

UHPFRC SOLUTIONS FOR THE RETROFIT OF NUCLEAR REACTOR CONTAINMENT WALLS

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Abstract

The containment walls of nuclear reactors must obey rigid air tightness criterion when it comes to ensuring the security of the surrounding population in an accident scenario. Tests must be performed regularly in order to verify leakage criterion. At a nuclear facility in France, higher than expected leakage rates, but below criterion, were discovered for some reactors, causing EDF/SEPTEN (Electricité de France/Service d'étude et projets thermique et nucléaire) to set up a research program that would identify robust repair solutions. The leakage rate is always respected but current solutions (by the inner face) must be enhanced, in some cases, to extend the working life of the structure up to 60 years. The use of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) for the reinforcement and air-tightness of the inner walls is a promising solution. Technological solutions using UHPFRC have been tested extensively and are presented in this paper.

Résumé

Les enceintes de confinement des réacteurs nucléaires doivent respecter des critères d'étanchéité à l'air dans l'éventualité d'un accident nucléaire afin de protéger la population environnante. Des essais de l'enceinte sous pression sont régulièrement réalisés afin de vérifier les taux de fuite des installations. Certains réacteurs possèdent des taux de fuite, qui bien que respectant le critère fixé, justifient la mise en place d'un programme de recherche de solutions de réparation par EDF/SEPTEN. L'enjeu réside dans une extension de l'exploitation jusqu'à 60 ans au minimum. L'utilisation de BFUP en solution d'étanchéité sont prometteuses et ont été testées de manière étendue et présentée dans cette contribution.

1. INTRODUCTION

Nuclear reactors must confine radioactive products to ensure necessary safety within an accidental scenario. As well, strict air tightness criteria must be respected and tests are regularly performed in order to check the leaktightness. At a nuclear facility in France, higher than expected leakage rates were discovered for some reactors, causing EDF/SEPTEN

(Electricite de France/Service d'étude et projets thermique et nucléaire) to set up a research program that would identify the most robust repair solutions to extend the working life of the structure up to 60 years.

A research program was set up between Lafarge and EDF SEPTEN to develop a repair solution. Two main solutions were tested: the first one utilized two layers of a customized UHPC with no shrinkage, cast between a formwork, while a second solution involved the use of hand-portable UHPC plates connected with a joint fill technology. (Figure 1)

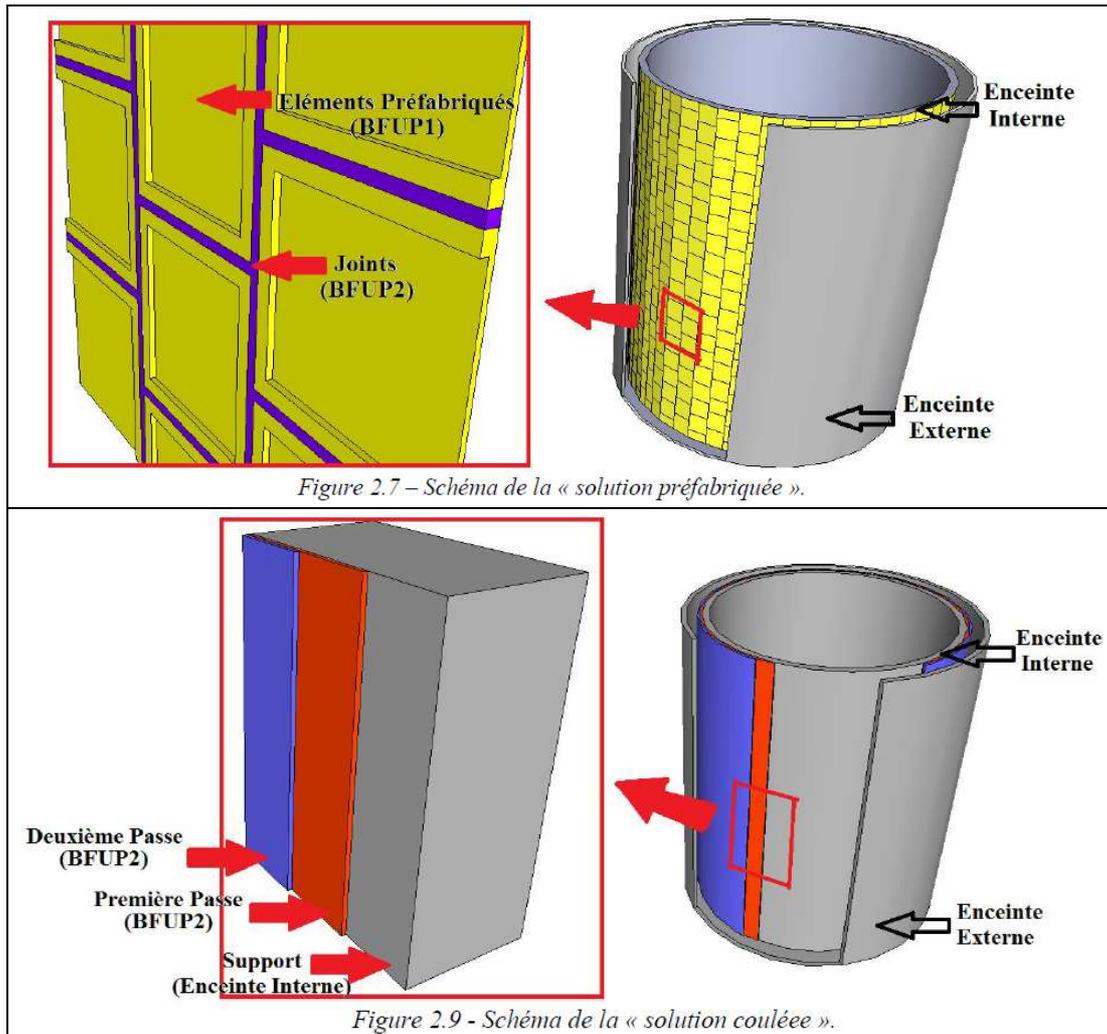


Figure 1: Explored UHPC solutions

In the first case, a specific mix design that has been developed to accommodate shrinkage will be detailed. Mechanical characteristics will be then presented according to fibre content.

In the second part, we will focus on specific testing chosen by SEPTEN to qualify the systems such as “under pressure”, bonding strength and permeability. The under-pressure test consisted of simulating an application defect of 20 cm² on a crack. This test is extremely severe for coating placed on the outside and the most composite coatings have failed. The coating is applied on a concrete slab and pressurized air (6 bars) is injected at the interface

between the coating and the support. The test is successful if the coating remains intact. A blister is tolerated. Moreover, the coating must cover the cracks without failure (not tested for UHPFRC) and a pull-out test is performed (strain breakout must be over 2 MPa).

In the last part, testing on prototype at scale 1:1 on MAEVA Mock-up will be presented. The MAEVA mock-up is a representative of the cylindrical portion at a scale of 1:1 in the thickness and at scale of 1:3 for the diameter of a containment building. This mock-up will be pressurized at 6 bar. At this pressure level, the concrete deformations are about 200 $\mu\text{m}/\text{m}$ (approximately the same level as containment concrete deformations) and the wall contains some cracks. Therefore, this test provides an excellent example of a coating used in a real situation.

2. UHPC CUSTOMIZATION

2.1 Compensating shrinkage in UHPC

2.1.1 Shrinkage in UHPC

Due to its brittle behaviour and low tensile strength, concrete can crack when loaded in tension or flexure. The consequences of concrete cracking include: aesthetical defects on concrete surfaces; increase of permeability; a reduction of the mechanical section; and reduced steel reinforcement protection (which can compromise durability). Indeed, shrinkage produces a dimensional change on concrete and can stress the material when its displacement is restricted and can't deform freely.

At the early stages (less than 24 h), cracking can occur in concrete because it can be subjected to dimensional changes and, due to shrinkage, it can generate loads which are greater than the low strength capacity of the material at this stage. The shrinkage phenomenon can be divided into two scenarios: drying shrinkage (external desiccation) and autogenous shrinkage (internal desiccation).

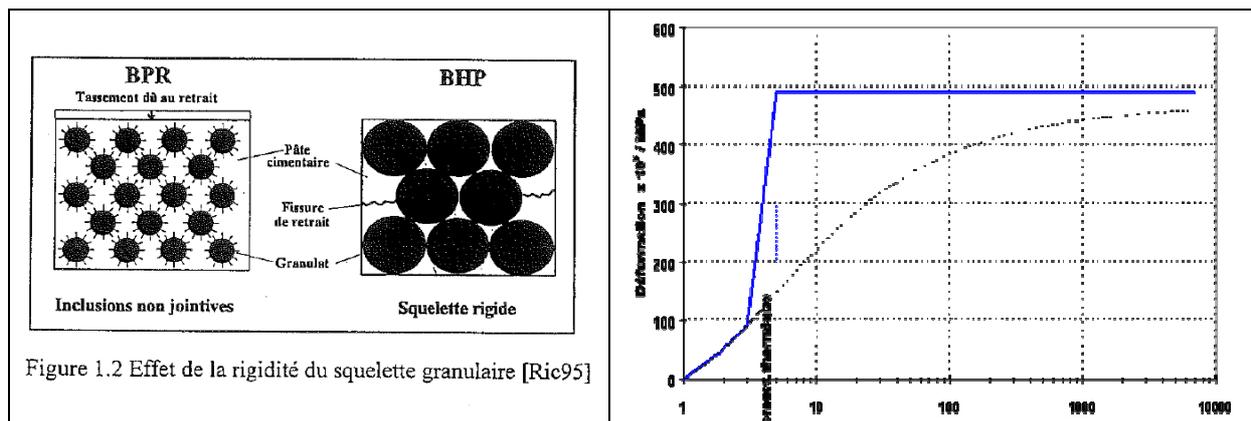


Figure 2: Shrinkage in UHPC

In standard concrete, with a water to cement (w/c) ratio higher than 0.45, drying shrinkage (if drying is allowed to occur), has been described as the most important cause of shrinkage at early ages. This is especially the case in members with highly exposed surfaces, such as floor slabs or precast panels.

The UHPC presented here has a low w/c ratio (typically around 0.19 and 0.23) and external desiccation, with a convenient curing, is rather small compared to autogenous shrinkage. Indeed, the typical granular skeleton mesostructure of concrete is replaced by a cement paste that is not blocked during hardening. The formulation of UHPC, with a limitation of sand, is selected so that the aggregates do not form a rigid skeleton but a set of inclusions are embedded in a continuous matrix. Consequently, shrinkage of the cement is locally blocked around each piece of aggregate, but the overall shrinkage is not blocked against the rigid skeleton.

2.1.2 A necessary compensating shrinkage technology

Shrinkage compensating concrete is, according to the ACI 223 report, a concrete made with an expansive cement or component system in which the expansion, if properly restrained, induces compressive stresses that approximately offset tensile stresses caused by shrinkage. A proprietary technology has been implemented for the UHPC to obtain a limitation of autogenous shrinkage to 100 $\mu\text{m}/\text{m}$ by compensating tensile stresses.

2.2 Mechanical properties according to fibre content and rheological requirements

Self placement in thin layers and pumpability requires shorter fibres than normal UHPFRC. Fibres 6 mm-long were used here.

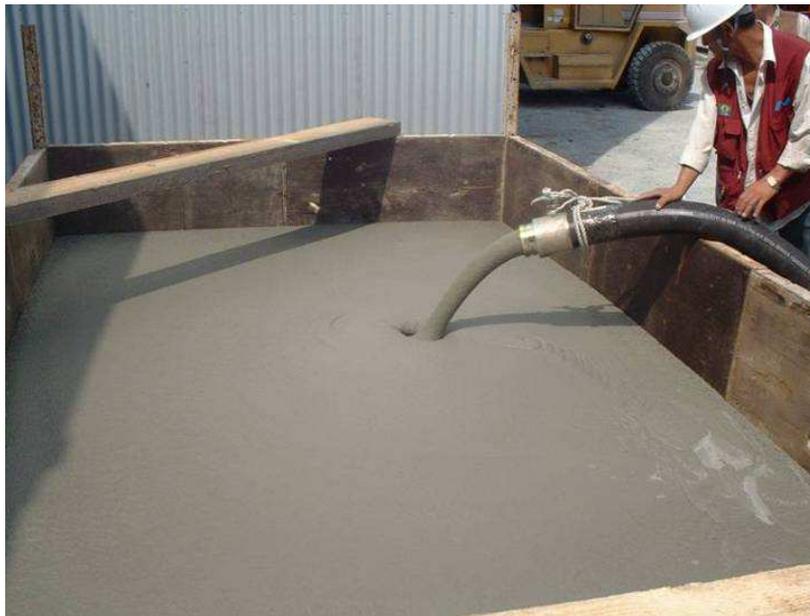


Figure 3: UHPC pumping

Mechanical properties of NaG3SR 1% have been assessed including:

- compressive strength greater than 130 MPa;
- Flexural strength greater than 15 MPa; and
- Elastic Limit in Flexure of 10 MPa.

This UHPFRC mix is not hardening in direct tension but will be able to redistribute bending stresses in case of a crack opening.

Table 1: Mechanical performances

Determination		NaG3 SR FM 1.0% 28J 20°C 100% RH
Compressive strength on 70 mm cylinders in MPa	Value	130,4
		134,7
		135,2
	Mean	133,4
	S.D.	2,6
4 points flexural strength on 7x7x28 prisms in MPa	Value	17,6
		18,3
		12,6
	Mean	16,2
	S.D.	3,1
Elastic Limit in Flexure in MPa		10,1
Young's Modulus in GPa		51,2

3. PRELIMINARY QUALIFYING TESTS

Specific tests have been chosen by SEPTEN to qualify the systems: such as “under pressure”, bonding strength and permeability.

3.1 Permeability

For the past 20 years, the laboratory of Centrale Lille (France) has developed permeability measurement techniques which involve the use of a confinement cell. Confining enables the maintenance of lateral tightness between the jacket around the cylindrical sample and the material submitted to an axial gas flow. The test chosen here is in quasi-permanent injection regime. This test is easy to perform and provides a direct measure of permeability through the application of Darcy’s law. The results obtained are far above the requested value. (10^{-17} m²).

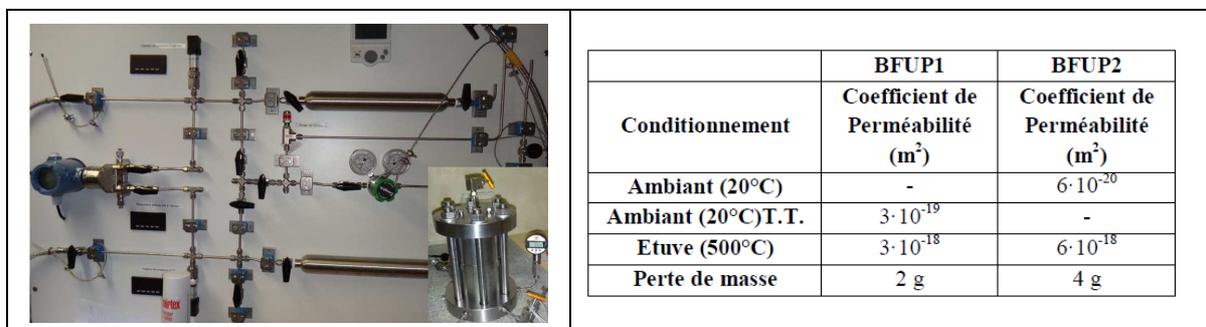


Figure 4: Permeability instrumentation and results

3.2 Bonding

A pullout test that measures bonding properties must be performed and the strain breakout must be over 2 MPa. The first series of tests did not perform well. It has been noted therefore, that preparation of the support is key. A saturated surface, with no water excess, is needed to avoid plastic shrinkage.

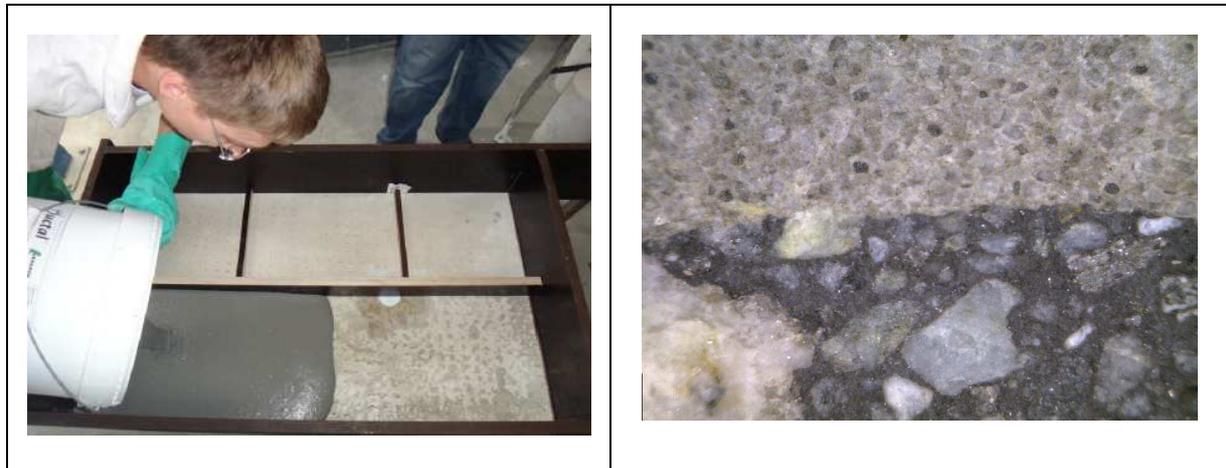


Figure 5: Specimen preparation and interface

Echantillon	Dimensions		Masse volumique [kg/m ³]	Résistance à la traction		Interface de rupture, remarque
	Ø [mm]	h [mm]		F _{max} [kN]	f _{cf} [N/mm ²]	
A	51.5	46.6	2'380	4.9	2.4	à l'interface, grain béton arraché
B	51.5	46.7	2'380	5.8	2.8	à l'interface, grain béton arraché
C	51.5	47.0	2'390	5.6	2.7	à l'interface, grain béton arraché
D	51.5	46.7	2'410	5.2	2.5	à l'interface 80%; dans BFUP 20% (zone plus épaisse)
moyenne :			2390		2.58	
écart type :			14.14		0.19	

Table 2: UHPC Pullout test results

3.3 “Under pressure” strength

The under pressure test involves the simulation of an application defect of 20 cm² on a crack. This test is extremely severe for a coating placed on the outside and the most composite coatings have failed. The coating is applied on a concrete slab and pressurized air (0.6 MPa) is injected at the interface, between the coating and the support. The test is successful if the coating remains intact. A blister is tolerated.

The test was successful at 6 bars (0.6 MPa) during 24 hours and the material performs well before stopping with a maximum pressure of 15 bars during 2 hours, without failure.

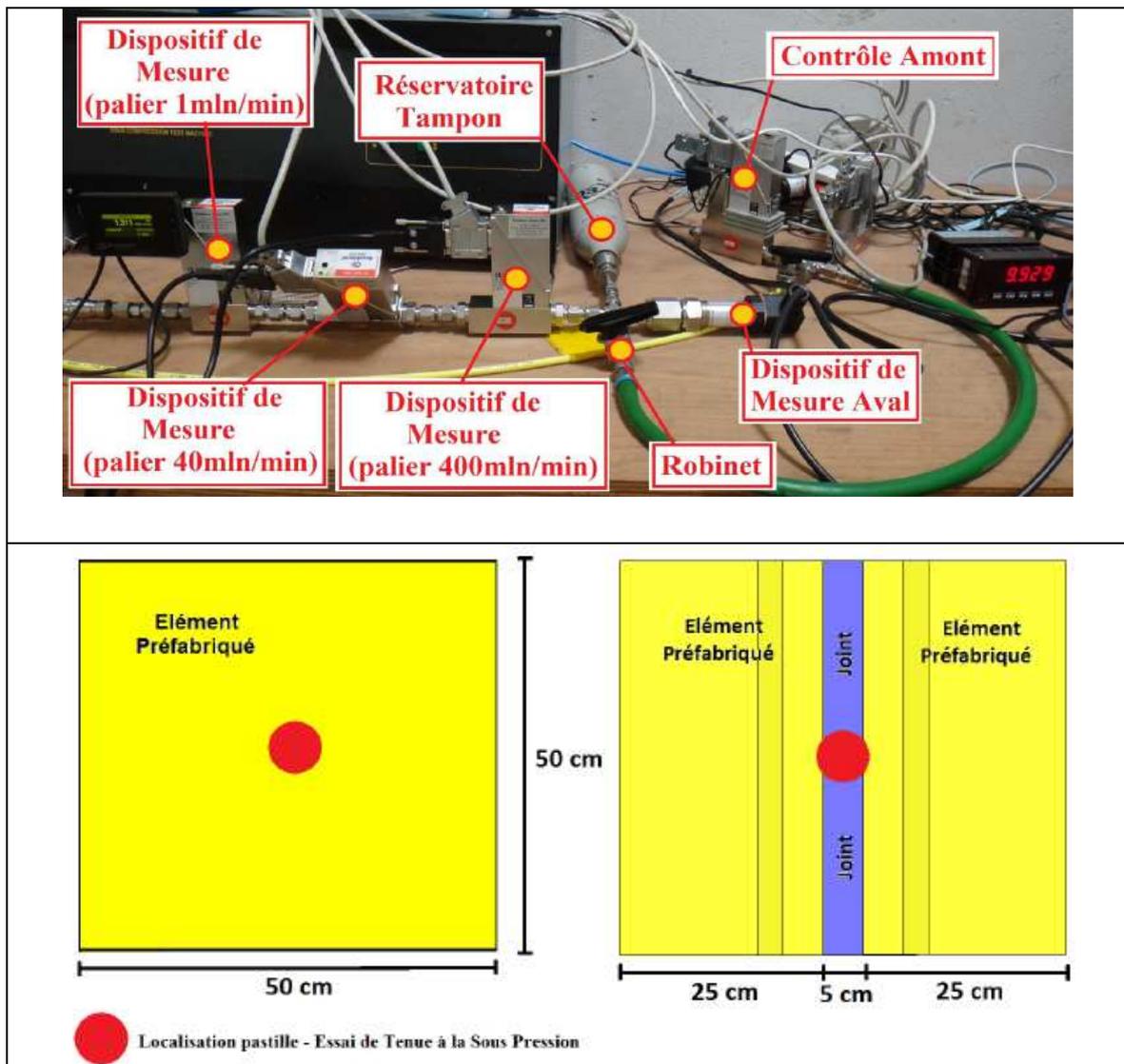


Figure 6: Experimental set-up for “under-pressure” and configurations tested

4. CENTRALE LILLE WALL AND MAEVA MOCK UP

The structural effect must be taken into account to be sure that the coating (UHPFRC wall) will be resistant in real configurations and, in particular, during the containment test. The under pressure test may be not enough penalizing to represent reality. Indeed, the pressurization of a porous network is not simulated in this test. In the case of a containment test, it is only a matter of time but the pressure in the pores in contact with the coating will reach 5 bars (equal to the pressure containment test). This pressure causes a thrust on the coating which is not simulated in the under pressure test.

Otherwise, during the containment test (with pressurization), the inner wall is subject to elastic deformations that induce shear stress at the interface. This phenomenon does not exist in the under pressure test.

To take into account these two effects, a structural test will be performed on the “Centrale Lille” wall and on the MAEVA mock up.

4.1 “Centrale Lille” Wall

The “Centrale Lille” wall is situated in Lille, France, on the campus of École Centrale. The laboratory performing the tests is the LML (Laboratoire de Mécanique de Lille).

The wall is constructed with a self-placing concrete, in which gas diffusers and pipes (0,5 cm diameter) are placed. The gas diffusers are positioned at 5 cm from the outside, ensuring gas propagation in the porous network. The pipes pass through the concrete and allow the performance of under pressure tests, in contact with a sleeve or on the concrete surface, to simulate two types of defects.

The test is performed in three phases. The first phase consists of pressurizing (5 bars) the porous network with the diffusers. A calibration test will be done beforehand to estimate the time required, to be in steady flow. The first phase test is performed during t_s+24h . For the second phase, pipes are supplied with a 5 bar pressure during 24h. The porous network remains supplied with air (5 bars). The coating test will be considered successful if there is neither damage nor flow at the end of the second phase. The third phase is a burn-out test. The porous network remains supplied with air (5 bars) while the supply pressure of pipes increases from 1 bar per hour to breakdown. If no damage is observed at 10 bars, the test goes on for 12 hours and then stops. This third stage allows for estimation of the margins.

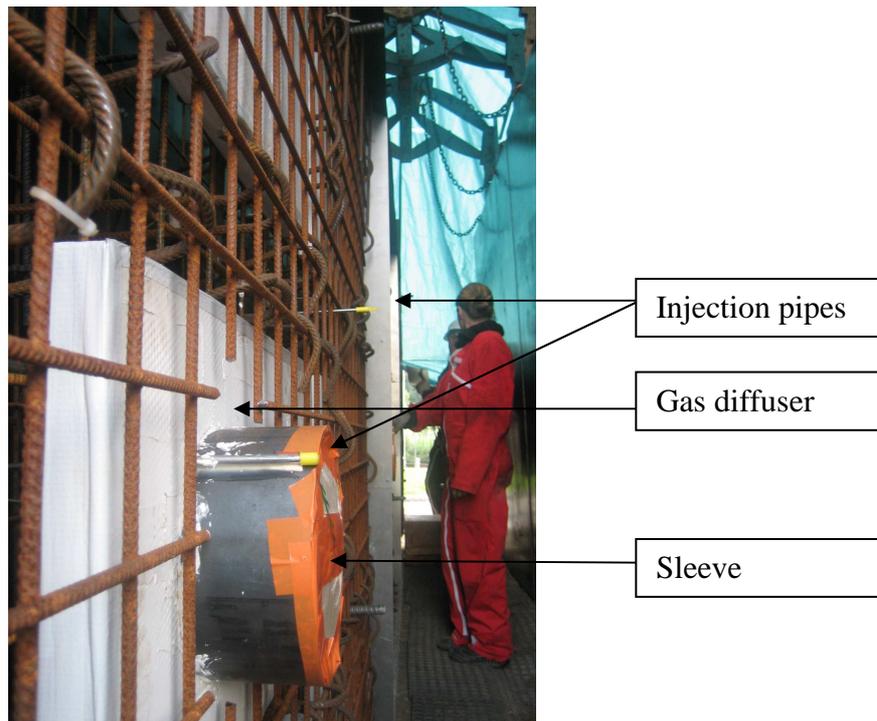


Figure 7: View of the wall before concrete

4.2 Maeva Mock up

The MAEVA mock-up consists of the cylindrical portion at a scale of 1:1 for the thickness and at a scale of 1:3 for the diameter of a containment building. The radius is 8m, the height 4.94m and the thickness 1.20m: This mock-up will be pressurized at 5 bars. At this level, concrete deformations are about 100 $\mu m/m$ in the tangential direction (about the same as containment concrete deformations). There is no vertical deformation because the cylinder is

disconnected from the upper and the down slabs. With this design, the mock up is not perfectly representative of containment where vertical deformations are about 150 $\mu\text{m}/\text{m}$.

The wall contains some cracks as containment and the flow rate is about 25l/h/m². The compliance with the containment criterion leads to a flow rate about 15l/h/m². So, EDF believes that this test, completed with the other evaluations, will be representative enough for a coating in a real situation. The test will be performed by increasing the internal pressure to 5 bars with a gradient of 1 bar per hour. After 24h at 5 bars, the pressure decreases to 1 bar (atmospheric pressure) in 4 hours. After one day, the pressure increases again to 6 bars and keeps constant until breakdown or 24 hours. The purpose is to evaluate the margins and realize a cycle (inflation - deflation - inflation) to prove that the coating remains effective after being subjected to a containment test.

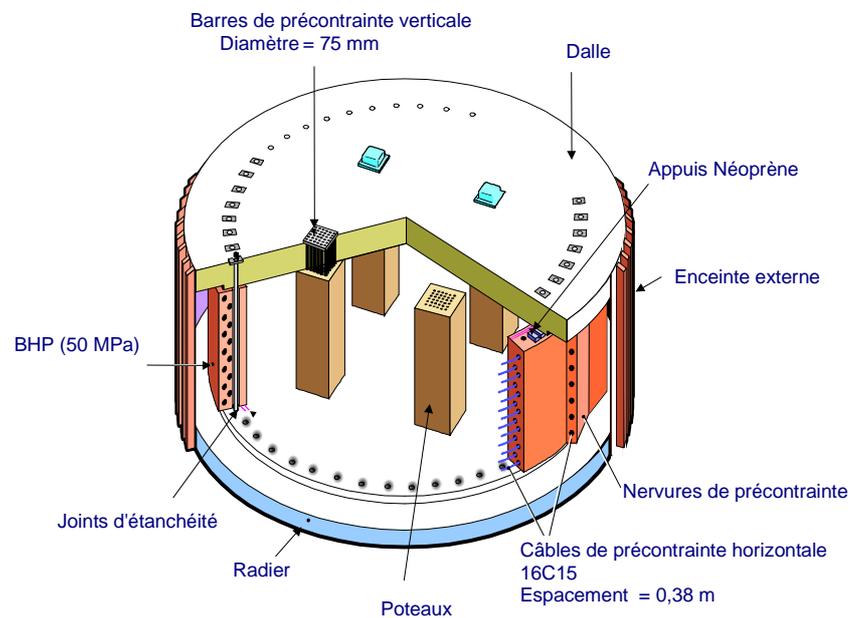


Figure 8: View of the MAEVA Mock Up

5. CONCLUSIONS

To conclude, the UHPC appears to be a promising solution for the retrofit of the nuclear reactor containment walls, in order to extend their usable lifetime. Air thickness permeability and good bonding properties are two major advantages of this solution. The roadmap, including a 1:1 test, has been launched in order to check full feasibility of the solution. The results will be available at the end of 2015.

ACKNOWLEDGEMENTS

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