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Long-term hygrothermal performance of nuclear reactor concrete containments – Laboratory evaluations of measurement setup, in situ sampling, and moisture flux calculations

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ABSTRACT

A measurement setup for in situ sampling of internal relative humidity and temperature in concrete structures was developed. The setup was used to evaluate the moisture conditions and to determine whether drying of the concrete components within a nuclear reactor containment contributes to the moisture conditions. The measurement setup was tested for accuracy and thereafter installed in Swedish nuclear reactor containments for in situ monitoring. Results from the measurements confirmed that the setup is suitable, especially for long-term measurements at depths of 50 mm or more. Complementary moisture transport calculations showed that the moisture flux from the concrete to the interior of the reactor containment have a noticeable effect on the environmental conditions in the containments. The calculations of the moisture condition in the concrete show that 15–30% of the evaporable water in the concrete has been dried out during the 30 years of operation.

1. Introduction

The reactor containment (RC) at a nuclear power plant (NPP) is one of the most important structures as it is the final barrier against radioactive leakage, e.g. in case of an LOCA (loss of cooling accident). All primary components, such as the reactor vessel, are located in the RC.

In Sweden, two reactor types are used: boiling water reactor (BWR), e.g. Forsmark 2 (Fig. 1a), and pressurized water reactor (PWR), e.g. Ringhals 4 (Fig. 1b). In both types, the RC is a cylindrical structure, which consists of an exterior and an interior concrete wall embedding a steel liner. The steel liner ensures leak tightness and is located within the concrete at a depth of ca 300 mm from the inner surface. Apart from acting as load-bearing structures, the concrete cylinder walls also protect the liner from external damages and degrading mechanisms such as corrosion.

Knowledge of the state of the structures in an RC is important, especially for long-term operation. Because of the long-term exposure of the structures to high temperatures, it is necessary to evaluate how these conditions affect the concrete structures and whether the drying rate is sufficiently large to impact the ambient humidity in the RC. High temperatures in combination with low ambient relative humidity could result in a large driving potential for the drying of concrete. Moreover, the humidity conditions in the RC can affect the life of mechanical components and the corrosion on steel surfaces due to surface condensation.

Regardless of the RC design, there are large quantities of concrete within the RC. In addition to the inner cylinder wall, there are different types of internal structures, such as the thick concrete biological shield, which prevent the spread of radiation from the reactor vessel to the ambient surroundings. A Swedish BWR RC contains about 2000 m^3 of concrete, and a PWR contains ca 8000 m^3 [1].

Fresh concrete contains a large quantity of water. When fully hydrated, the cement binds with ca 22.6% of its weight of water to form different hydration products [2]. When concrete has a w/c (water–cement) ratio of 0.45, this means that close to 50% of the initial water is not bound and can be dried out over time, i.e.

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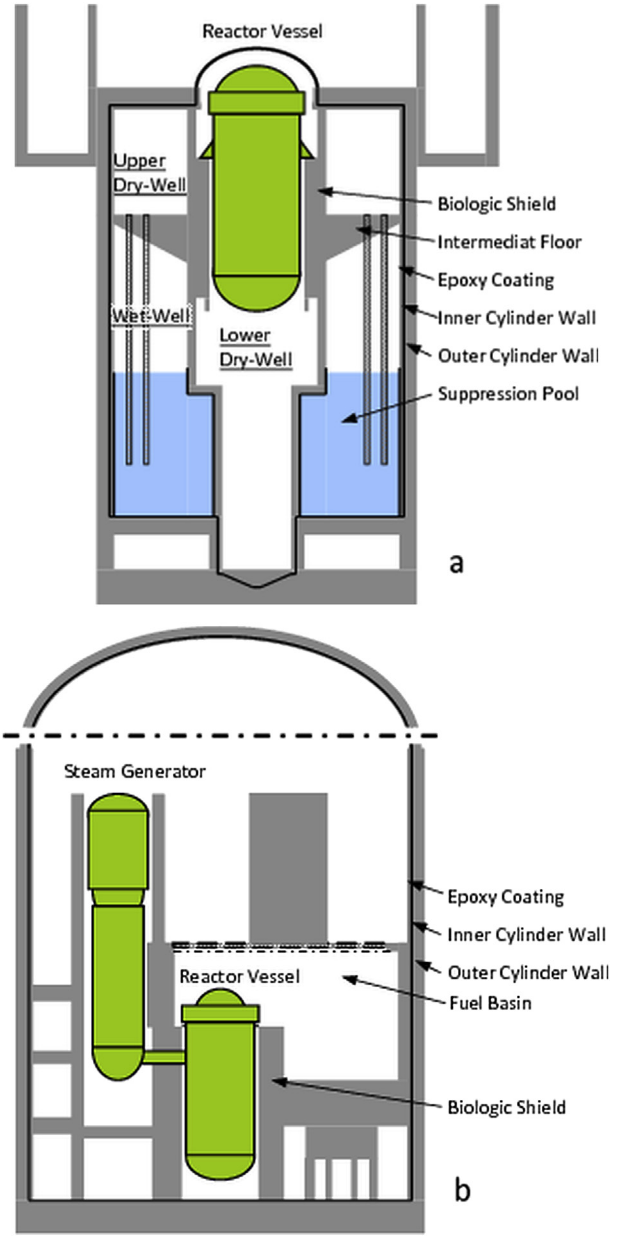

Fig. 1. Schematic illustration of **a)** a BWR (from Oxfall et al. [1]) and **b)** a PWR.

evaporable water. There are several potential moisture sources inside an RC, and the steam pipes are often considered as the main sources. The influence of moisture from the internal concrete structures has not yet been investigated. Other sources of moisture include the fuel basin in a PWR and the suppression pool in a BWR. However, the PWR fuel basin is not water-filled during operation, and the suppression pool is steel-coated and separated by concrete walls from the drywell. Therefore, moisture contribution from the suppression pool has to go through the concrete walls; however, this moisture flux is not included in this study.

The moisture content in concrete has been studied globally in several fields, mainly focusing on the drying of concrete slabs and walls in buildings e.g. Refs. [3,4] and the influences of the moisture content on creep and shrinkage e.g. Refs. [5–9]. Most moisture-related studies on concrete have been carried out in controlled laboratory environments, usually at approximately 20 °C, or by computer modelling, and only a few studies have focussed on the environmental effects [10,11].

In their study, Andrade et al. [10] used prefabricated specimens, with cast-in sensors. The specimens were exposed during one year to the outdoor climate in Madrid. Apart from the natural fluctuations where the specimens exposed for short artificial changes, such as cooling in refrigerators, heated in climate chambers and artificial rain. Andrade et al. concluded that rain and temperature changes were the two factors that had the largest impact on the measurements. These results were in line with the later findings by Ryu et el. [11] who focused on the effects from rain in cracked and non-cracked concrete specimens. In their study they primarily measured relative moisture content (RM) and concluded that the changes from the artificial exposure of the non-cracked specimens mainly affected the surface.

Some studies on the moisture content of concrete in nuclear power structures have been conducted by different plant owners, e.g. an evaluation of different measurement techniques by the French power company EDF [12]. In their study, they focused on three techniques used for in situ monitoring of concrete structures over time, time domain reflectometry (TDR), capacitive probes and gas-pressure-pulse-decay technique. Apart from the studies by utility owners, there have also been a few studies by researchers that deal with the moisture level in RCs [13,14]. In addition, moisture measurements on the outer cylinder walls of three Swedish NPPs [14–16] have been carried out.

Hilsdorf [13] presented in 1967 a model for prediction of moisture content in neutron radiation concrete shields. Apart from the model he described some of the techniques for moisture content measurements he considered suitable, such as measurements on cut out specimens or indirect methods e.g. equilibrium relative humidity (RH), electrical properties or radiation methods. In the later studies by Nilsson and Johansson [14–16], RH and temperature were measured in the concrete surfaces of the containment walls as well as in the ambient surroundings at the two nuclear power plants included in the study. Specimens from a closed reactor were also extracted and evaluated. The data was later used to verify a simplified model to predict future and past conditions in the outer containment walls. They showed in their studies that the drying of the containment wall on the nuclear power plants was a very slow process and that large differences in conditions between the two reactor types occurred. One key observation was the large temperature variations in the containment wall in a PWR and much more stable conditions for the BWR.

In hygroscopic conditions, the moisture content is often quantified in terms of RH, degree of capillary saturation, moisture content by mass, or moisture ratio. When measuring the moisture content in situ on a structure, when destructive testing is not possible, and when the moisture distribution is monitored over time, the measurement of RH is the most suitable method. The most common method for data transfer from sensor to logger is with cables, but other techniques such as radio frequency integrated circuit (RFIC) transfer has been evaluated [17]. They showed that the techniques might work but that more research regarding e.g. the continuity and stability of the signal transmission is needed [17].

When measuring in situ, the effects of different error, heat, and moisture sources have to be considered. Moreover, the measurement setup has to be constructed so that it is reliable for a long period. Most measurements reported in literature, concerning specimens exposed to field conditions, were conducted on specially fabricated test specimens [10,11,17] and often with the measurement setup installed before casting. When measuring on existing structures, the measurement setup has to be installed on site, leading to greater uncertainty due to the higher risk of incorrect