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Division V

Digital Twins factory for long-term operation management of Concrete Containment Building in Nuclear Power Plants: from VeRCoRs to Civaux 1

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ABSTRACT

EDF operates a large fleet of Nuclear Power Plants (NPPs). In the EDF NPPs fleet, 24 containment buildings are double-walled containments. In case of accidental situations, the safety of those containments relies on three barriers: fuel cladding, primary circuitry, and the reactor building associated with its dynamic containment. The leak-tightness of the reactor containment building is checked and validated every 10 years during the Integrated Leakage Rate Test (ILRT) which success is mandatory to continue the plant operation. To ensure the respect of safety requirements, EDF acquired a long experience of certified repair coating solutions and developed a digital twin's factory that allow to describe the evolution of concrete ageing and to predict the evolution of the leak rate of containment buildings over the years. In this work, the digital twin used to predict the mechanical and leak-tightness behavior for the upcoming second ILRT of the "Civaux 1" concrete containment building (CCB) is presented. The corresponding study carried out leads to the conclusion that, with different proposed coating solutions prior to the next ILRT, the Civaux 1 CCB will meet the leakage criterion.

INTRODUCTION

The EDF fleet of Nuclear Power Plants (NPPs) is composed by 56 reactors containment buildings. In the EDF NPPs fleet, 24 containment buildings are double-walled containments. The safety those containments is based on three different barriers: fuel cladding, primary circuitry, and the reactor building associated with its dynamic containment. The passive leak-tightness function of the French 1300-1450 MWe NPP reactor building is provided by a reinforced and pre-stressed concrete inner wall without steel liner and an outer reinforced wall assuring the protection against external effects. The leak through the internal wall is collected in the annular space being permanently maintained slightly below atmospheric pressure. The technical objective, in term of leak-tightness, is to maintain the rate of gas escape under a legal criterion. The compliance with the rule is evaluated by measuring the quantity of air leak, obtained during a periodical pressure test at ambient temperature. This test is the so-called Integrated Leakage Rate Test (ILRT) done every 10 years.

The leak-tightness of the reactor building is highly dependent on the inner prestressed reinforced CCB. The post-tensioning of the inner prestressed CCB is calibrated to ensure that in case of an accident the concrete remains in compression. Tendons are grouted on these containments; therefore, increasing post-tension is not an option.

To guarantee the respect of a fixed reglementary leakage criterion, EDF gained a long experience of certified repair coating solutions. The in-situ feedback is positive, but their operational implementation remains a technical and organizational challenge. To maximize the safety of the containments, maintenance policies require a detailed knowledge of (i) the behavior of the concretes used in the containment buildings for the prediction (ii) the future evolution of their delayed strains (iii) their subsequent effects on leak-tightness. To centralize, automate and capitalize on all these developments, EDF has developed a digital twin's factory that allow to describe the evolution of concrete ageing and hereby to predict the evolution of prestress loss and of the leak rate of containment buildings over the years. In this work, the digital twin used to predict the mechanical behavior of the "Civaux 1" CCB and the evolution of its leak-tightness for the next ILRT are presented.

METHODOLOGY STRATEGY OF THE DIGITAL TWIN FACTORY

The digital twin factory consists of an informational system which allow the automation of a series of physico-numerical steps necessary for the prediction of ageing behavior and the leak-tightness of the CCB. This IT structure is a tool developed by EDF R&D called ARMORIC. The methodology and the digital twin factory have been developed while taking advantage of the VeRCoRs experiment (Charpin, 2021) (Masson et al., 2016), and have been applied to Belleville 1, Belleville 2, Flamanville 1 and Civaux1 containments (Charpin et al., 2021).

To better represent the strategy of a leak prediction study, Figure 1 describes its different steps as well as the necessary input data (in purple) for each of them. To summarize, a leak study is typically composed of an ageing calculation (in blue at the top), a comparison to measurements calculation (in green at the right) and a leak calculation (in orange at the bottom). The leak rate evaluation combines the local leak (bottom left), the porous leak (bottom right) and the leak rate evaluation with consideration of the coating solutions (post_predict_coating_leak).

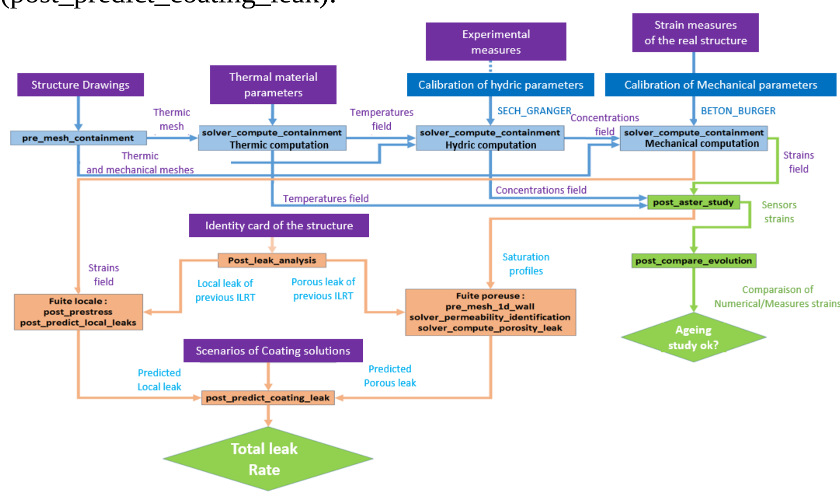

Figure 1. Methodological strategy for leakage prediction

The Strategy represented in Figure 1 can be phenomenologically structured according to the following steps:

- Step 1 - Initialization and meshing: definition of the case to be treated, meshing according to the structure plans.
- Step 2 - Thermo-hydro-mechanical (THM) ageing calculation: retrieval of the available material parameters, identification of the missing parameters while using measurements of the CCB auscultations, running the thermo-hydro-mechanical computations.
- Step 3 - Validation of the ageing calculation: by comparing numerical results with available strain measurement curves, temperature profiles and water content (or saturation) profiles.
- Step 4 - Prediction of the porous leak and the local leak: by using the outputted numerical saturation profiles from the thermo-hydric computation and the prestress losses from the mechanical computation.
- STEP 5 - Prediction of the total leak rate without coating solutions and with coating solutions while optimizing and studying different coating scenarios.

APPLICATION TO THE CIVAUX 1 CONTAINEMENT BUILDING

The double walled CCB of Civaux 1, a unit of the N4 level, was built between 1988 and 1993. This CCB was subjected until now to four ILRTs: a pre-operational test in 1993, a first inspection visit VC1 in 2001, a second inspection visit VC1bis in 2001 and a ten-year inspection visit VD1 in 2011. Two complementary visits were done in 2017 and 2020. During all the latter visits, the total leak rate was measured and verified to respect the reglementary leak criterion. The Civaux 1 NPP has undergone different repair coating works on the intrados and the extrados of the inner CCB, especially near the equipment access opening, the CCB's cylindrical wall and its gusset plate: approximately 4200 m^2 were placed on the intrados surface whereas 4000 m^2 were placed on the extrados one.

The upcoming ILRT VD2 will take place in 2022. Prior to this test, some repair coating works are planned: EDF is currently considering placing about 1000m^2 on the intrados of the inner CCB and 5000 m^2 on its extrados. To evaluate more accurately the need for these coatings and to optimize their surfaces, a prediction of the total leak rate for the upcoming ILRT of Civaux 1 is required and is presented in this work.

The thermo-hydromechanical (THM) behavior study (Steps 1 to 3)

In general, to predict the total leak rate of a CCB, it is necessary to carry out beforehand an ageing study of the latter structure. The objective of this study is to determine the thermal, hydric, and mechanical state of the CCB during the ILRT for which we want to predict the leak rate.

A finite element model is used to perform the ageing study. It is therefore necessary, as a first step (Step 1) of the leak prediction strategy, to create a 3D mesh of the inner CCB. More precisely, it is necessary to create two meshes: a linear mesh for thermal and hydric calculations and a quadratic mesh for the mechanical calculations. The prestressing cables are modelled in the mechanical mesh by wire elements to correctly represent the state of stress of the CCB and subsequently the deformations of the structure. In the current approach, the reinforcement is not integrated in the mechanical mesh due to their negligeable effect on the ageing behavior of the concrete. In another hand, the meshes must have a proper refinement in accordance with the gradients of the simulated phenomena, in particular the hydric gradient. Figure 2 represent the corresponding mesh of the concrete and of the prestressing cables used for Civaux 1 CCB.

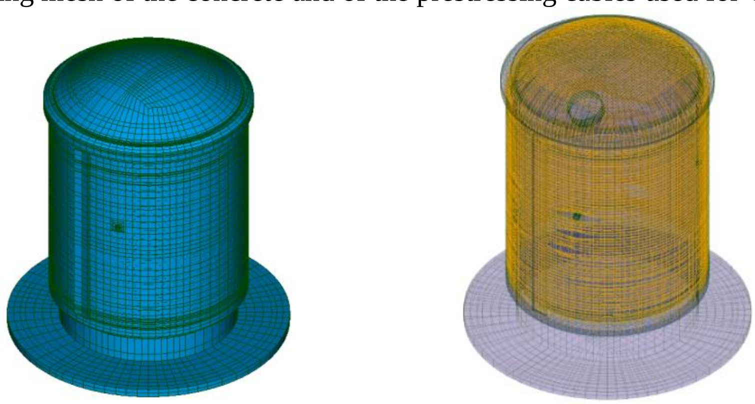

Figure 2. Mesh of the inner CCB of Civaux 1 (left) and of the corresponding prestressing cables (right)

The thermal computation is the first step of the THM computation. It is performed using a linear heat diffusion equation as given in equation (1):

$$\rho C_p \frac{\partial T}{\partial t} = div\ (\lambda \Delta T) \tag{1}$$

Where ρ is the density of concrete, C_p is its thermal capacity, and λ its thermal conductivity. Values of $\rho C_p = 2400000\, J/Kg/K$ and of $\lambda = 1.6\, W/m.K$ were used for this study based on (Semété et al., 2016). The boundary conditions are fixed temperatures imposed at the surfaces of concrete. Convection conditions can also be attempted but these conditions are not used for the current study.

The hydric drying computation is based on a non-linear diffusion equation (equation 2) developed in (Granger, 1995) and available in Code_Aster (www.code-aster.org) under the name of SECH_GRANGER.

$$\frac{\partial C}{\partial t} = div\,(D(C,T)\Delta C) \qquad (2)$$

Where *C* is the water concentration in time and *D* the diffusion coefficient of the concrete. This coefficient can be expressed as a function of the concentration, the temperature and material parameters *A*, *B* and *Q/R* (known as the activation energy of the concrete). The values of those parameters were determined in previous works of (Boucher, 2016) and are given in Table 1.

Finally, concerning the mechanical computation, we consider as loads the ortho-radial and vertical compressions induced by the prestressing cables and the weight of the structure. The mechanical behavior of the concrete is predicted while using a model present in Code_Aster named BETON_BURGER (Bottoni 2015) and that is based on the works of (Granger 1995) (Benboudjema 2002). It consists of an additive decomposition of the total strain between the thermal strain, elastic strain, the drying shrinkage strain, the basic creep strain, and the desiccation creep strain. This model requires several physical parameters that are given in Table 1.

Table 1: Identified drying, shrinkage and creep parameters

Described phenomenon	Parameter	Value	Unit
Drying model of Granger	A	4.3 10^{-13}	m^2/s
	B	0.07	-
	Q/R	4679	-
Drying Shrinkage	K^{des}	1.016e^{-5}	m^3/kg
Drying Creep	η^{fd}	3.421e^{11}	Pa.s
Activation energy for creep	Q/R	2264.98	°K
Reference Temperature for creep	T_0^{flu}	20	°C
Poisson ratio for creep	ν^{flu}	0.2	-
Reversible basic creep	$\chi = (1+\nu^{flu}) / (1 - 2\,\nu^{flu})$	2	
	k^{RD}	3.831e^{10}	Pa
	k^{RS}	$\chi * k^{RD}$	Pa
	η^{RD}	1.808e^{17}	Pa.s
	η^{RS}	$\chi * \eta^{RD}$	Pa.s
Irreversible basic creep	η^{ID}	5.531e^{17}	Pa.s
	η^{IS}	$\chi * \eta^{ID}$	Pa.s
	κ	2.135e^{-4}	-

As a second step of the prediction strategy, it is necessary to retrieve the THM parameters required for the computation. Those parameters are obtained usually by a calibration of the THM model on available measurements of the CCB auscultations, while using a smaller representative mesh of the cylindrical wall. For the Civaux 1 CCB, different on-site measurements (strains, temperature, water content) are used for this identification work. Regarding the mechanical identification, vibrating wire strain sensors submerged at the mid-height of the cylindrical wall are considered. The values of the calibrated parameters are given in Table 1. The comparison between the numerical and the measured strains is given in Figure 4. It can be observed that the identified set of mechanical parameters overestimates the long-term strains. This can lead to an overestimation of the predicted prestress loss and hereby of the predicted leak rate for the upcoming ILRT. This set of mechanical parameters is considered conservative and is retained for the current prediction of the leak rate.

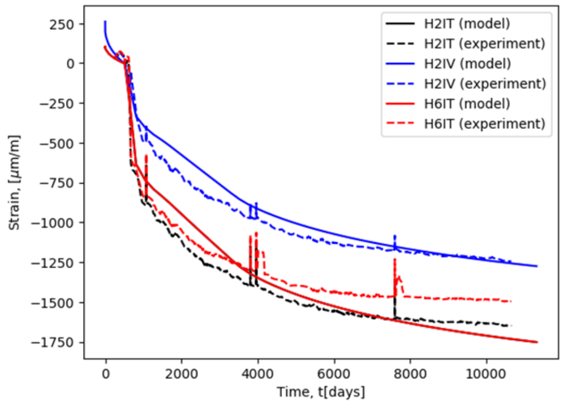

Figure 4. Comparison between the numerical and the measured strains near sensors at mid-height of the cylindrical wall.

As for the thermo-hydric identification, we referred to temperature measurements by sensors that were placed at the mid-height of the cylindrical wall, on the intrados and extrados surfaces of the inner CCB. This identification led to the temperatures given in Table 2. The relative humidities were respectively calculated by using the works of (Boucher, 2016).

Table 2: Identified temperatures, relative humidities and water concentration

Period	Parameter	Value at the intrados	Value at the extrados
Prior to putting the reactor into operation	Temperature	14.03	14.03
	Relative humidity	70.95 %	70.95 %
	Water Concentration	80.18 L/m^3	80.18 L/m^3
Posterior to putting the reactor into operation	Temperature	36.21	25
	Relative humidity	18.25 %	55%
	Water Concentration	23.91 L/m^3	52 L/m^3

The assessment of the water concentrations of the concrete (as described in equation 2) while using the relative humidities calculated in Table 1, is done by the mean of the so-called “desorption isotherm” of the concrete. This isotherm links the water concentration (or saturation) in a porous material to the ambient relative humidity for a given temperature. In this work, the concrete isotherm was determined using a numerical fit model of (Leverett, 1941) on experimental measurements done at EDF R&D (Semété, 2016).

Once all the input parameters and boundary conditions are set, the thermo-hydro-mechanical computation on the structure scale is launched. The model used with the identified set of parameters is validated by a comparison of the numerical results with the available auscultations measurements.
Figure 5 represents a comparison of the numerical mechanical strains with the measured ones at different locations of strain sensors placed in the inner CCB. The numerical results are quite satisfactory and show, in most cases, an overestimation of the strains. This overestimation goes in a more penalizing direction and thus in the direction of a safer prediction of the leak rate of the Civaux 1 CCB.

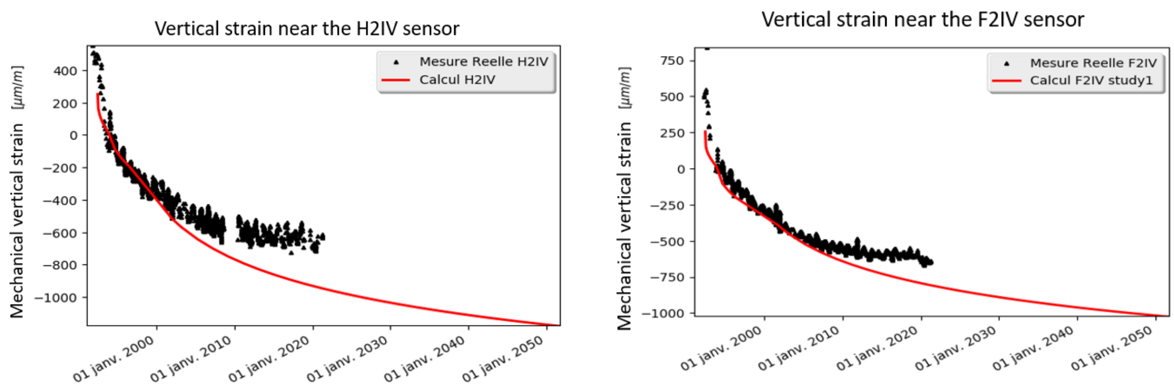

Figure 5. Comparison between the numerical and the measured mechanical strains near sensors placed on the cylindrical wall of Civaux 1 inner CCB

Figure 6 compares numerical temperature profiles with measured profiles by temperature sensors situated at the mid-height of the cylindrical wall (sensor H1), in the gusset part (sensor G2) and in the dome part (sensor I1). Generally, the numerical results are quite close to the sensors measurements. However, some improvements regarding the thermo-hydric boundary conditions that are considered (currently based on a constant imposed temperature and relative humidity along the CCB's height) can be envisioned in future works.

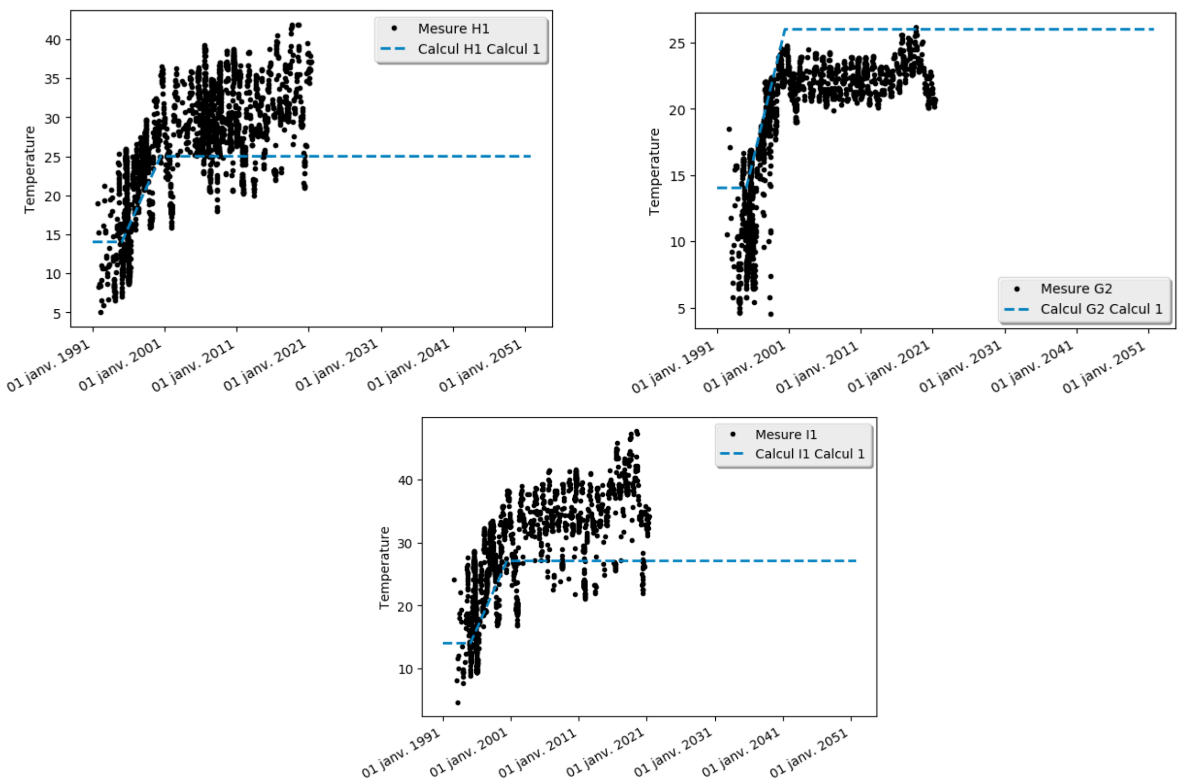

Figure 6. Comparison between the numerical and the measured temperature profiles near sensors located at the cylindrical wall (sensor H1), at the gusset part (sensor G2) and at the dome (sensor I1)

Finally, Figure 7 represents the expected water concentration profiles at the mid-height of the cylindrical wall for the upcoming ILRT (the VD2) and for further ILRTs (VD5 in 2050). As for the validation of the drying computation, it is done by a comparison of numerical water saturation profiles with corresponding measurements done by (Coyne et Bellier, 2007). This comparison is presented in Figure 8. Despite some differences in the intermediate values of water saturation inside the CCB wall, the modelled drying kinetic is considered close to that of the measured one.

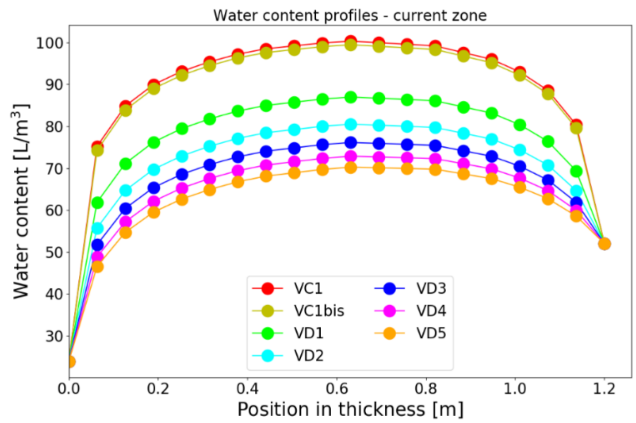

Figure 7. Water concentration profiles prediction for future ILRTs of Civaux 1 CCB until 2050 (VD5)

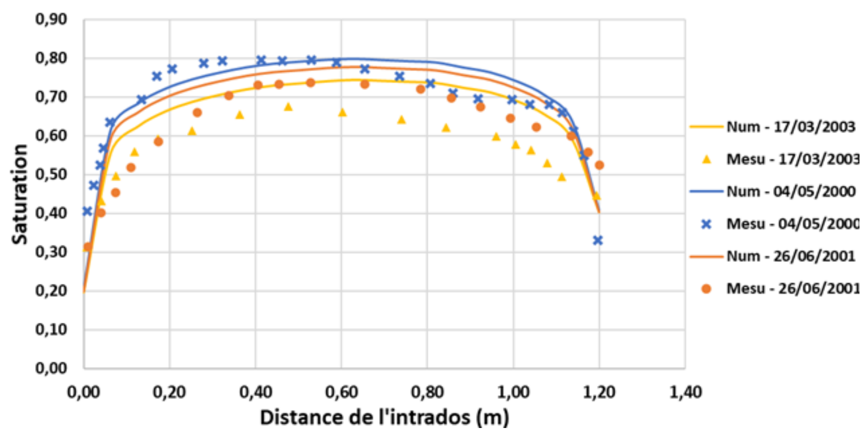

Figure 8. Comparison of numerical vs measured saturation profiles inside the Civaux 1 inner CCB – at a height of 17m (Coyne and Bellier, 2007)

The leak rate prediction of the next ILRT (Steps 4 and 5)

The prediction of the global leak is based on a decomposition of the latter (that can be accurately measured) in two categories: the so-called "local" leak caused by cracks in the concrete of the CCB and the so-called "porous" leak due to the porosity of the concrete. During an ILRT, a given local leak can be measured by a soap water sprinkling test using a leakage collection box (LCB). It is assumed that that the total local leak during an ILRT is obtained by summing the flow leaks of all the LCBs, even if, not all the flowing defects are necessarily visible or measurable. As for the porous leak, it is the difference between the global leak and the total local leak.

The prediction of the leak rate for the next ILRT is based on the results of the ageing study presented in the previous section but also on the leak and coating data of the previous ILRTs. As a first step, the prediction of the leak rate is done while considering zero coating surfaces after the previously considered ILRT. Then, as a second step, this leak rate is updated while testing different scenarios of repair coatings.

Regarding the porous leak, it is considered that its evolution is related to the quantity of water present in the pores of the concrete. The more water there is in the concrete, the more difficult it is for air to penetrate the concrete. For a given previous ILRT, this leakage is not measurable, but it is deduced from the difference between the global measured leak and the local measured leak. For a prediction of the porous leak of a future ILRT, an intrinsic permeability of the concrete is calibrated on the drying profile of the previous test and the porous leak of the future ILRT is calculated while using this permeability and a predicted drying profile (refer to Figure 7) of the latter test. This method is valid under a condition of iso-coating between two successive tests. To account for the addition of new coatings, we consider that adding coating surfaces to the CCB removes a fraction of the porous leak rate as described in equation (3):

$$Q_{FP(VD)_n,PAR} = Q_{FP(VD)_n,PSR} - \left[\frac{S_i}{S_{tot}} \cdot Q_{FP(VD)_n,PSR} . Eff_{int,porous}\right] - [\frac{S_i}{S_{tot}} . Q_{FP(VD)_n,PSR} . Eff_{ext,porous}] \quad (3)$$

Where $Q_{FP(VD)_n,PSR}$ is the porous leak with no new coatings added before the next ILRT, $Q_{FP(VD)_n,PAR}$ is the porous leak accounting for new placed coating surfaces, S_i is the ith coating's surface, S_{tot} is the total surface of the inner CCB, $Eff_{int,porous}$ and $Eff_{ext,porous}$ respectively the intrados and the extrados efficacities of the coatings for the assessment of the porous leak. In this study, the latter coefficients are taken of 40% for the intrados surface's coatings and 25% for the extrados' one. Those values are based on previous prediction studies done on the Flamanville 1 and Belleville 2 CCBs.

As for the local leak evaluation, it is considered that its evolution is mainly due to the prestress loss: the less the prestressing tension in the cables is, the more the cracks that develops during the early age of the structure will be able to open up during the upcoming ILRTs, and thus allowing more air to pass through. From the ageing study, it is possible to extract the average tension of each cable at the dates of each of the ILRTs. Knowing the initial prestress tension of the cables, it is possible to deduce the prestress loss for each cable and hence to deduce the average predicted prestress loss for the whole structure.

To predict the local leak rate of a next ILRT, the approach adopted consists in placing on a graph the local leak measured at the previous ILRTs as a function of the numerically estimated prestress losses. While using a linear interpolation and the predicted average prestress loss for the next ILRT, the corresponding local leak can be predicted (refer to Figure 9). This method is valid for predictions with iso-coatings between two successive tests. For this case study, we propose to predict the local leak of the upcoming ILRT (VD2) from the local leak measurements made during the Preoperational test and the first inspection visit (VC1).

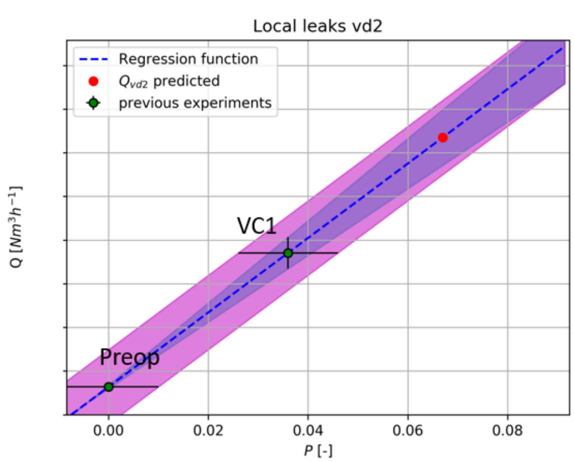

Figure 9. Prediction of the local leak for the upcoming ILRT

Then, to consider all the new coatings that were placed after the VC1 test, equation (4) is used:

$$Q_{FL(VD)_n,PAR} = Q_{FL(VD)_n,PSR} - \frac{Q_{i(VD)_{n-1},mes}}{Q_{FL(VD)_{n-1},mes}} . Q_{FL(VD)_n,PSR}\left[1 - (1 - Eff_{\mathbf{int},\,local})(1 - Eff_{ext,\,local})\right] \quad (4)$$

Where $Q_{FL(VD)_n,PSR}$ is the local leak with no new coatings placed before the next ILRT, $Q_{FL(VD)_n,PAR}$ is the porous leak accounting for new placed coatings surfaces, $Q_{i(VD)_{n-1},mes}$ is the measured local leak through the ith coating zone at the previous ILRT, $Q_{FL(VD)_{n-1},mes}$ the total measured local leak at the previous ILRT , $Eff_{int,local}$ and $Eff_{ext,local}$ respectively the intrados and the extrados efficacities of the coatings for the assessment of the local leak. In this study, the coefficient $Eff_{int,local}$ was calibrated on the local leak measurements done during the VC1bis and the VD1 tests. The calculated values are of $Eff_{int,local} = 0.87$ based on the VC1bis measurements and of $Eff_{int,local} = 0.9$ based on those of the VD1. To respect a more penalizing direction, the value of 0.87 is retained for the prediction of the local leak of the next ILRT.

As a final step, the global leak rate for the next ILRT is calculated by summing the previously predicted local and porous leaks. Due to the confidentiality of the results, the value of the predicted global leak cannot be communicated. However, Table 3 presents for different coating scenarios, the reduction (in %) of the global leak rate at the next ILRT with respect to a global leak rate that is predicted under the assumption of no new coatings placed after the VD1 ILRT.

According to the prediction done in this study, it is concluded that with the placement of the intrados coatings prior to the upcoming ILRT (VD2), the Civaux 1 CCB will be able to meet the reglementary leakage criterion.

Table 3: Global leak rate at the next ILRT

Coating scenarios	Total Coating Surfaces (m^2)	Global leak rate decrease with respect to a VD1 iso-coating condition (in%)
No new coatings placed after the VD1	2632 en intrados	0
Coatings placed at the VP2017 and VP2020	4228 on the intrados 4062 on the extrados	7.15
Intrados coatings placed at the VD2	5285 on the intrados 4062 on the extrados	9.57
Intrados and extrados coatings placed at the VD2	5285 on the intrados 9156 on the extrados	36.79

CONCLUSION

An informational system called "digital twin" has been developed at EDF R&D and has been used to produce and update simulations associated with ageing and leaking prediction studies. In this work, a digital twin of the "Civaux 1" reactor of EDF has been used to predict the ageing of the reactor and to predict the leaking rate for the upcoming 10-years reglementary investigation.

This paper presents the ageing calculation predicting the physical thermo-hydro-mechanical behavior of the containment and a calculation to predict the evolution of the different leak rates during future ILRTs. All the input data necessary for this study have been identified by a calibration work and summarized in this paper. In addition, a validation of the used numerical model used along with the adopted input parameters has been done while comparing numerical results (strains, temperatures, water contents) with in-situ measurements. The ageing simulation of the CCB lead to a prediction of the evolution of the prestress losses and of the water content profiles during time. Both later physical quantities represent important inputs for the prediction of the porous leak and local leak.

Finally, in this paper, different repair coating solutions for the upcoming ILRT (VD2) have been tested. The study carried out with assumptions that seem rather conservative (creep strains overestimation) leads to the conclusion that, with the proposed coating solutions, the Civaux 1 internal containment will meet the leakage criterion at the next ILRT.

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