även att analyser av fukt- och temperaturtillstånden måste inkluderas i analyser av spännings- och töjningstillstånden i en reaktorinneslutning. En förutsättning för att utföra tillförlitliga analyser av en inneslutnings beteende är att ha tillgång till relevanta mätdata för att kunna verifiera både själva modellen och indatan till modellen. Detta innebär att det måste vara möjligt att utföra mätningar på själva konstruktionen men även finnas tillgång till tillförlitlig materialdata, t.ex. från tester på små provkroppar.

Summary

The project ACCEPPT (Ageing of Concrete and Civil structures in nuclEar Power PlanTs) is a result of cooperation between several European nuclear power producing companies. ACCEPPT regarded the ageing of prestressed nuclear reactor containments with an internal steel liner and was divided into two major parts.

The first part focused on the containment liner with regard to functionality, i.e. the ability of the liner to fulfil the required tightness. This included review of liner designs and damages, evaluation of non-destructive examination (NDE) methods for detecting liner defects, review of repair techniques and modelling and testing of the interaction between liner and concrete. The results of the investigation of observed liner damages showed that the most commonly observed damages are blistering and corrosion damages of the steel liner and cracking of liner welds. The review of NDE methods showed that for global inspection of defects in the steel liner acoustic cameras or Microflown sensors should be applicable during containment pressure tests. For local detection of liner defects ultrasonic hand held devices such as Rotoarray are able to detect defects such as delamination and corrosion. Investigation of the interaction between liner and concrete were performed through structural tests of a liner mock-up during loss of coolant accident (LOCA) conditions and numerical modelling of the test. Results from the test indicated that the liner will maintain its integrity during LOCA conditions. Measured strains were significantly lower than the ultimate tensile strain and no cracks or separation between liner and concrete were observed. Modelling of the studied interaction between liner and concrete were in good agreement with the measurements and resulted in a calculation method that could accurately describe the behavior of the liner during LOCA conditions. The method was recommended to be applied for reactor containments when analyzing the effects of long-term mechanisms on the behavior of the liner.

The second part dealt with the prestressed containment with focus on functionality requirements, i.e. whether or not the structure and its constituents fulfil the design requirements. This included summary of containment designs, review of observed degradations and modelling of the long-term behavior of the containment regarding changes in the state of stress and strain including modelling of moisture and temperature conditions. The investigation of observed degradations showed that few cases of concrete damages have been noticed/published by NPP owners. Observed damages are mainly due to mistakes during the construction phase and not due to ageing effects or degradations of the different materials. The long-term behavior of a pressurized water reactor containment was modelled and verified against performed measurements. The results showed that both axisymmetric and 3D non-linear analyses are applicable for determining overall stresses, strains and displacements due to relaxation of tendons, creep and shrinkage of the drying concrete and temperature variations. In addition, all condition assessments and analysis of long-term behavior regarding stress and strain conditions of reactor containments must include analysis of the moisture and temperature distributions. It is also crucial to have the possibility to calibrate and verify both the models and input data in order to make reliable predictions of the structural behavior of reactor containments. Thus it must be possible to perform measurements on the studied structure but also to take samples from the structure and monitor different physical and mechanical properties of the materials on site.

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1 Introduction

1.1 BACKGROUND

This report compiles the work accomplished within the project ACCEPPT (Ageing of concrete and civil structures in nuclear power plants), which regarded the ageing of prestressed nuclear reactor containments with an internal steel liner. ACCEPPT was a project in the NUGENIA (Nuclear generation II & III association) portfolio. NUGENIA is an International non-profit-making association, according to 1921 Belgian law, established in Brussels on November 14th, 2011.

The participating companies in ACCEPPT were: AREVA, Germany, CEZ, Czech Republic, EDF, France, Fortum, Finland and Vattenfall, Sweden. The project started in October 2012 and was finalized in May 2015. During the project creation it was decided that ACCEPPT should only address major issues regarding reactor containments and that the technical work should be carried out within two Work Packages (WP). The WPs and their activity domains are the following:

1.1.1 WP1: Containment liner

WP1 dealt with the containment steel liner with regard to functionality, i.e. the ability of the liner to fulfil the required tightness. Examples of items among the major issues addressed were reported damages of embedded liner, non-destructive examination methods, repair techniques for accessible parts and interaction between liner and concrete.

1.1.2 WP2: Prestressed concrete containments

WP2 dealt with the prestressed containment with primary focus on functionality requirements of the concrete structure and post-tensioned reinforcement, i.e. whether or not the structure and its constituents fulfil the designed or possibly new requirements. The following items were among the major issues which were addressed:

- Changes in the state of stress and strain in reactor containments and post-tensioned tendons,
- Ageing and degradation of concrete and the reinforcements caused by different physical, chemical and electro-chemical degradation processes.

1.2 REACTOR CONTAINMENT

The reactor containment enclosing the reactor is the most important safety barrier in a nuclear power plant. The main purpose of the containment is to prevent radioactive discharge in case of a severe internal accident but also to protect the reactor from external hazards. In Europe the most common design of the containment is that of a concrete cylinder prestressed both horizontally and vertically. In Figure 1 the principal design of the containments for boiling water and pressurized water reactors are shown. On the inside of the containment a steel liner secures the leak tightness of the structure. The main accident scenario which the containment is designed to withstand is the so-called loss of coolant accident (LOCA). A LOCA can be initiated by e.g. a pipe rupture in the cooling system causing a discharge of steam into the containment. The release of steam increases both the temperature and pressure inside the containment, which induces tensile stresses in the concrete walls. Primarily, the function of the prestressing system is to counterbalance these tensile forces, i.e. maintain the concrete in a compressive state. The function of the steel liner is to further increase the leak tightness and thus the integrity of the containment, especially at local discontinuities such as pipe penetrations.

Due to long-term effects in the materials the tendon forces in the prestressing system will decrease over time, which will influence the safety of the structure negatively. These prestress losses are thus important to monitor, e.g. in containments with unbonded tendons this is performed through measurements with hydraulic jacks. In containments with bonded tendons no direct measurements are possible and hence more advanced methods for estimating the containments safety is thus needed. The estimation of the long-term behavior of containments is one of the primary objectives of WP2.

The integrity of the steel liner is primarily affected by damages mainly due to corrosion. Furthermore, the interaction between steel liner and the concrete during an internal over pressure may also have a major impact on the integrity of both the steel liner and the containment. The behavior and degradations of the steel liner is the major objective of WP1.

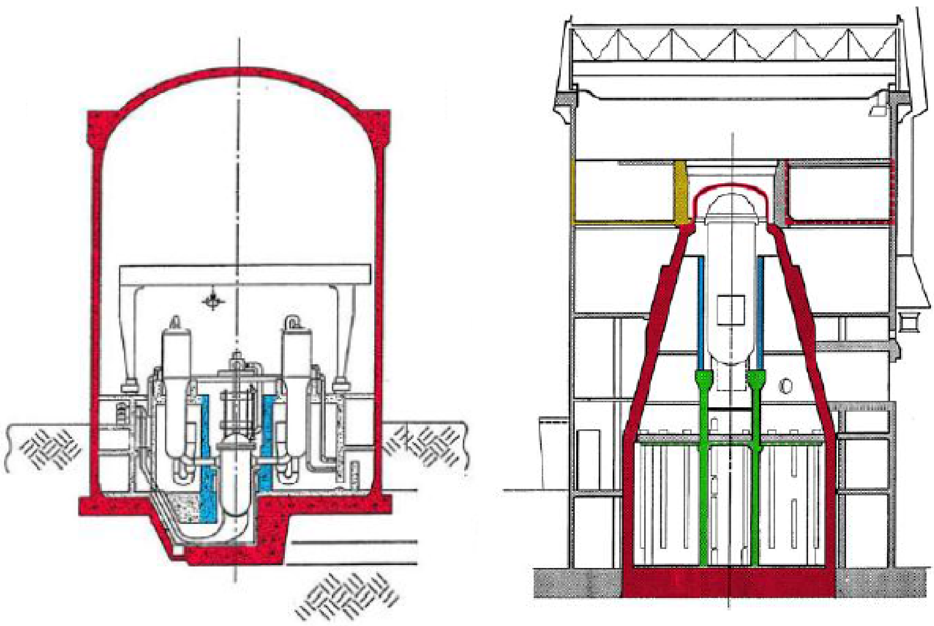

Figure 1. Principal layout of containment design (red) for a pressurized water reactor (left) and a boiling water reactor (right) [1].

2 Work Package 1: Containment liner

2.1 INTRODUCTION

The objective of WP1 was to investigate different aspects regarding the ability of the steel liner to fulfill the required tightness criteria.

The work within WP1 was subdivided in the following five groups (G):

- G1 – General characteristics of liners in European power plants, which regarded the compilation of general information of the liners in the reactor containments owned by the partners in the project,
- G2 – Non-destructive examination, which regarded the investigation of both global and local non-destructive testing methods for detecting damages on the steel liner,
- G3 – Liner repair techniques which regarded the compilation of used techniques for repairing damages to steel liners in reactor containments,
- G4 – Structural interaction of liner and concrete. A mock-up of a part of a containment wall was tested in order to investigate the behavior during a loss of coolant accident. The behavior of the mock-up was also modelled numerically,
- G5 - Compilation of general report, a summary of the results from WP1.

2.2 G1: GENERAL CHARACTERISTICS OF LINERS IN EUROPEAN POWER PLANTS

In WP1:G1 the general properties and observed defects of the steel liners in the containments owned by the partners in the project were compiled. In addition, based on the leak tightness requirements, the critical size of a defect in the liner which needs to be found using the non-destructive methods in G2 was proposed. From the compiled information the following conclusions were drawn:

- The mechanical properties of the liners are similar for all the studied containments. Typically, the yield strength varies between 200 MPa and 300 MPa and the ultimate strength is approximately 500 MPa. The liner thickness varies between 3 and 10 mm,
- The most commonly observed damages are blistering, corrosion and of the liner and cracking of welds,
- The size of a critical defect was determined to a 100 mm long and 0.1 mm wide opening, which is also equivalent to a circular hole with 0.2 mm diameter.

2.3 G2: NON-DESTRUCTIVE EXAMINATION

The study in WP1:G2 consisted of three parts: Part 1: Literature review, Part 2: Defining requirements for a new development of non-destructive examination (NDE) techniques and Part 3: Demonstration of performance of the techniques. The objective of the studies was to identify and propose one or several NDE methods that can be used to verify the leak tightness of the steel liner. This means that the methods should be able to detect a defect of the size determined in G1, either a 100 mm long and 0.1 mm wide crack or a circular hole with 0.2 mm in diameter.

2.3.1 Part 1: Literature review

The literature review comprised of two steps, in the first step a global method for inspecting the entire liner area, which can be up to 20 000 m^2, was investigated. The priority was to identify NDE methods that could be used during a containment pressure test. The second step was to identify NDE methods for local inspections, in this case to find a leak in a 3 m diameter disc equivalent to a 1.6 x 4.8 m part of the cylindrical wall of a containment. The strategy for detecting defects is to implement one global method during the pressure test to identify areas with defects. In these smaller areas the local method should be implemented to more accurately determine the position of the defect. Several different methods were investigated and the following methods were presented as promising for global detection and should be tested. All the proposed methods take advantage of the deformations that could take place due to the increased internal pressure which may generate airborne or structure-borne acoustic or ultrasonic signals.

- Microflown sensor, which is a probe measuring the velocity field in the air based on the hot wire principle. A sensor typically consists of three orthogonally positioned wires thus being able to determine the direction of the air flow from a single measuring point,
- Acoustic camera, which consists of several cameras and microphones. Due to the number of microphones this measuring device can determine the direction to the source of the acoustic emission,
- Acoustic emission methods which measure mechanical waves in the concrete and/or steel liner. These methods could also be used for monitoring of the containment during normal operation.

For the local inspections methods the following techniques were proposed to be tested.

- Hand held ultrasonic transducer, an example is the RotoArray which consists of a 100 mm wide roller housing a 64 channels ultrasonic array,
- Lock-in thermography in which the liner will be heated and the response of the liner will be monitored by a thermal camera. E.g. voids between liner and concrete can be detected since the liner will not be cooled by the concrete in this section and thus detected by the thermal camera.

In Figure 2, examples of devices for the proposed global and local NDE methods are shown.

Figure 2. Examples of transducers for the proposed NDE methods. A hand held ultrasonic device, RotoArray from General Electric (left), and an acoustic camera from Brüel & Kjaer for global inspection (right).

2.3.2 Part 2: Defining requirements for a new development of NDE techniques

In part 2 the requirements for the NDE techniques were stated. It was proposed that the inspection of the liner should be performed in the following steps:

1. Global inspection of the the entire liner area of 10 – 20 000 m^2 where regions of approximately 8 m^2 containing suspected defects are detected. Both the Microflown sensor and the acoustic camera are probably capable of doing this, however, this need to be confirmed through tests,

2. Locate the points where defects are present in the previously defined 8 m^2 area. Both lock-in thermography and the Rotoarray are capable of performing this,

3. When the position of the defect is identified local methods able to determine the characteristics of the defect should be applied. Depending on the cause of the defect this may require a set of different sensors/techniques to accurately characterize the defect.

2.3.3 Part 3: Demonstration of performance of the techniques

An 800 x 1200 x 250 mm concrete mock-up with one surface covered with a steel liner was manufactured. A number of defects affecting the bond between liner and concrete were added, e.g. one missing stud, a number of delaminations of different sizes, simulated corrosion and a defect in one weld. A Rotoarray transducer was tested on the mock-up and was able to detect the studs, delamination and corrosion between the liner and concrete. In Figure 3 an example of a simulated delamination between liner and concrete are shown along with the image of the delamination obtained by the Rotoarray device. An acoustic array mounted on a wedge producing guided waves was able to detect the simulated crack in the weld.

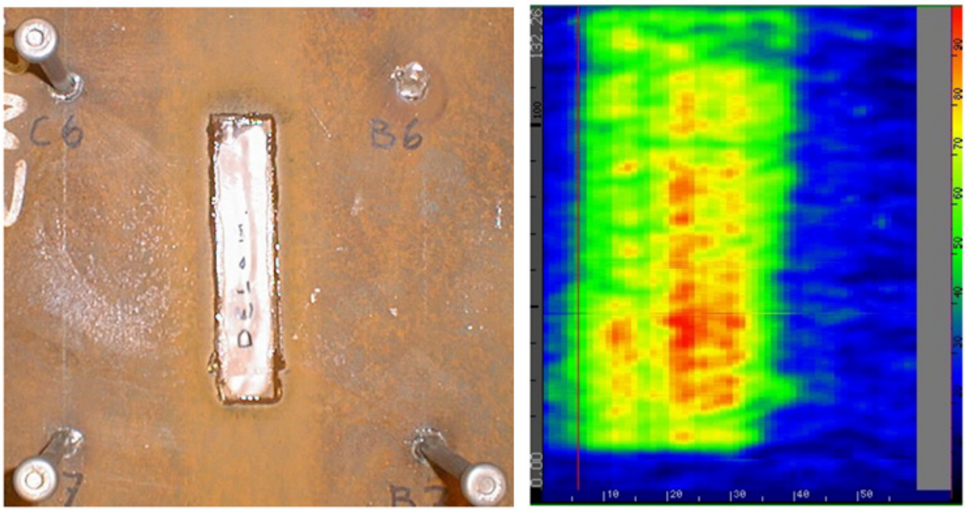

Figure 3. Simulated delamination between liner and concrete (left) and the image of the delamination obtained from the Rotoarray device (right).

As a feasibility study for using the proposed global methods, i.e. Microflown or acoustic camera, the acoustic environment during the pressure test in one reactor containment was established by the use of microphones. It was found that during the increase of the internal pressure the noise level was too high to permit acoustic analysis but during the periods with static over pressure such detection was possible. In fact, several acoustic emissions were detected during the static over pressure.

2.3.4 Conclusions

From the work conducted within WP1:G2 the following main conclusions could be drawn:

- A survey for defects should be divided into three steps: global inspection, local inspection and characterization of located defects,
- Ultrasonic hand held devices such as a Rotoarray are suitable for local detection of areas up to 8 m^2 and are able to detect defects such as delamination and corrosion,
- Mapping of the acoustic environment during a pressure test in one containment showed that acoustic cameras or Microflown sensors should be applicable for global inspection of the liner. Tests of these sensors during a pressure test were thus recommended to be performed.

2.4 G3: LINER REPAIR TECHNIQUES

In WP1:G3 a review of proposed and/or used techniques for repairing liner damages were performed. The results from the review showed that the available information on this subject is very poor. However, the following four proposed methods for repairing corrosion damages were found:

- The replacement plate welding procedure,
- The double-plate welding procedure,
- The stiffener plate welding procedure,

- The surface overlay welding procedure.

The first and second methods include removal of the damaged liner and the cause of the corrosion, cleaning the concrete and welding a metallic plate to the original liner. The leak tightness of the repair is then checked. The two last methods do not include removal of damages liner or the cause of the corrosion. They only consist in adding an additional steel thickness to the liner. The advantage here is that leak tightness does not need to be checked after the performed repair since the liner has not been perforated. However, the corrosion process will still be active. Important to note is that these proposed methods are only applicable to liners with one accessible side and is thus not applicable for Swedish and Finnish containments where the inside of the steel liner is protected by an concrete wall.

2.5 G4: STRUCTURAL INTERACTION OF LINER AND CONCRETE

In WP1:G4 a structural test of a mock-up representing a section of a containment wall was performed. The purpose of the test was to investigate the structural behavior of the liner during a loss of coolant accident (LOCA), i.e. during an internal over pressure, and also taking the effect of creep and shrinkage as well as liner buckling into account. In addition, the behavior of the mock-up was simulated using finite element (FE) analysis.

2.5.1 Mock-up test

The mock-up had a height and width of 2.3 m and 1.71 m, respectively, with a thickness of 50 mm. The steel liner consisted of three steel plates with a height of 766 mm each and had a thickness of 6 mm. Similarly to the liner in a containment the liner was supplied with four horizontal stiffeners and studs with a distance of 150 mm. For the concrete part the concrete quality C60/75 was used. Conventional steel reinforcement bars were installed with a distance of 207 mm in both vertical and horizontal directions. Vertical prestressing was simulated by the use of a test frame and horizontal prestressing by the use of hydraulic jacks. Long-term effects, i.e. creep and shrinkage of concrete, and the loads during LOCA were simulated by applying a temperature load on the liner thorough the use of heating mats, see Figure 4. In order to simulate buckling of the liner, imperfections were introduced during the manufacture of the liner. These imperfections consisted of a global sinusoidal imperfection with amplitude of 20 mm and three local imperfections of 5 mm at certain stud locations. In addition, one stud was deliberately missing to simulate the failure of a stud.

Creep and shrinkage was simulated by increasing the temperature of the mock-up by 100°C. To simulate the conditions during LOCA, the temperature was increased an additional 100°C.

Several different measurement devices were used to monitor the behavior of the mock-up during the test. The three smaller imperfections were instrumented with strain and displacement gauges and the global behavior of the mock-up were monitored by an optical measurement system. In addition, temperature gauges were installed both inside the concrete and on the surface of the steel liner.

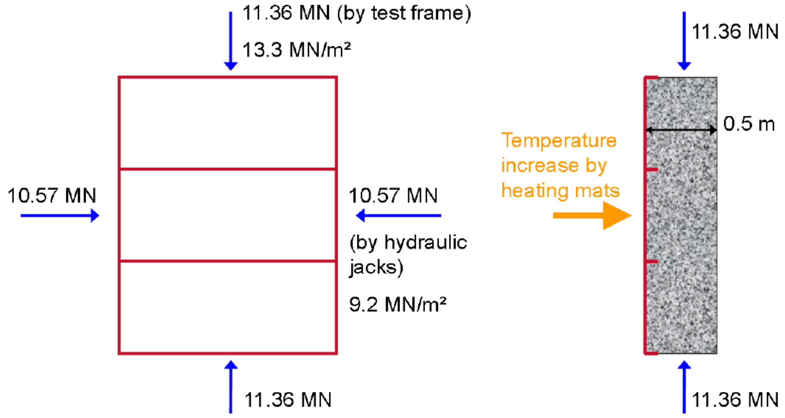

Figure 4. Application of prestressing forces and temperature loads on the mock-up.

In Figure 5 the measured strains and temperature at the position of the missing stud are shown. At this position the maximum liner strains were measured during the test. Plastic deformations was observed in the liner, however, the strains were significantly lower than the ultimate tensile strain indicating that the liner integrity will be maintained during LOCA. The maximum deformation due to liner buckling was 5 mm at the position of the missing stud. After the test was finalized, additional measurements to investigate the separation between liner and concrete were performed. It was only at the positions of the imperfections were separation could be detected. Furthermore, a penetrant test that was performed showed that the integrity of the liner was maintained during the test and no cracks in the liner could be detected.

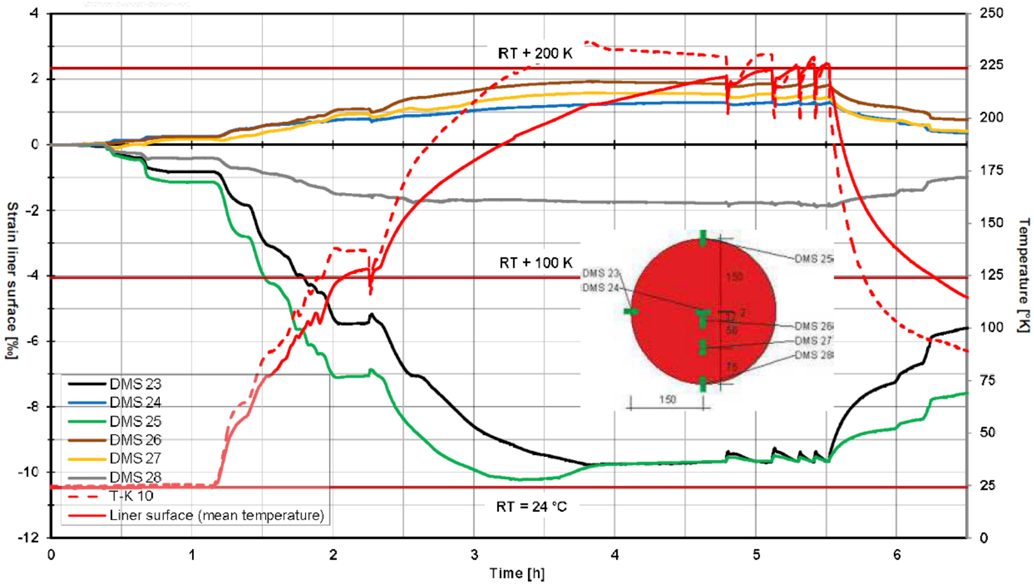

Figure 5. Results from the test of the mock-up, measured strains and temperatures at the position of the missing stud.

2.5.2 Modelling

The objective of this study was to develop a method for predicting the effect of ageing phenomena in the concrete, such as creep and shrinkage, on the behavior of the liner. The behavior of the mock-up was modelled using two different FE-models.

- A linear elastic FE-model for simulating the global deformations of the wall, in this model no imperfections or studs were included. The results from this model, i.e. deformations due to prestressing and temperature gradient, were used as input for the shell FE-model.
- A shell FE-model including all details of the mock-up and based on non-linear material properties. The liner studs and stiffeners were modelled separately as discrete springs. In order to model the studs and stiffeners more realistically their behavior was based on load-displacement curves for both axial and shear loading determined through tests. The manufactured imperfections in the mock-up were also included. The measured temperatures from the test of the mock-up were applied on the model either as a temperature distribution through the thickness of the mock-up or as a mean temperature. Friction and adhesion between concrete and liner was also included. To investigate the influence of different values of the adhesion and the two different ways of implementing the temperature 18 different cases were studied. Creep and shrinkage was simulated by applying an equivalent temperature field.

In Figure 6 and Figure 7 the results from the modelling of the strains in the liner at the position of one of the small imperfections and the missing stud are shown. The different lines in the figures correspond to different cases with varying values of the adhesion between liner and concrete. For all these cases the temperature was applied as the temperature distributions. The results from these cases were those who were in best agreement with the measured results. As can be seen the cases 12d and 13 are in good agreement with the measurements at both imperfections. Furthermore, the results from the modelling confirmed that the strains in the liner are significantly lower than the ultimate tensile strain during LOCA conditions.

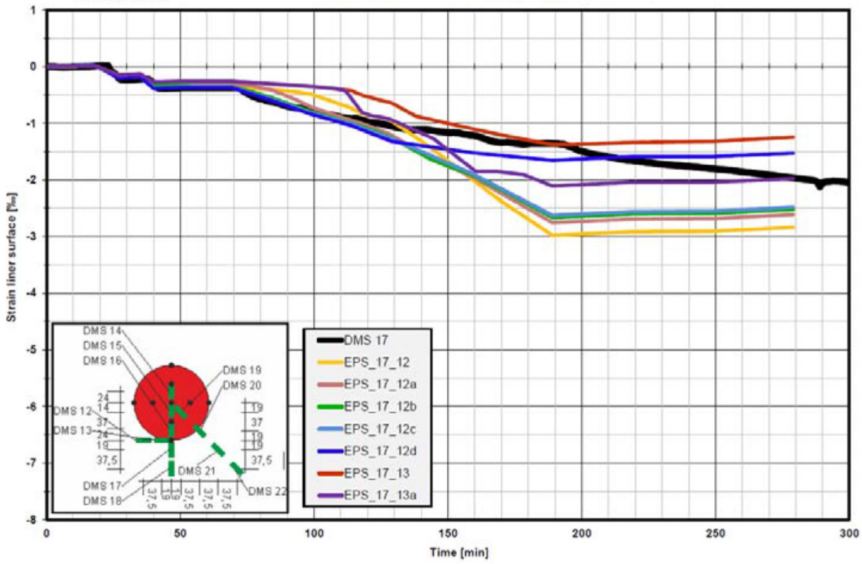

Figure 6. Results from the FE-modelling of the liner behavior at the position of one of the small manufactured imperfection during LOCA conditions.

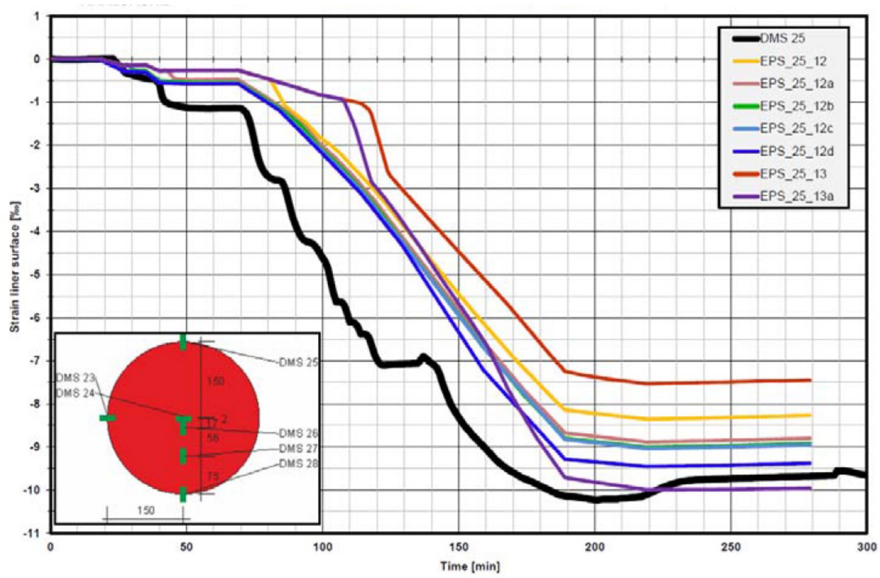

Figure 7. Results from the FE-modelling of the liner behavior at the position of the missing stud during LOCA conditions.

From the results it was concluded that the proposed liner calculation method was validated and was recommended for application on other liner structures in reactor containments.

3 WP2: Prestressed concrete containments

3.1 INTRODUCTION

The main objective of WP2 was to predict the service life of the reactor containments through determination of changes in the state of stress and strain in reactor containments and post-tensioned tendons and ageing and degradation of concrete and the reinforcements caused by different physical, chemical and electro-chemical degradation processes. It should be noted that since no degradation processes which seriously compromise the safety of the reactor containment have yet been observed, and due to shortage of the economic resources the first item predominated the work within WP2.

The work within WP2 was subdivided in the following five groups:

- G1 – Nuclear power plant structures and materials, which comprised of compiling information about the reactor containments owned by the partners in the project.
- G2 - Degradation matrix and state-of-the-art concerning degradation processes which are observed in different plants.
- G3 - Structural analysis – numerical simulations. An axisymmetric model was established as a first step. As a second step stress concentrations and crack risks were analyzed by means of 3D analysis.
- G4 - Determination of current and future conditions of moisture and temperature in the structure. The results were needed to carry out the 3D analysis in G3. The project included modelling of the temperature and moisture condition of the reactor containment.
- G5 - Compilation of general report, which compiled the results of WP2.

The work within WP2 was limited to only focus on prestressed concrete containments with an internal steel liner.

3.2 G1: NUCLEAR POWER PLANTS STRUCTURES AND MATERIALS

In WP2:G1 the main features regarding structural and material properties of nuclear reactor containments with an internal steel liner owned and operated by the participating companies are presented. In addition, important experiences during construction and operation, e.g. observed defects, ageing and damages, are briefly described.

From the information compiled in WP2/G1 the following general conclusions were drawn:

- Since the majority of the containments were built in the seventies and early eighties the principal features in design are similar. Examples are dimensions of containments with similar reactor types, tendon layout, design pressure (around 0.5 MPa) and the use of conventional non-prestressed reinforcement.
- Outline and placement of the steel liner are similar for all containments, some main differences are e.g. the thickness of the steel and that Swedish and

Finnish liners are protected by an internal concrete wall, i.e. the liner is embedded in the concrete wall.

- The variation of the initial tendon forces is relatively large, which is somewhat expected since different post-tensioning systems have been used and the containments vary in size. Thus the induced compressive stresses in the concrete vary to the same extent; typically the concrete stresses are approximately 50 % higher in PWR containments compared to BWR containments.
- Generally, containments with bonded tendons are more rigorously instrumented than containments with unbonded tendons, which most probably is due to the possibility to measure tendon forces in unbonded tendons during the containments service life.

3.3 G2: THE FACILITIES DETERIORATION MATRIX AND OBSERVED DETERIORATION CASES

WP2:G2 focused on establishing a state-of-the-art report through a literature review regarding degradation mechanisms/damages observed in the containments owned by the participating companies. In addition, degradation matrix and description of degradation mechanisms which may occur in a containment structure were described.

The summary of degradation mechanisms showed that cracking of the concrete, e.g. due to freezing and thawing, is the most prevalent manifestation of concrete degradation. From the review of observed damages it was found that few damages have been reported by nuclear power plant owners and that the major damages that have occurred in Europe are corrosion damages to the steel liner. Generally, observed damages are due to the mistakes during the construction phase and not due to the ageing effects or degradations of the different materials.

3.4 G3: STRUCTURAL ANALYSIS – NUMERICAL SIMULATIONS

The work within WP2:G3 was divided into two subgroups: G3.1: Numerical simulations using axisymmetric analysis and G3.2: Analysis of stress concentrations and crack risks using a 3D FE model, comprising the modelling of the long-term behavior of an existing prestressed nuclear reactor containment. Results from the modelling were compared to strain and displacement measurements performed continuously since the prestressing of the tendons at the studied containment. The studied reactor containment was a typical PWR containment with horizontal and vertical tendons in the cylinder wall and three layers of tendons in the dome.

3.4.1 G3.1: Numerical simulation using axisymmetric analysis

Analysis

Within G3.1 the modelling of the containment was performed by both analytical calculations and an axisymmetric FE model. In both models the long-term behavior of the containment was taken into account by using models for creep and shrinkage of concrete and relaxation of the prestressing steel. In addition, linear elastic material properties were assumed for both concrete and steel.

As a first step of the analysis of the long-term behavior of the containment, i.e. the development of stresses and strains in the containment, analytical calculations were performed. The stresses and strains in the structure were calculated at six different points in time during the containments service life. The first five points regarded the different points in time where measurements have been performed, in this case the first four periodical pressure tests and the latest measurement during service at an age of the containment of 30 years. The final point was a prediction of the future behavior at the end of the service life of the containment, i.e. 60 years after the tensioning of the tendons. Examples of phenomena taking into account in the calculations of the structural behavior were: long-term effects modeled using equations for concrete creep and shrinkage and relaxation of the prestressing steel according to Eurocode 2 [2] and ETC-C [3], the influence of liner, conventional steel reinforcement and tendons on the biaxial stress state in the concrete.

The second step was FE modeling performed using an axisymmetric model. In addition to the analysis of the long-term behavior of the containment similar to that performed in the analytical analysis the simulations of a crack in the cylinder wall, a tendon failure and the stress state in the ring beam were analyzed. These three additional analyses were assumed to occur during the event of a maximum over pressure at the end of the service life of the containment. In the analysis of the long-term behavior the stresses and strains calculated in the analytical analysis was used in the FE-model and was applied as a temperature load (decrease in temperature) corresponding to the calculated creep and shrinkage strains.

The results from the calculations using the two analysis methods described above were compared to the measured strains and diameter variation both during periodical pressure tests and those obtained during the latest measurement 30 years after tensioning of the tendons.

Results

The results for the cylinder wall from both the analytical and FE-analyses were in good agreement with the measurements of the long-term development of the strains. The calculated response during the periodical pressure tests was in good agreement with the measured strains for both the analytical model and the FE-model, except for the initial pressure test where the deviation from the measured strains was almost 50 %.

In Figure 8, the calculated concrete stress in the containment during the entire service life of the containment according to the FE-analysis is shown. As can be seen the induced compressive stress in the concrete due to the tendons decrease with time. At the latest pressure test tensile stresses of approximately 0.2 MPa occur in the structure and at the end of the service life, 60 years after the prestressing the tensile stresses during an internal over pressure has increased to 1.1 MPa. This will not influence the safety of the structure since the maximum tensile stresses during an internal over pressure is well below the characteristic tensile strength of the concrete, which is equal to 2.4 MPa.

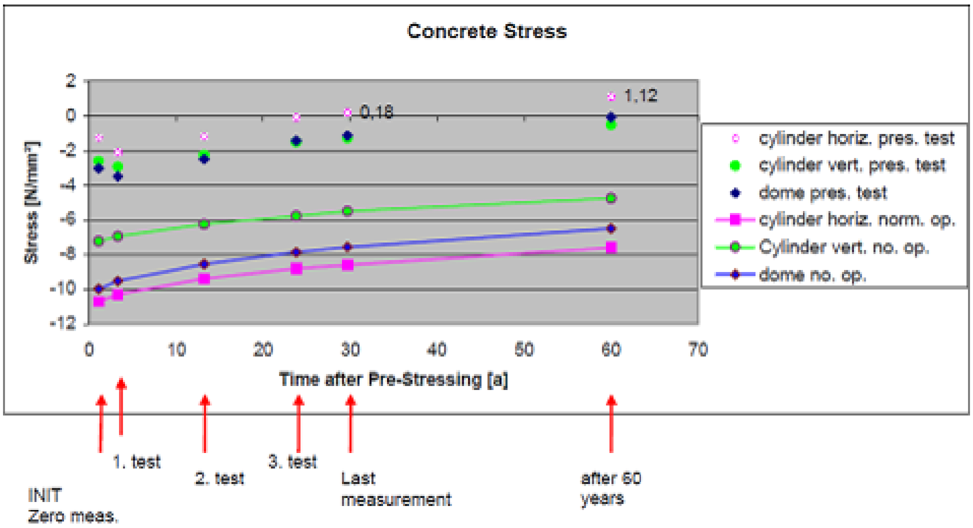

Figure 8. Variation of the stress in the concrete during a period of 60 years, results from FE-calculations.

The analysis of a tendon failure in the cylinder wall showed that for each lost tendon the compressive stress in the concrete was reduced by 3-4 %. During an internal over pressure at the end of the service life of the containment this will correspond to a decrease in the compressive stress in the concrete by 0.25 MPa, i.e. an increase of the tensile stresses by 22 %. The simulation of a crack in the cylinder wall showed that the crack will influence the stress in the concrete along a length of approximately 3 m in the vertical direction (1.5 m in each direction from the center of the crack). At an internal over pressure at the end of the service life of the containment the crack will influence the tensile stresses in the concrete in both the vertical and horizontal direction. However, this influence is too small to be detected by one of the installed strain gauges.

3.4.2 G3.2: Analysis of stress concentrations and crack risks

A nonlinear 3D FE-model was developed based on the geometry from the 2D FE-analysis in G3.1. Additional geometric details, e.g. the major penetrations in the containment and the internal steel parts, were included in the model. The behavior of the concrete was described by a non-linear material model taking cracking of the concrete into account. All steel components were modeled using elasto-plastic material models. The long-term effects in the concrete and prestressing steel were modeled using the same equations as in G3.1. In order to increase the accuracy of the models the results from G4 regarding temperature and moisture conditions were used as input to the analysis. Due to the size of the model relatively coarse mesh had to be used to reduce computational time, therefore a sub model was analyzed comprising a ring cut out of the cylinder wall where a significantly finer mesh could be used.

Results

In Figure 9, the results from the global long-term analysis regarding crack propagation in the containment are shown for three different points in time, directly after the prestressing, after the 1st periodical pressure test and at the end of the service life of the containment (60 years after prestressing). As can be seen cracking of the containment occurs to some extent during the prestressing of the tendons. During the first periodical pressure test the cracks in the dome and in the connection between cylinder wall and bottom slab have propagated further. In addition, new cracks have developed in these two regions as well as around the equipment hatch at mid height of the containment. At the final time step, all previously observed cracks have propagated further and additional cracks have developed in the dome and the upper parts of the cylinder wall. However, the cracks observed from the results are only surface cracks and do not propagate more than 75 mm into the structure. This can be seen from the results in Figure 10, showing the results from the sub-model of a horizontal section at mid-height of the containment. The sub-model was comprised of a much finer mesh than the global model thus describing the cracking in the outer parts of the containment in more detail.

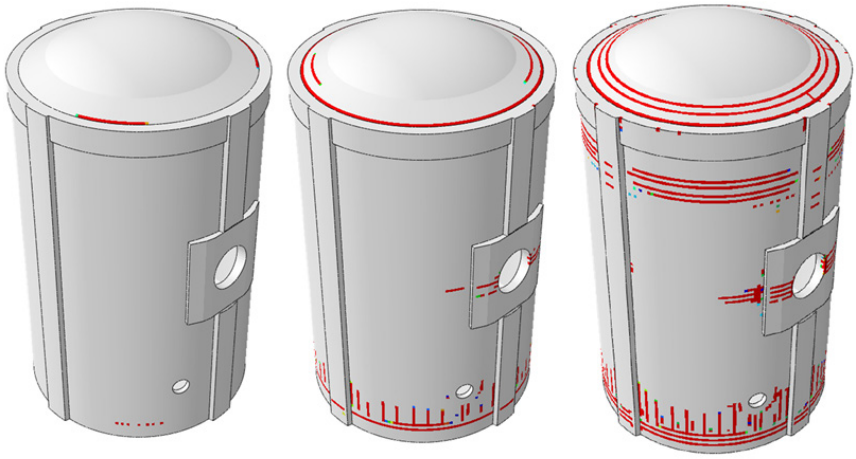

Figure 9. Results from the global long-term analysis showing the propagation of cracks at three different steps of the analysis, after prestressing (left), at the first periodical pressure test (middle) and after 60 years of reactor operation (right).

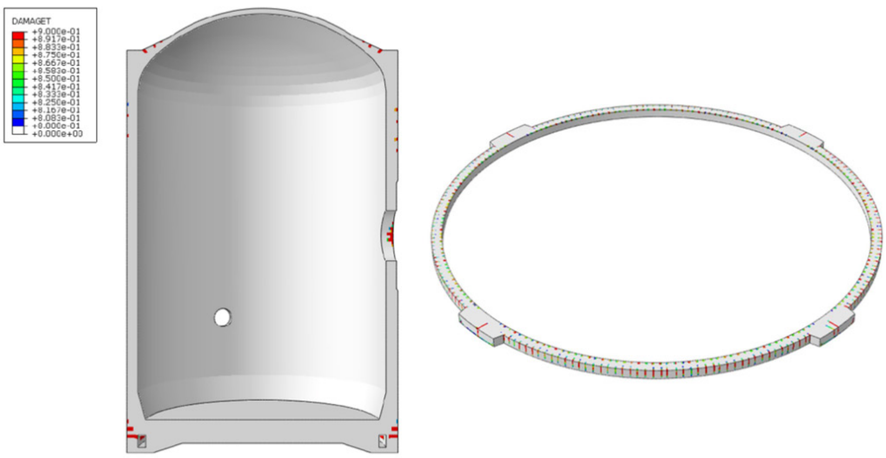

Figure 10. Section through the containment (left), result from the sub-model at a height of 47 m above the foundation (right).

The results from the long-term analysis of the containment are shown in Figure 11. The left figure shows the results when the calculated strains have been zeroed simultaneously as the measurements, i.e. all strains developed prior to the first periodical pressure test have been removed. The right figure shows the calculated strains from the start of the simulation, only the strains due to the prestressing procedure have been removed. This procedure was used since the boundary conditions used in the moisture analysis causes a too early development of the strains in the outer part of the concrete, thus removing too much of the strains when zeroing the results.

However, this procedure will also lead to an overestimation of the strains from the time prior to the prestressing thus affecting the reliability of the simulation negatively to some extent. As is apparent the agreement between the measurements and the simulations was increased substantially when excluding the zeroing of the strains.

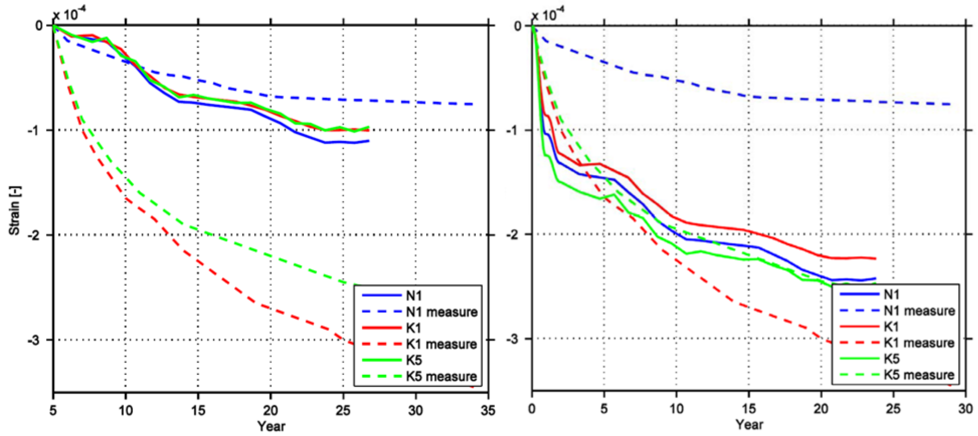

Figure 11. Results from the calculated development of strains (left) and results including all strains, even those developed before the start of the measurements (right).

Conclusions

The following general conclusions can be drawn from the work conducted within G3.

- Both axisymmetric and 3D non-linear analyses are applicable for determining overall stresses, strains and displacements due to relaxation of tendons, creep and shrinkage of the drying concrete and temperature variations.
- The agreement between measurements and simulations was better for the short response of the containment during the periodical pressure tests than the long-term predictions of the containments behavior. This is most probably due to the limitations in the used prediction models for estimating creep and shrinkage.
- All condition assessments and analysis of long-term behavior regarding stress and strain conditions of a RC must include analysis of the moisture and temperature distributions.
- In order to make reliable predictions of the structural behavior of a concrete structure it is crucial to have the possibility to calibrate and verify both the model and input data. Thus it must be possible to perform measurements on the studied structure but also to take samples from the structure and monitor different physical and mechanical properties of the materials on site.
- The results from the measurements with the strain gauges show that the majority of the strains due to creep and shrinkage develop during the first 10 years after prestressing. This behavior was also verified by the analyses in both G3.1 and G3.2.

3.5 G4: DETERMINATION OF CURRENT AND FUTURE CONDITIONS OF MOISTURE AND TEMPERATURE IN THE STRUCTURE

The objective of WP2:G4 was to further develop an existing model for estimating the current and future temperature and moisture distributions in the concrete wall and dome of the reactor containment studied in G3. The results from this work were used as input in G3.2 in order to increase the accuracy of the performed 3D-analysis.

Analysis

Two different models were used for estimating the temperature and moisture distributions in the containment and their variation over a period of 60 years, 1-D and 3-D FE-calculations, respectively. The 1-D analysis was performed at two different heights of the containment, at the base of the cylinder wall and at a height of 20 meters from the bottom slab. The analysis in 3-D was performed for the entire containment using the same geometry model as in G3.2. Since the 3D-analysis was used in G3.2 and is thus considered the most important of the two models, the 1-D-model will not be further discussed in this report.

Since no measurements were possible to perform at the studied containment due to legal restrictions all boundary conditions and material properties were based on either measurements on Swedish containments, from the literature or tests on a replica concrete with similar compositions as the concrete used for the containment.

The material properties needed for the numerical analysis are desorption isotherms, moisture transport coefficients, heat capacity and heat conductivity of the concrete. In Figure 12 the effect of the temperature dependency of the desorption isotherm and the desorption isotherm used in the 3D-analysis are shown. The moisture transport coefficient was partly adopted from the performed tests on the specimens of the replica concrete.

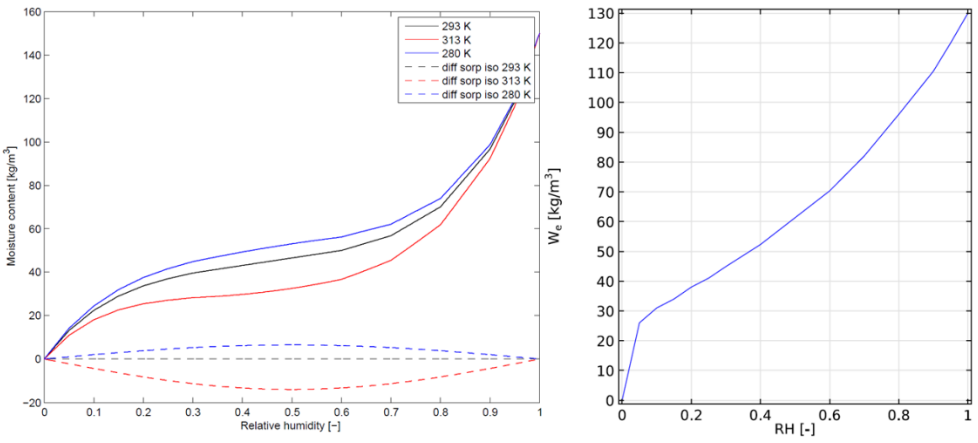

Figure 12. Variation of the desorption isotherm at different ambient temperatures (left) and desorption isotherm used in the 3-D analysis, which is partly based on measurements on specimens of replica concrete (right).

The annual variation in the temperature and RH of both the outside and inside climate was modeled as a sine function. The temperature inside the containment was varied with the height with a mean value of 23 ºC at the bottom and a value of 40 ºC at the top.

RH was used as the driving potential for the moisture transport. It was assumed that the self-desiccation of the concrete during the first 30 days after casting of the concrete reduces the RH in the concrete from 100 % to 92 %, i.e. 92 % RH was assumed as the start value of the drying process. As a first step the temperature development in the structure was simulated and the result was used as input to describe the temperature dependency of the moisture properties of the concrete. The same geometry model was used as for the calculations in G3.2.

Results

In Figure 13, the result from the temperature simulation for the winter of the 59th year after the casting of the concrete is shown. As can be seen the maximum temperature is approximately 42°C and is located at the center of the top of the dome.

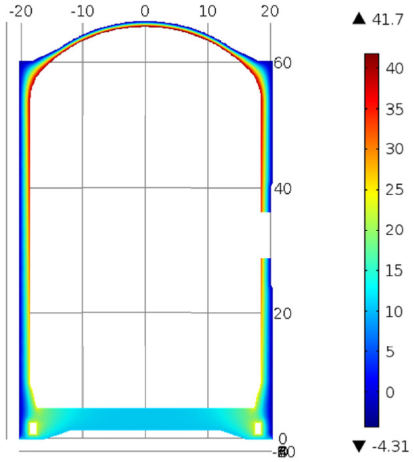

Figure 13. Results from the temperature simulation during the winter the 59th year after casting of the concrete.

With the results in Figure 13 as input, the RH and moisture content distribution in the containment were simulated, the results for two different levels in the containment are shown in Figure 14. The curves represent different years; 0, 10, 20 up to 60 years after the casting of the concrete. In this case drying will occur to a depth of approximately 300 mm from the outside surface of the containment. The decrease in moisture content compared to the initial state at the outer surface varies between 16 – 20 kg/m^3 for the studied period of 60 years. In addition, it was found that the simulation with moisture properties of the concrete estimated from the literature qualitatively were in the best agreement with measurements performed on a Swedish pressurized water reactor in a previous study [4]. Thus the results showed that measurements on newly cast concrete specimens do not describe the properties of old structural concrete realistically.

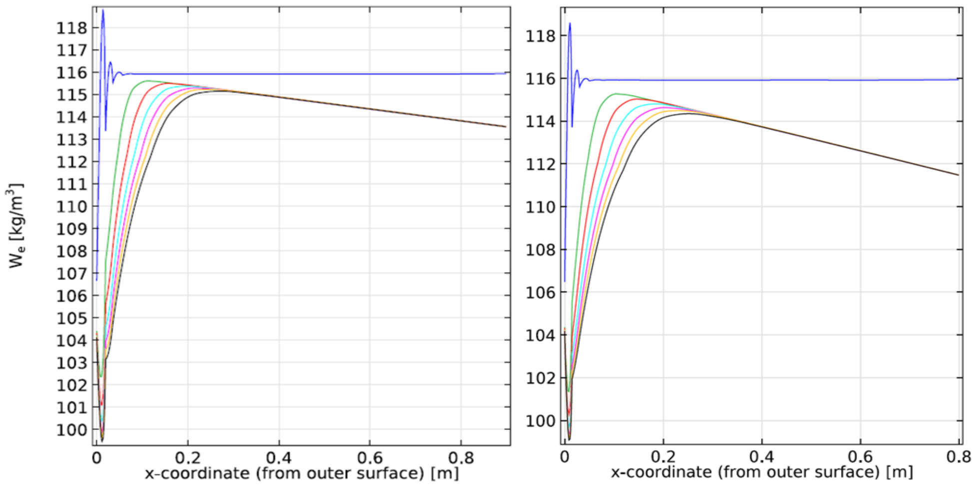

Figure 14. Moisture content distribution at a level of 10 m above the foundation (left) and at the center of the dome top (right).

Conclusions

From the work conducted in G4 the following conclusions were drawn.

- The simulations based on material properties estimated from the literature correspond qualitatively to measurements performed on the containment of a Swedish pressurized water reactor.
- Different values of material properties were investigated and it was found that the diffusion coefficient of the concrete is an important parameter affecting the moisture conditions in a containment wall significantly. The moisture capacity has only a minor impact on the drying of a containment wall.
- Taking results from laboratory measurements on replica concrete did not increase the accuracy of the simulations. Instead, the results showed that measurements on newly cast concrete specimens do not describe the properties of old structural concrete realistically.
- Since the concrete close to the steel liner still has high moisture content, the risk for corrosion in areas where the liner is not in direct contact with the concrete is thus increased.

4 Conclusions

The following main conclusions were drawn from the work conducted within ACCEPPT:

- Few cases of concrete damages have been noticed/published by NPP owners. Observed damages are mainly due to mistakes during the construction phase and not due to ageing effects or degradations of the different materials.
- Generally, the most commonly observed damages are blistering and corrosion damages of the steel liner and cracking of liner welds.
- For global inspection of defects in the steel liner acoustic cameras or Microflown sensors should be applicable and tests of these sensors during a pressure test should be performed.
- For local detection of liner defects ultrasonic hand held devices such as a Rotoarray are suitable and are able to detect defects such as delaminations and corrosion.
- Structural tests of a liner mock-up indicated that the liner integrity will be maintained under LOCA conditions. Results showed that although plastic deformations were observed in the liner, strains were significantly lower than the ultimate tensile strain. In addition, no cracks were observed and separation between liner and concrete was only observed at positions with fabricated imperfections.
- Modelling of the studied interaction between liner and concrete in the mock-up resulted in a calculation method that could accurately describe the behavior of the liner during LOCA conditions. The method was recommended to be applied for reactor containments when analyzing the effects of long-term mechanisms on the behavior of the liner.
- Both axisymmetric and 3D non-linear analyses are applicable for determining overall stresses, strains and displacements in reactor containments due to relaxation of tendons, creep and shrinkage of the drying concrete and temperature variations.
- All condition assessments and analysis of long-term behavior regarding stress and strain conditions of reactor containments must include analysis of the moisture and temperature distributions.
- In order to make reliable predictions of the structural behavior of a concrete structure it is crucial to have the possibility to calibrate and verify both the model and input data. Thus it must be possible to perform measurements on the studied structure but also to take samples from the structure and/or monitor different physical and mechanical properties of the materials on site.
- A majority of the strains due to creep and shrinkage develop during the first 10 years after prestressing.

5 References

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[3] AFCEN ETC-C 2010 EPR Technical Code for Civil Works, 2010.

[4] Nilsson L-O, Johansson P., Förändringsprocesser i reaktorinneslutningar – betongväggarnas klimatförhållanden och uttorkning, Elforsk rapport 09:100, 2009 (in Swedish).

ACCEPPT – AGEING OF CONCRETE AND CIVIL STRUCTURES IN NUCLEAR POWER PLANTS

The project ACCEPPT (Ageing of Concrete and Civil structures in nuclEar Power PlanTs) was a result of cooperation between several European nuclear power producing companies. ACCEPPT regarded the ageing of prestressed nuclear reactor containments with an internal steel liner and focused on the functionality of these systems from an ageing point of view.

For the steel liner, investigations of non-destructive examination (NDE) methods for detecting liner defects, study the interaction between concrete and liner and reviews of liner repairs and defects were performed. The liner studies resulted in proposed NDE-methods for both global and local detection of liner defects, a summary of typical liner damages and a model for analyzing effects of long-term mechanisms on the mechanical behavior of the liner. In addition, tests also indicated that the integrity of the liner is not endangered due to an internal over pressure in a reactor containment.

The studies of the long-term functionality of reactor containments included summary of containment designs, review of observed degradations and modelling of the long-term behavior of the containment regarding changes in the state of stress and strain also including modelling of moisture and temperature conditions. It was found that few concrete damages have been reported and that observed damages mainly are due to construction flaws. The results also showed that both axisymmetric and 3D non-linear analyses are applicable for determining overall stresses, strains and displacements due to relaxation of tendons, creep and shrinkage of the drying concrete and temperature variations in the structure. All condition assessments and analysis of long-term behavior of reactor containments must include analysis of the moisture and temperature distributions.