CONDITION ASSESSMENTS AND CORROSION MEASUREMENTS OF COOLING WATER CHAMBERS IN A NUCLEAR POWER PLANT

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ABSTRACT

This research was done as a part of the project Aging Management of Concrete Structures in Nuclear Power Plants (MANAGE) in The Finnish Research Programme on Nuclear Power Plant Safety 2011–2014, SAFIR 2014. The aim of this research was to carry out condition assessments and corrosion measurements to evaluate the condition of the reinforced concrete structures of the cooling water chambers in a Finnish nuclear power plant and to verify the possible state of corrosion of the reinforcement.

The condition assessment was based on concrete samples taken from the structures above the water level, at the range of the water level, and under the water level. The concrete samples were subjected to the following analyses: the carbonation depth, the chloride profile, and the study of the microstructure based on thin sections. Concrete cover measurements and visual inspection of the concrete structures and exposed reinforcements were done to approve the corrosion measurements. These determinations and measured Half-Cell potentials were used with the Pourbaix-diagrams for steel to estimate the state of corrosion of reinforcement.

The measured depths of concrete cover correlated the design value 60 mm. The average depth of carbonation of concrete was very small; varying between 0 mm and 12 mm. Estimations for the state of corrosion of reinforcement according to the Pourbaix-diagrams showed the reinforcement to be in passive state. Visual inspections confirmed the estimation; all of the exposed reinforcing bars were intact. The cathodic protection installed in the cooling water chambers may have had a protecting influence on the reinforcing bars.

INTRODUCTION

The most obvious consequence of the corrosion of steel reinforcements is the deterioration of reinforced concrete, a topic that has been widely studied and reported. The lack of basic knowledge of substantial corrosion processes prior to and after maintenance and repair measures is a drawback in structural rehabilitation. This lack of knowledge causes unexpected expenses and even fatal errors when decisions are being made about the methods of extending the service life of concrete structures. Focusing on cooling water channels in a nuclear power plant, it is essential to gain actual condition survey data for making reliable estimations of the service life of reinforced concrete structures.

This research was performed under the project MANAGE (Aging Management of Concrete Structures in Nuclear Power Plants) which is a part of the Finnish Research Program SAFIR 2014 (National Nuclear Power Plant Safety Research 2011 – 2014). The corrosion measurements made a continuation to the condition assessment carried out in cooling water channels in 2010 (Vesikari, 2011). Research problem concentrates on the limited possible condition survey occasions, and methods

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available. The aim of this study was to research the factors influencing the state of corrosion of the reinforced concrete structures of the cooling water chambers in a Finnish nuclear power plant. The objective of the study was to evaluate the condition of studied cooling water chambers. The research methodology concentrated on condition assessments and corrosion measurements. The condition assessment was based on concrete samples taken from the structures in the positions: above the water level, at the range of the water level, and under the water level at two chambers (Chambers One and Two) in 2010 (Vesikari, 2011), and at other two chambers (Chambers Three and Four) in 2011 (Vesikari, and Ferreira, 2011). The corrosion and the cover depth measurements were targeted at the same two cooling water chambers as with the condition assessment carried out in 2010 (Piironen, and Sistonen, 2012).

The study concentrated on the cooling-water inlet structures. This study was focused on the following exposure classes (SFS-EN 206-1:en, 2000): corrosion caused by carbonation XC1 (dry or permanently wet) or XC4 (cyclic wet and dry), and corrosion caused by chlorides XD2 (wet, rarely dry) and XD3 (cyclic wet and dry). The exposure classes XC4 and XD3 represent the most severe exposure circumstances. The structures of the inlet side of the cooling system have been cathodically protected using both impressed current and sacrificial zinc anodes.

EXPERIMENTAL SET-UP

The studies included visual examinations, the determination of the concrete cover depth, the carbonation depth, and chloride profiles based on the determination of the average acid soluble chloride content at successive depths, thin section analysis, the measurement of the electrochemical properties, and the moisture condition. Each measurement in the research work was needed to analyse the long-term properties of reinforcement bars. The carbonation depth was determined from four cooling water chambers with twelve broken specimens using a 1 vol% phenolphthalein solution according to the standard (SFS-EN 13295:en, 2004). Furthermore, the depth of concrete carbonation and the cover depth were determined in 2011 at Chambers One and Two in-situ by using the 1 vol% phenolphthalein solution, and a Profometer 3 equipment.

The chloride profiles were determined in four chambers with twelve specimens from powder samples taken at different depths from the surface. The acid soluble chloride was determined from the powder samples according to Nordtest method (NT Build 208, 1996). Petrographic thin sections were prepared according to the standard (ASTM C856-04, 2004), and nordtest method (NT Build 381, 1991). The thin-sections were studied using a Leica DM LP polarization and fluorescence microscope with a Leica Qwin-image analyzer.

The rate of corrosion, corrosion potential, and the resistivity of concrete were determined according to the standard (ASTM C876-91, 1999) using a GalvaPulse unit produced by Germann Instruments. A silver/silver chloride half-cell (Ag/AgCl) was used as a reference electrode. The corrosion measurements were started by localizing the reinforcement of the concrete walls on the above mentioned positions with a Profometer 3 equipment. Location of the reinforcement was marked by lines on the surface of concrete wall. Both the horizontal and vertical reinforcement was localized and marked. While the chambers were drained during the corrosion measurements cathodic protection was switched off (e.g. due to safety reasons). Visual inspection of the concrete structures and exposed reinforcements were executed to support the corrosion measurements. The moisture conditions were determined using a Squirrel logger with a Vaisala Oy (Ltd.) HMP 44 temperature and relative humidity probe. The measurement points were situated in the structure near the depth of the reinforcement bar (app. 60 mm) above the water level zone and at the ambient air.

RESEARCH RESULTS AND DISCUSSION

The average carbonation of concrete specimens was very small; varying between 0 mm and 12 mm. In tidal zones and in submerged areas carbonation was negligible. Furthermore, carbonation of concrete was in all of the in-situ measurement points insignificant i.e. between 0 mm and 1 mm. Based on

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the results carbonation of concrete does not pose a threat to the durability of the structure. However, carbonation may promote the penetration of chlorides in concrete and thus have a shortening effect on the service life of the structures. The measured depths of concrete cover correlated the design value 60 mm moderately varying between 53 mm and 89 mm. Chloride profiles determined were similar excluding two samples, which were severely leached. According to the measured concrete cover depths the total chloride (Cl^-) content by the weight of cement at the reinforcement was clearly under the assumed critical chloride content 0.4wt% (Cl^-) in all of the examined positions except under the water line in the Chamber Two (Figure 1, and Figure 2).
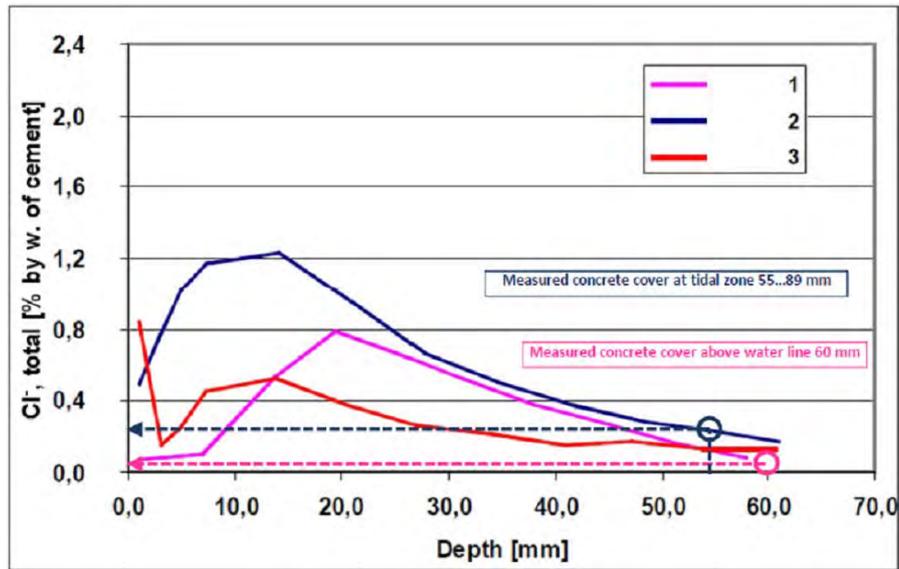

Figure 1. Measured depths of concrete cover compared to the chloride profiles in the Chamber One in 2011: 1 above water level, 2 at the tidal zone, and 3 under water level.
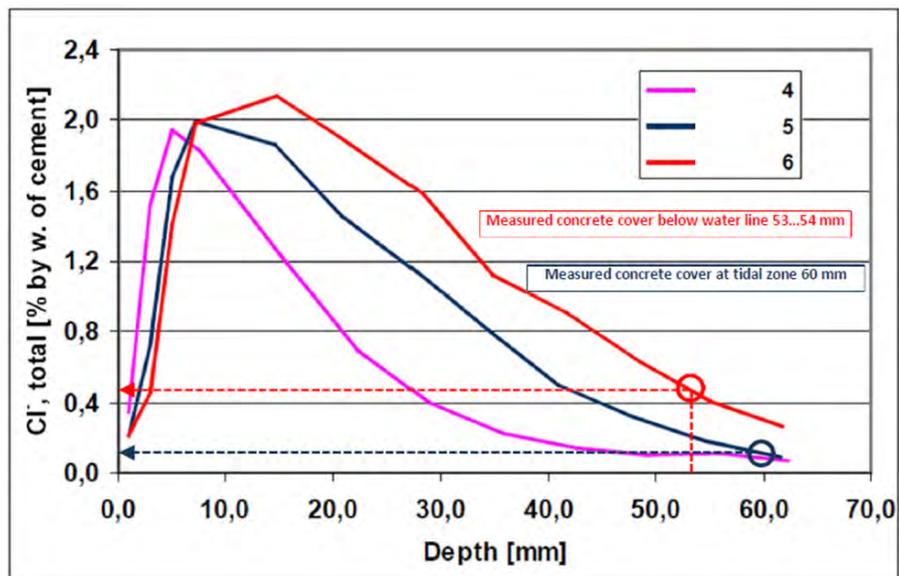

Figure 2. Measured depths of concrete cover compared to the chloride profiles in the Chamber Two: 4 above the water level, 5 at the tidal zone, and 6 under the water level.

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In the micro structural studies of concrete small internal cracking was observed. Cracking may promote carbonation and chloride penetration into concrete. On the surface of the structure it may cause also deterioration of the concrete itself although so far such deterioration has not been observed. Furthermore, analyses of the thin sections revealed that concrete quality was generally good. Unhydrated cement particles were observed. This is a common feature in low w/c concrete and does not necessarily implicate any fault. Some crystal formation was observed in the air pores of submerged and tidal zone concrete.

The results of the measured Half-Cell potentials vs. Ag/AgCl-reference electrode for the reinforcement in the Chambers One and Two were converted to Half-Cell potentials vs. Cu/CuSO$_4$-reference electrode. That was made to harmonise the results with the Half-Cell potential limits for state of corrosion of ordinary steel reinforcement bar in chloride contaminated concrete used in standard (ASTM C876-91, 1999). The silver/silver chloride reference electrode measures 110 mV higher potentials than the Cu/CuSO$_4$ (CSE) electrode (ASTM C876-91, 1999). The calculated average corrosion potentials (vs. CSE) were compared to Pourbaix-diagrams (Pourbaix, 1963) for steel in water to estimate the state of corrosion of the reinforcement. Pourbaix-diagrams are graphical presentations (Electrode potential / pH-diagram) of the thermodynamic equilibrium states of a metal-electrolyte system. Due to the low chloride content at the depth of reinforcement the Pourbaix-diagrams for steel in water was used.

According to the insignificant carbonation of concrete, the pH-value of concrete in the Chambers One and Two at the depth of reinforcement can presume to be about 12…13 (Figure 3, Left). The state of the corrosion of reinforcement under the water level was estimated with the assumption of presence of chlorides. According to the assumed critical chloride content 0.4wt% (Cl$^-$) was slightly exceeded in the depth of reinforcement at that level. The range of calculated corrosion potentials (vs. CSE) varied between -172.4 and -360.8 mV. Assuming the pH-value of non-carbonated concrete to be about 12…13 a range-area for estimation of the state of the corrosion under the water level can be defined with a Pourbaix-diagram for steel in chloride contaminated water (Figure 3, Right).
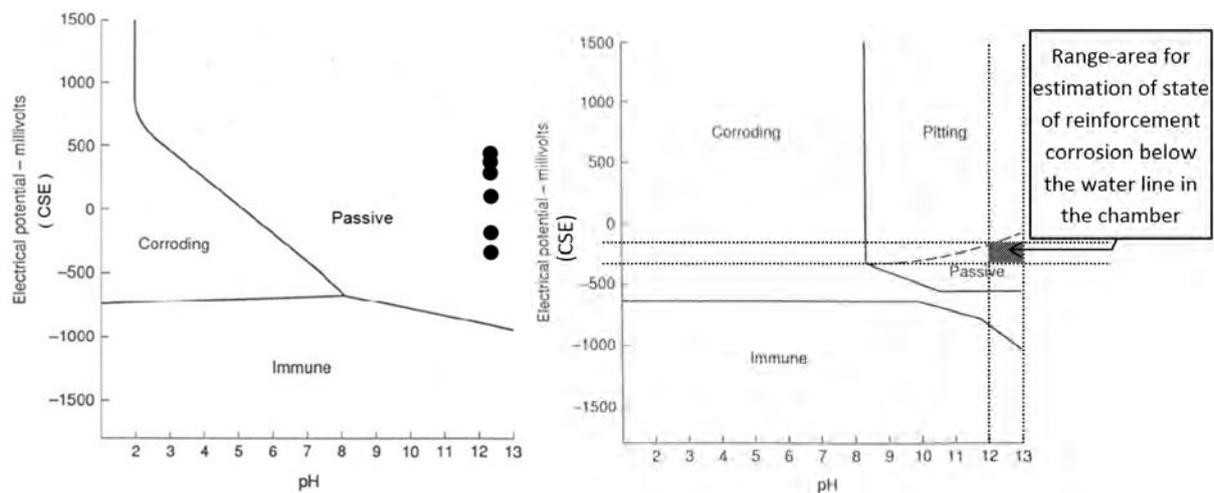

Figure 3. Left: Estimation of the state of the corrosion of reinforcement in the Chambers One and Two according to Pourbaix-diagrams for steel in water. Right: Estimation of the state of the corrosion of reinforcement under the water line in the Chamber Two. Pourbaix-diagram for steel in chloride contaminated water. Range of measured corrosion potentials (vs. CSE) and pH-values of non-carbonated concrete marked with dotted-lines.

According to Figure 3, Right the reinforcement under the water level is in passive state. The visual observation of the exposed reinforcement confirms the interpretation. However, according to the values shown in the standard (ASTM C876-91, 1999) and the average corrosion potential -242mV (vs.

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CSE) the risk for reinforcement corrosion under the water level is moderate. That is contradictory to the visual observation of the exposed reinforcement.

The possible state of corrosion of reinforcement based on corrosion current, and resistivity of concrete is shown in (Andrade, and Alonso, 2001). With ordinary steel a current of 1 µA/cm^2 corresponds to a rate of corrosion of 11.6 µm/a. According to the measured average corrosion rates the possible state of corrosion of reinforcement in both of the chambers is high. That is completely contradictory to the visual observation of the exposed reinforcement. The cathodic protection was switched off during the measurements and it did not affect the measurements. The measured resistances of concrete have been converted to resistivity of concrete as follows:

$$R = 2 \cdot R_0 \cdot CD ,$$ (1)

where R is the resistivity of concrete [kΩ·cm],
R$_0$ is the resistance of concrete [kΩ], and
CD is the diameter (7 cm) of the GalvaPulse counter-electrode [cm].

According to the average resistivity of concrete the possible state of corrosion in the Chamber One and at the tidal zone in the Chamber Two is low and varies between moderate to high under the water line in the Chamber Two. The assumption for the reinforcement corrosion under the water line is contradictory to the visual observation of the exposed reinforcement.

The correlations between the measured Half-Cell potentials (E$_{corr}$) and corrosion rate (I$_{corr}$), Half-Cell potentials (E$_{corr}$) and resistivity of concrete, and corrosion rate (I$_{corr}$) and resistivity of concrete was studied, see Figure 4 – Figure 6. Separate correlation-graphs for both of the chambers with limiting value lines and statements representing the possible states of corrosion were made. Corrosion measurements showed that no correlation between the measured Half-Cell potentials and corrosion rate, Half-Cell potentials and resistivity of concrete or corrosion rate and resistivity of concrete was found. The presence of chlorides may have led to an overestimated rate of corrosion values (Andrade, et al., 2004). Furthermore, in passive regions, the GalvaPulse overestimates the corrosion rate (Germann Instruments, 2010). A quite distinct behavior between Chambers One and Two seen in graphs is partly possibly due to the heterogeneous material properties of concrete. In addition, the moisture conditions of the concrete surface and cracking are possible source of errors.
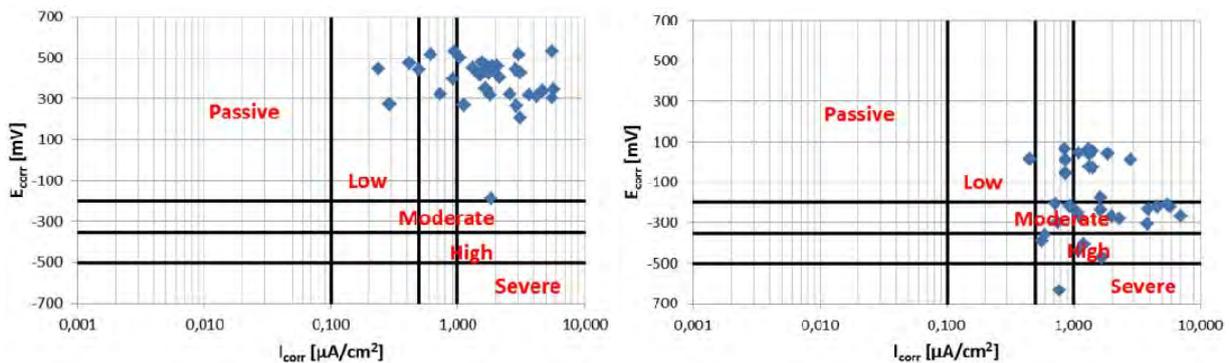

Figure 4. Correlation between the measured Half-Cell potentials (E$_{corr}$ vs. CSE) and corrosion rate (I$_{corr}$). Chamber One (left), Chamber Two (right).

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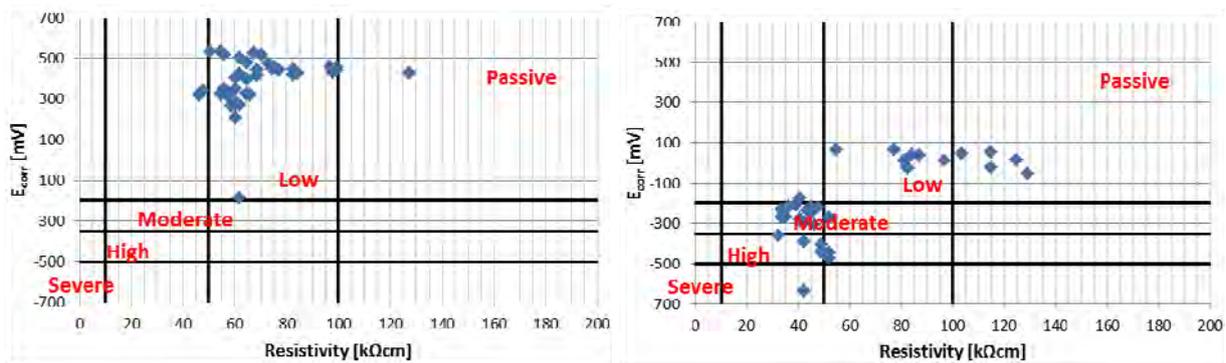Division VIII (Issues Related to Operations, Inspection and Maintenance)

Figure 5. Correlation between the measured Half-Cell potentials (E_{corr} vs. CSE) and resistivity of concrete. Chamber One (left), Chamber Two (right).
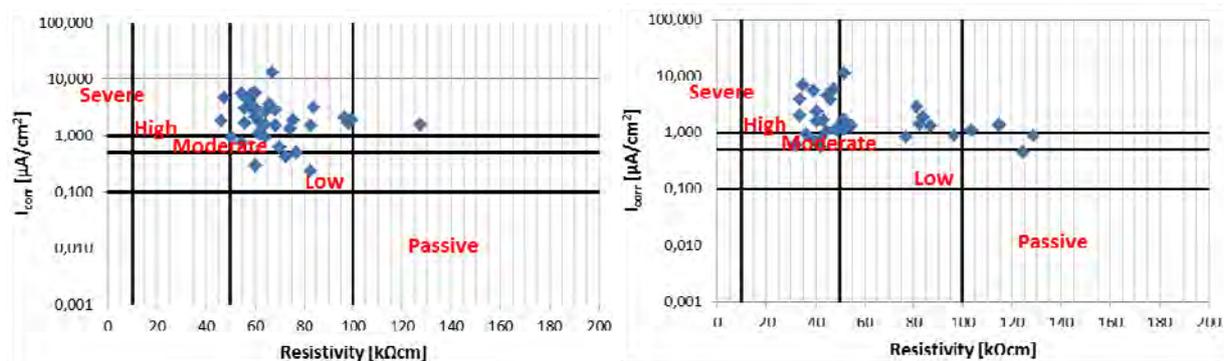

Figure 6. Correlation between the measured Half-Cell potentials (E_{corr} vs. CSE) and corrosion rate (I_{corr}). Chamber One (left), Chamber Two (right).

Visual inspections at both chambers confirmed the estimation that all of the exposed reinforcing bars were intact. Visual inspection of the concrete structures showed no critical factors decreasing durability of concrete: only minor surface cracking and biological growth were noticed. At the tidal zone and under the water line the flora and fauna has fastened on the concrete surface and the range of water line was clearly visible. However, there might be a risk of leaching of the concrete and the abrasion of concrete by the water flow. These factors were not measured during corrosion measurements. It should be noted that the leaching of concrete was noted at the Chamber Four studied at the same time with the drilled samples. Furthermore, the concrete cover was recognized as a substantial concrete when removing with a demolition hammer and horizontal reinforcement bars were exposed before corrosion measurements.

During the half-cell potential measurements the hygrothermal steady-state conditions of the concrete wall at the reinforcement above the water level and of the ambient air in the Chamber One were approximately 95 RH% / 20 °C and 78 RH% / 20 °C, respectively. Such measurement values enable the wet concrete as an electrolyte to activate reinforcement bar corrosion. However, it should be noted that corrosion potential difference is needed between anodic and cathodic areas. This prerequisite of corrosion cannot be fulfilled as far as the pH value of the pore water at reinforcement bar is high (app. 12 – 13) or the chloride content is low.

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CONCLUSION

Estimations for the state of corrosion of reinforcement according to the Pourbaix-diagrams showed the reinforcement to be in passive state. Visual inspections at the Chambers One and Two confirmed the estimation; no sign of on-going reinforcement corrosion was found, and all of the exposed reinforcing bars were intact. According to the sample observations in years 2010, and 2011 with the expected cover thickness of 60 mm, the assumed critical chloride content has not been exceeded excluding two severely leached samples. However, the cathodic protection installed for preventing corrosion in the cooling water chambers may have had a protecting influence on the reinforcing bars. More comprehensive condition assessment, including measurements of the concrete cover and visual observations on the corrosion of reinforcement, is recommended.

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