Drying of reactor containment walls of concrete during past and future decades

Lars-Olof Nilsson

Laboratory of Building Materials, Lund Institute of Technology, Lund University, Sweden

ABSTRACT

Two types of nuclear reactor containments are studied, for BWR reactors and PWR reactors in Sweden. They both have a thick concrete wall with a steel lining inside, but the BWR containment walls are enclosed in a building, protecting it from the outdoor climate. The PWR containment walls are exposed to outdoor weather conditions. The conditions inside the containment walls include high temperature, up to around +40-50°C.

Such a concrete structure, with one-sided drying of a 0.8 m thick wall, will dry extremely slow, in spite of the very high temperatures in part of the structure. This was seen in an earlier study after some 30 years of drying were moisture measurements were performed.

A drying model for concrete containments is presented and the various parts are described in detail and partly experimentally quantified. Especially the moisture effects on the extent of the cement reactions chemically binding water are discussed. A first prediction with a simplified model shows fairly good agreement with measured data.

INTRODUCTION

For most ageing processes in reinforced concrete structures the moisture conditions are important and sometimes decisive [1][2]. In nuclear reactor containments the moisture conditions in the concrete will mainly affect the shrinkage and creep of the containment walls and, as a consequence, the stress losses of the prestressing reinforcement [3]. For the possibility, and rate, of metal corrosion the moisture conditions are also decisive [2].

Nuclear reactor concrete containments change their moisture conditions extremely slow, because of the significant dimensions of the structures, in spite of their exposure to high temperatures. Parts of the structures are exposed to very high temperatures, above +50°C, for decades. Since the inner parts of the walls simultaneously are very humid, the cement reactions continue during the service period, binding water chemically to the cement.

In this paper the drying processes of the concrete containment walls are further examined, following the ideas by several researchers, from Hilsdorf (1967) [4] to Nilsson (2006) [5].

BOUNDARY CONDITIONS

The first series of measurements of the climatic conditions were performed on a running BWR reactor, at the outer surfaces of the containment wall [6]. The general layout of that reactor containment is shown in figure 1. Temperature and relative humidity (RH) were recorded during several months at the concrete surfaces and in the outdoor air. The measuring points are shown in figure 1.

From the measurements it was clear that the BWR containment walls do not have a significant temperature gradient, not even at the top of the containment, where inside temperatures reach some +50°C. It was also clear that the concrete surfaces are very dry, below 15 % RH at the top.

MEASURED DRYING PROFILES

After some 30 years of service, moisture measurements were performed in a BWR reactor containment wall [7][8]. The coring points are shown in figure 1. In figure 2 the measured relative humidity (RH) profiles through the bottom of a containment wall are shown. The temperature during service was here around +25°C.

From the measured moisture profiles it is obvious that the walls are still drying, after 30 years. In the lower parts of the wall RH still is above 90 % in the inner part next to the steel plate. In the upper part where the temperature has been close to +50°C during some 30 years of service, RH still is around 85 % close to the steel plate [7]. The drying-out process is obviously extremely slow, because of the one-sided drying of the very thick walls.

From the measured RH-profiles it is also obvious that the warmer parts of the wall are drying in very much dryer conditions. An extrapolated RH at the concrete surface in Figure 2 fits well with the RH at the drying surface measured by [7], corresponding to 35-40 % RH. In the upper part where the temperature during service was around +50°C, a surface RH of 10 % RH was found [7], which corresponded well with the measured profiles.

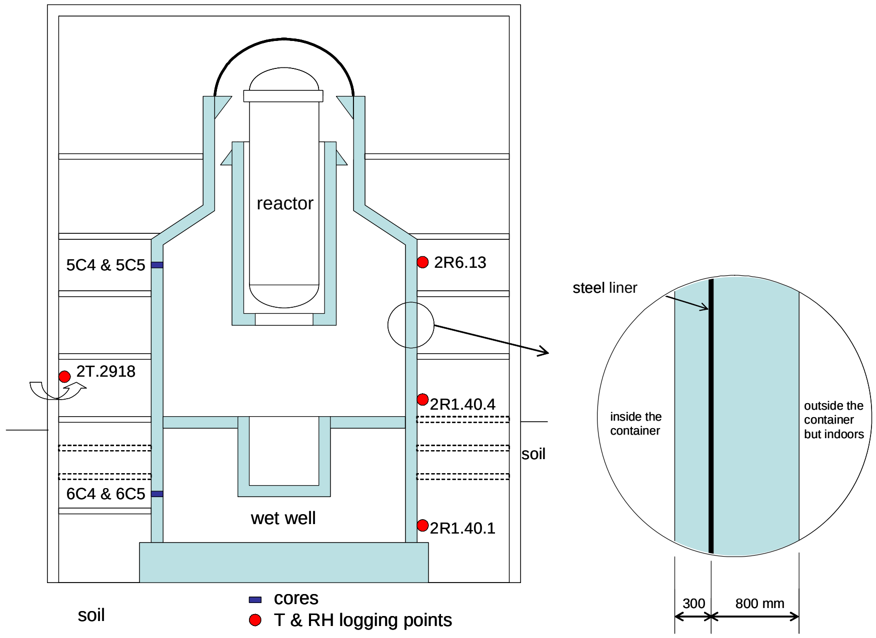

Fig. 1 A general layout of a BWR containment wall with the coring points in a previous study [7] and a cross section detail of the wall showing the steel liner position.

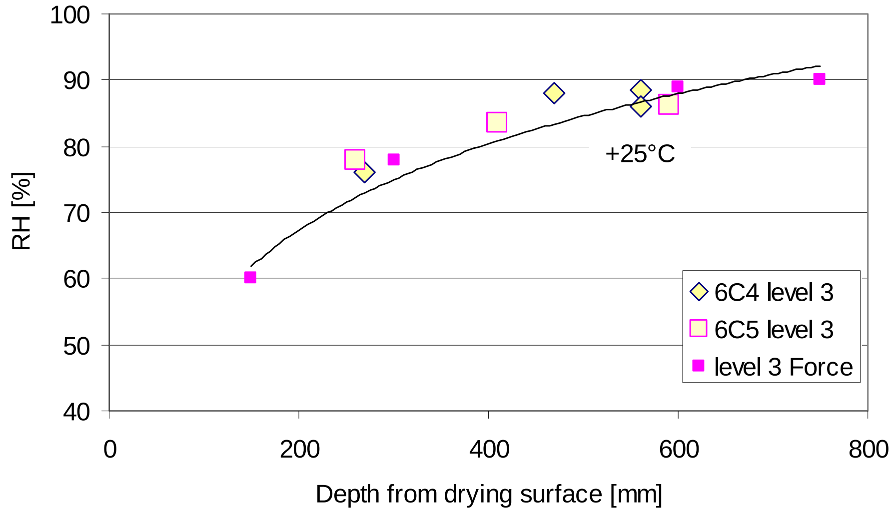

Fig. 2 Measured RH-distributions through the containment wall in drilled holes (level3 Force) and on two cores, at level 3 where temperatures were around +25°C during service [7]. The uncertainty is around 2 % RH (on samples) and 3 % RH (in holes) respectively.

DRYING MODEL

The moisture conditions in a drying concrete structure can be predicted by solving the mass balance equation for moisture [9]

$$\frac{\partial w_e}{\partial t} = -\frac{\partial g}{\partial x} - \frac{\partial w_n}{\partial t} \qquad (1)$$

where w_e and w_n are the evaporable and non-evaporable moisture contents [kg/m^3], respectively, g is the moisture flux [kg/(m^{2}s)], t is time [s] and x is the position [m] in the wall.

To be able to solve this mass-balance equation, to predict the changes of moisture distribution with time, four main tasks have to be completed.

1. describe the boundary conditions T(x=0) and RH(x=0) at the concrete surfaces, considering the surrounding climate and the temperature differences between the air and concrete surface,
2. describe the local moisture equilibrium $RH(w_e, \mathrm{x})$ at any point x, by quantifying the (de)sorption isotherms $w_e(\mathrm{RH, T}, \alpha)$ for the concrete, as a function of temperature and degree of hydration α,
3. describe the flux of moisture g, by defining one or more proper moisture transport potentials and quantify the moisture transport properties as functions of moisture content, or state of moisture, considering the temperature level, temperature gradients and the aging of the material,
4. describe the chemical fixation of water $\frac{\partial w_n}{\partial t}$, by considering the local temperature and moisture conditions and the degree of hydration α.

The parameters in the drying model are quantified experimentally and the model is verified against separate laboratory and field measurements. Several experiments are carried out or are in progress.

CHEMICAL FIXATION OF WATER

The last term in Eq. 1 describes the chemical fixation of water by the cement reactions. Since the inner parts of the walls still are humid, and have been for many years, the cement reactions must have been able to continue for a very long time. In the parts where RH now is around 90 % those reactions are still possible, after 30 years.

This has been analysed by determining the chemically bound water w_n at different depths in cores from two levels where the temperature has been different during service [7][10]. Continuous cement hydration will give higher and higher w_n. The results from samples from four cores are shown in Figure 3, as chemically bound water per weight of cement.

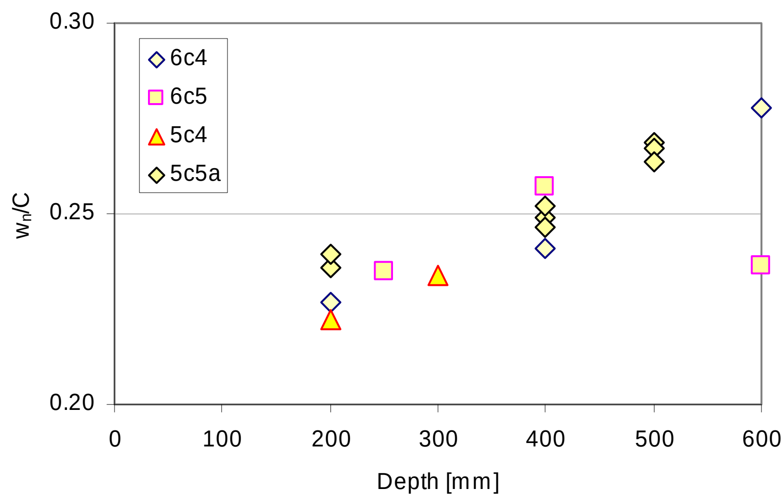

Fig. 3 Chemically bound water w_n [kg/kg cement] through the containment wall, measured on samples from four cores, at level 3 and 6 respectively [7]

The scatter is significant but there is an obvious tendency that the amount of chemically bound water is larger at larger depths, where the concrete has been more humid for a longer period of time. The absolute levels are remarkably high, with some values above $w_n/C = 0.25$, which is what one would expect for a degree of hydration of $\alpha = 1$. Part of the weight loss in the TGA may originate from the aggregate and the cement, which was not corrected for [7].

Further analysis of the remaining unhydrated cement was performed to clarify these observations. An example of the result of a microscopical analysis is shown in figure 4. Less than some 5 % of the cement clinker components remain unreacted, corresponding to a degree of hydration of $\alpha > 0.95$. The sample is taken from a depth of 300 mm, i.e. the degree of reaction is most probably even larger at larger depths.

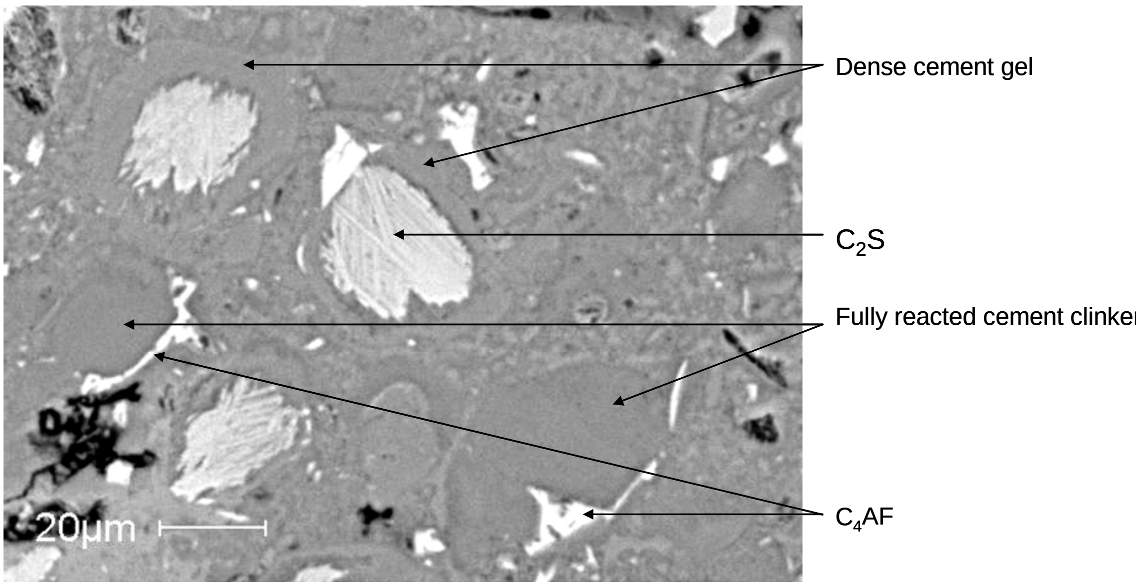

Fig. 4 Limited remaining unreacted cement clinker components in a sample from a depth of 270-350 mm in core 5CS taken from a containment wall [7].

There is no significant difference in maturity between parts that have had very different temperatures during service [7]. Parts that had a higher temperature should have had larger rates of reactions but on the other hand, those parts have dried to lower levels of humidity which decrease the rate of reaction. Those two effects may have cancelled out each other.

These results show that the concrete in a containment wall must be treated as very different in maturity, i.e. degree of hydration, at different depths and in parts where the drying conditions have been different. As a consequence, the material properties of the concrete do not only vary with age but also with depth.

LOCAL MOISTURE EQUILIBRIUM

The local equilibrium between the content of moisture and the state of moisture, expressed as RH, can be described by a desorption isotherm $w_e(RH)$. On the small samples in this case, it was difficult to measure the moisture content w_e with great accuracy. Instead, the degree of capillary saturation S_{cap} was determined. By plotting the measured RH and S_{cap} from each depth, a sorption isotherm for the concrete could be estimated, cf. Figure 5.

There is a small difference between the desorption isotherms from concrete that has been exposed to different temperatures. This is in line with previous research [9][11][12] that shows lower sorption isotherms at higher temperature, which is the same as a higher RH at a higher temperature, for a constant moisture content. There should also be a small effect of different maturity between the samples from small depths and large depths, i.e. the points with lower RH versus points with a higher RH.

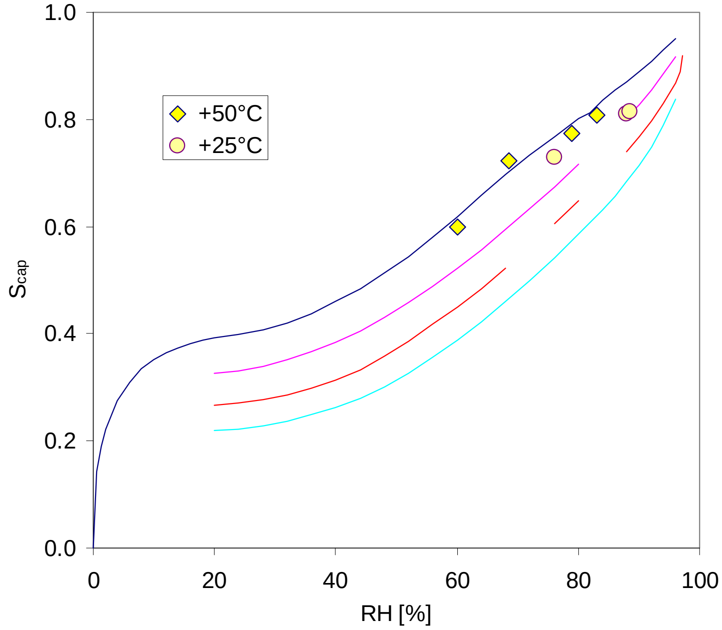

Fig. 5 Points (S_{cap}, RH) on the desorption isotherms, with different temperatures during service. The curves are for different maturity or temperature levels.

The temperature effect on the desorption isotherm was measured directly [9][11][12], as a change in RH when the temperature of a sealed sample is changed. Results at temperatures higher than +20°C are shown in figure 6.

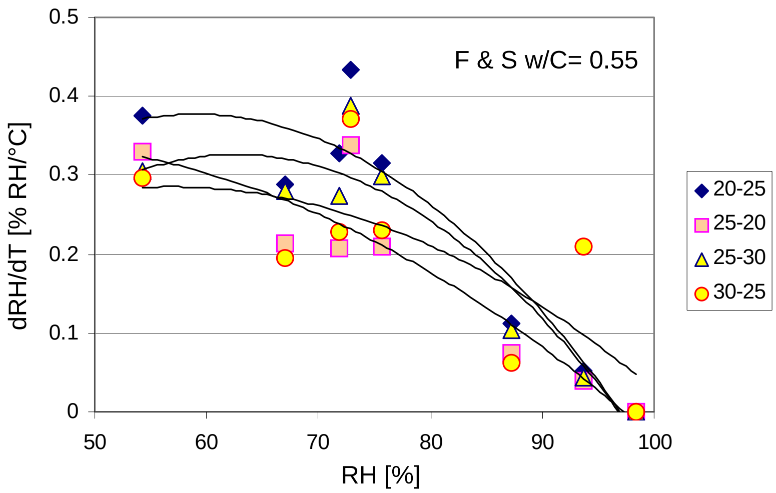

Fig. 6 Temperature effect on the desorption isotherm, measured as a change in RH when the temperature of a sealed sample is changed. Based on data from [12]

MOISTURE TRANSPORT PROPERTIES

Moisture flow in concrete in general can be described with any driving potential as long as there are no temperature gradients. The moisture transport coefficient, however, is far from being a constant, but depends on the moisture level, maturity or degree of hydration α and possibly temperature [5]. With the vapour content as moisture transport potential, one gets

$$q = -\delta(RH, T, \alpha) \cdot \frac{\partial v(x)}{\partial t} \qquad (2)$$

where δ is the moisture transport coefficient with the vapour content *v* of the air in the pore system as the driving moisture potential. This coefficient has been quantified on discs from the four cores from Barsebäck nuclear power plant with the traditional cup method [7] using a thin disc as a lid on a glass cup with the edges sealed.

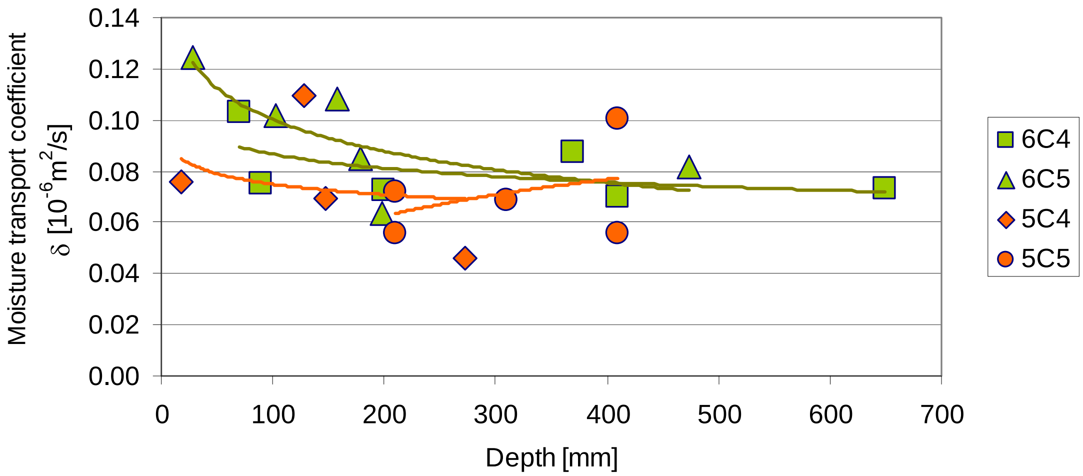

Fig. 7 Moisture transport coefficient as a function of depth, measured with the cup method on discs from four cores, at level 3(6C) and 6(5C) respectively

Even though the scatter is significant, there is a clear tendency that the moisture flow properties depend on the maturity of the concrete. The effect of curing temperature is not significant.

The data in figure 7 was determined at a temperature of +20°C. Since the temperature in the upper parts of a containment wall is much higher, the moisture transport properties at different temperatures should be quantified. The discs used for the data in figure 7 were used once again in similar cup methods, but now at a temperature of +50°C. The results are shown in figure 8 as a comparison between the data at the two temperatures. The scatter is, again, significant but the results show no major difference in moisture transport coefficients in the temperature range +20°C to +50°C. Consequently, the moisture transport equation, Eq. 2, could be simplified by excluding T. The temperature effect on moisture transport seems to be included in the large temperature effect on the vapour content *v*.

FIRST PREDICTION OF THE DRYING PROCESS

A first attempt to predict the drying process was done with simplified assumptions. A concrete composition with water cement ratio of 0.5 and a cement content of 380 kg/m^3 was the starting point. The degree of hydration was fixed at 0.8, giving a starting moisture content of 110 kg/m^3. The moisture transport coefficient was selected according to [13] which coincides fairly well with the data from the experiments. The moisture desorption isotherm was calculated from [9]. No temperature or curing effects were considered. The boundary conditions were set to 40 % RH for a drying temperature of +25°C and 10 % RH for a temperature of +50°C.

The results of these first calculations are shown in figure 9, as RH-profiles after 30 years of one-sided drying. The predicted curves are compared to the field measurements.

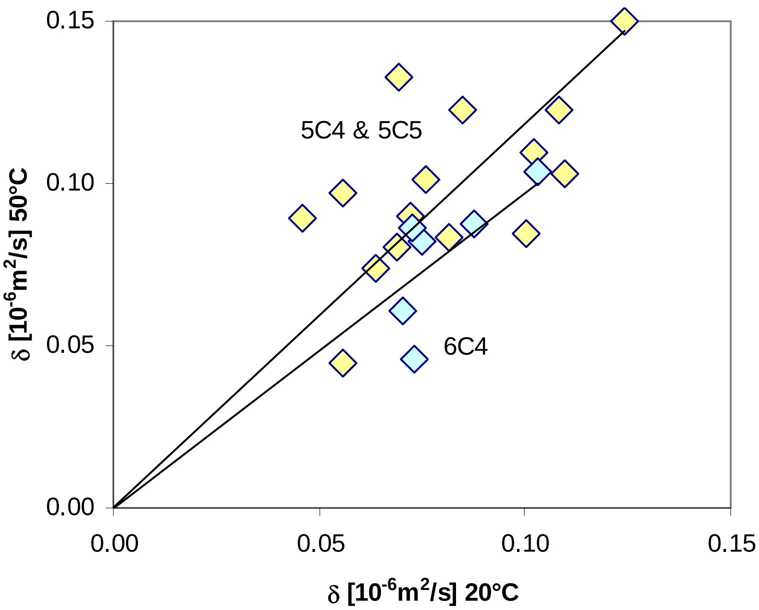

Fig. 8 Moisture transport coefficients for the concrete in a containment wall at two temperature levels, measured with the cup methods on the same samples.

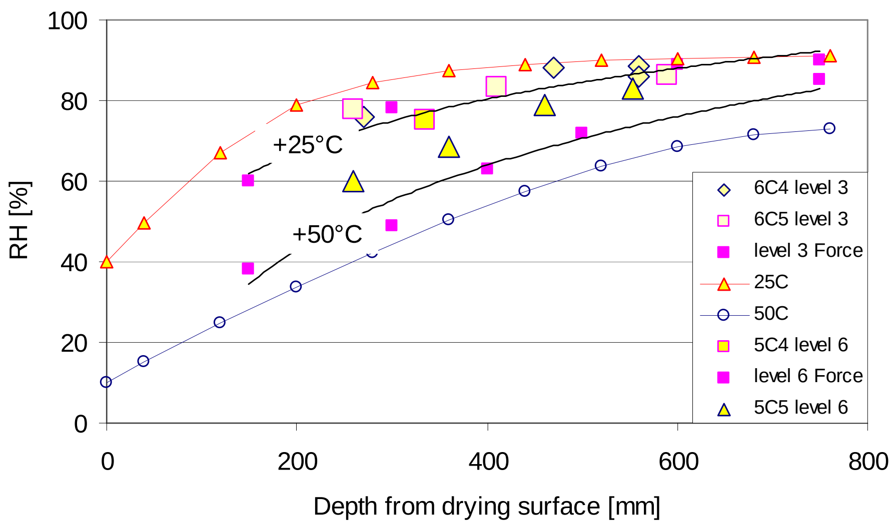

Fig. 9 The results of a first simplified prediction of the drying of the upper and lower part of a containment wall after 30 years. The assumptions are given in the text. The predicted RH-profiles are marked “25C” and “50C”, respectively.

The predicted results are “embracing” the measured data, cf. figure 9. The drying at +25°C is underestimated and the drying at +50°C is overestimated. Including further chemical binding of moisture could improve the prediction at +25°C, but the overestimation at +50°C would then be even larger. Further research is obviously required.

CONCLUSIONS

From the studies so far the following conclusions may be drawn.

- Drying of a nuclear reactor concrete containment wall is extremely slow, due to the large thickness and one-sided drying.
- Drying is very different in different parts of a containment wall due to very different temperature levels and outside climatic conditions. These conditions can be predicted from short term monitoring and weather data.
- During the long-term drying process, concrete continues to mature because the moisture conditions in the inner parts allow further cement hydration. Water continues to be consumed by the cement reactions and the material properties develop differently at different depths.
- To model the drying process a series of model components have to be quantified. Parameters are usually functions of humidity and maturity. Further research is needed to quantify these parameters.
- The first attempt to predict the drying process was not too successful, but the results were within some 10 % RH from the measured values.

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