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HW/1

Mechanical and leaktightness behaviour of a containment mock-up under severe accident

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ABSTRACT

In 1996, EDF has decided to construct a containment model at the scale 1:3, the MAEVA mock-up, in order to study the integrity of a prestressed concrete containment without liner in terms of mechanical strength and leaktightness, for loadings corresponding to its design and beyond design conditions. In parallel to the construction and testing of the mock-up, a R&D programme, the CESA project will make possible to compare predictive calculations of the behaviour of the mock-up to the experimental results.

1. INTRODUCTION

Beyond the first and second barriers, formed by the fuel rod cladding and the primary coolant boundary respectively, the reactor containment is the third and final barrier preventing the release of radioactive matter into the atmosphere in case of accident.

The validity of the design of the present containments, and particularly the way they withstand the standard design-basis accident (The Loss Of Coolant Accident (LOCA) considered in the design corresponds to P = 0.65 MPa abs. and T=160°C for the EPR type reactor and P = 0.53 MPa abs. and T = 140°C for the N4 series reactors) is currently based on two complimentary approaches :

- design calculations complying with current regulations, derived from experience feedback ;
- and a full-scale test, performed at the end of the construction and then periodically, during which the strength and overall leakage from the containment are measured while it is inflated with ambient-temperature air to design-basis pressure [3].

But this containment test does not fully recreate the characteristics of the design-basis accident, because the test takes place in ambient-temperature air and not in steam at 160°C (140°C on the concrete wall) for obvious technological reasons. However, when we look at how a containment behaves on real accidental conditions or when the pressure and temperature exceed design-basis conditions (this is called a "severe accident") we systematically apply a calculation approach using finite-element methods in order to study the thermo-mechanical behaviour of the concrete structure. In this case, the main difficulty is to represent with sufficient accuracy the distribution of the cracks, and particularly their size, so as to permit a precise evaluation of the leakrate of air or steam through the concrete.

The results of a number of laboratory tests [4] suggest that, as long as the cracks through the concrete wall are small in size (micro-cracks), the leakrate from a containment filled with a steam/air mix, following a primary pipe rupture, would be substantially lower than the air leakrate from the same containment. This phenomenon can be explained by the condensation of steam in the cracks and by the high surface-tension and friction forces resisting the displacement of the condensed water. However, in the case of a larger crack (macro-crack), this partial-plugging phenomenon has not been yet highlighted during experiment.

To make a decisive advance in this field, EDF proposed to construct a mock-up containment : the MAEVA mock-up (MAquette Echange Vapeur / Air) on the Civaux NPP site (figure 1). It is sufficiently representative in size to enable a good description of the mechanical, thermal and hydric phenomena that appear at the different stages of an accident.

The MAEVA Project (mock-up construction and testing) is mainly financed by EDF, and to a lesser extent by IPSN (French Institute for Nuclear Protection and Safety). The design and construction-related calculations were made by the Coyne & Bellier engineering consultancy and the construction performed by Freyssinet International.

In parallel to the construction and testing of the mock-up, a R&D programme, the CESA project (Containment Evaluation in Severe Accidents) will make possible to effectively compare predictive calculations of the mechanical and leakrate behaviour of the mock-up with the experimental results. The CESA Project is European in scope (involving 14 partners from four countries from the European Community (EC) : France, Italy, Germany and U.K.) and will be 50% financed by the EC as part of the *Nuclear Reactor Safety* programme [2].

2. AIMS OF THE TWO PROJECTS

The goal of the MAEVA mock-up is to study the integrity of a prestressed double wall concrete containment without liner to a scale 1:3 in terms of mechanical strength and leaktightness, for loadings corresponding to its design but also extending to levels that could be reached in case of a severe accident. This type of containment has been used in many plants (all the French 1300 MW and 1400 MW PWR units) and has been chosen for the EPR project (*European Pressurised Reactor*). The main aims of the tests on the mock-up are :

- to study the beyond-design-basis behaviour of the containment up to the rupture using an experimental simulation representative of the mechanical and thermal phenomena ;
- to evaluate the leakrates of a steam + air mixture (accident conditions) and to compare them with the air leakrate usually measured during a containment pressure test ;
- to study the behaviour of a composite liner on the inner wall of the containment.

In parallel to this experimental phase, a set of theoretical phases, predictive calculations and analysis of the results will be conducted as part of the CESA project. These phases will make it possible to analyse the results and to draw conclusions from the project. The aims of these theoretical phases are to :

- evaluate the performance of mechanical and leakage simulations, by a series of predictive calculations involving eight research organisations ;
- define the leakrate calculation through concrete cracks and aerosol retention in concrete ;
- analyse and integrate the results obtained, in order to improve the simulation of the behaviour of containment buildings in case of severe accident.

3. PRESENTATION OF THE MOCK-UP AND DESIGN ASSUMPTIONS

The MAEVA mock-up, has several components :

- a prestressed concrete cylinder of 8 m inside radius, 5 m height, 1.20 m thickness presenting a 0.7 m radius penetration half way up designed to simulate the many penetrations in a real containment. The model is biaxially prestressed :
  - horizontally, 13 16T15 tendons provide average prestressing of 5 MPa. They are anchored on two diametrically opposed ribs.
  - vertically, 70 Mac-Alloy bars of 75 mm dia. ensure an average prestressing of 3 MPa.
- two prestressed concrete "bases" (mat and cover) of 10.2 m radius and 1 m thickness ;
- four prestressed reinforced concrete columns linking the bases ;
- an external metal siding allowing compartmentalisation into 6 zones where the leakrates will be measured.

The concrete used to build the mock-up is a HPC (High Performance Concrete, compressive strength : $f_{c28} = 65$ MPa), which was used for the containment of the Civaux 2 reactor [1].

Lastly, in order to obtain a correct simulation of the standard section of a real containment, Neoprene pads, placed at the interface with the bases, leave the cylinder free to radial deformation. To ensure complete structural leaktightness, a double elastomer seal is fitted at the interface between the cylinder wall and the bases (mat and cover).

The model replicates, on a scale of 1:3, two standard-section lifts of the inner wall of a French double-wall containment without liner. The thickness of the wall has been kept full scale in order to facilitate interpretation of the leakrate measurement results and their transposition to a real containment (without needing to consider the reduction in scale on the properties of the fluid used to perform the tests). Lastly, about half the inner surface of the cylinder is covered by a composite liner, in order to keep the same volume/surface ratio as that of a full-size containment.

The measurements require co-operation from Freyssinet, which is in charge of installing the sensors, and from the DTG (EDF's General Technical Division, in charge of diagnostic monitoring), which will acquire and process the data.

Deformations are measured by vibrating strain gauges combined with temperature sensors. The total displacements of the mock-up are measured by telependula positioned on the extrados either side of three diameters of the mock-up. Cracks that appeared after the first air test will, in addition, be instrumented with fibre-optic sensors so that their development can be monitored externally. Lastly, two Mac-Alloy bars are instrumented using dynamometers.

As for the leakrates, the space between the inner wall and the metal siding is divided in four zones : one close to the penetration, one for the standard section, and two for the ribs, in order to determine the proportion of leakage from each zone. In the air tests, leakage can be deduced both from knowledge of the pressure and temperature in the different zones and inside the inner wall. In the high-temperature steam tests, leakage can only be deduced from the pressure, temperature and humidity level in each compartment of the space between the external wall and the cylinder ; with, in addition, consideration of the amount of steam that has condensed on the inner and outer walls. This water will therefore be collected and weighed.

The mock-up is designed so that the concrete remains in compression for an absolute design basis pressure of 0.65 MPa in air or steam. In this case, the containment exhibits only a very low leakrate, mainly through the micro-cracks that appeared during construction.

Above a pressure of about 0.75 MPa, the concrete goes into traction (in the tangential direction of the mock-up). As shown in figure 2, above this pressure micro-cracks and then macro-cracks start to appear. As a result, the leakrate rises substantially. At a pressure of about 1.6 MPa, the prestressed tendons yield ; soon afterwards they rupture and the mock-up collapses.

The mock-up tests represent two types of accident : a design-basis accident (LOCA) and a severe accident. These scenarios allow for pressure and temperature build-up to 0.65 MPa abs. and 160°C for the LOCA and to 1 MPa abs. and 180°C beyond the design basis according to the test protocol presented on figure 3.

For the air tests, pressurisation will be performed by compressors in accordance with a technique proven by application to the containment of plants commissioned by EDF. For the high-temperature steam tests, a boiler generating 13 T/h of steam with a 30 m^3 water tank will be used. Pressurised air or steam is introduced into the containment building via orifices located in the lower or upper slab respectively.

4 WORK PROGRAMME

The main stages of the project, co-ordinated by EDF-SEPTEN, are presented below.

Stage 1: Upstream or support studies [12/96 → 09/97]
This stage groups the experimental studies on reduced-size specimen and the theoretical developments for calculation of the leakrates and aerosol retention :

- *Theme 1 : Leakrate quantification*

Theme 1, performed by the CEA, has already permitted in previous years to measure the flowrate of a steam-air mixture through a crack of constant thickness simulated by two spaced parallel glass plates. The first results gave rise to the development of a computer model. For the years to come, the experiments and modelling will be carried out on micro-concrete.

- *Theme 2 : Aerosol retention in the concrete*

Theme 2 is piloted by AEA Technology, working in collaboration with ELECTROWATT and NNC. These three organisations have considerable experience of aerosol problems. Their work on this project involves proposing a way of modelling aerosol retention in leakpaths ; in particular, they will rely on a number of tests on reduced-size specimens.

- *Theme 3 : Materials characterisation*

This theme, done by the Technical University of Prague, groups a number of diffusion and permeability tests on concrete specimens brought to high temperature and, depending on the case, exhibiting micro-cracks.

- *Theme 4 : Modelling of steam and water migration in concrete*

Theme 4 is performed by CEA and aims to improve the finite-element calculation codes that allow consideration of steam and water transfers in the concrete under pressure and temperature gradients.

Stage 2 : Predictive calculations [12/96 → 12/97]
The partners directly involved in stage 2 are either design offices, government organisations or universities. These organisations were selected by EDF for their scientific and technical expertise in modelling prestressed concrete structures up to the rupture. In addition, they use different calculation techniques and codes (theories of yield, damage, probabilistic models, etc.). It will therefore be possible to test both the calculation codes and the modelling of the problem. It is important to understand that predicting the behaviour of this mock-up is a

difficult problem requiring a great deal of thought from the various organisations in order to consider the complexity of the modelling and the different thermo-mechanical couplings. The organisations will furnish three types of results :

- *Modelling of the thermal effects :*

On completion of this phase, the partners must propose a method of modelling the thermal effects in the containment wall. The required results will be graphs of temperature as a function of time for the different mock-up test phases, in the standard section and close to the penetration.

- *Mechanical behaviour of the mock-up :*

The organisations must propose a modelling method that allows consideration of the initial state of the prestressed reinforced concrete, of the load cases and of the boundary conditions. Lastly, they must be able to use a set of behaviour laws that make it possible to quantify damage of the concrete during the different test phases. Using the results obtained with their computer model, an analysis must be carried out to quantify the state of structural cracking. At the end of this phase, the partners must be in a position to provide results in terms of :

- global mock-up deformation (in particular close to the sensors used during the test) ;
- state of stress ;
- and damage to the mock-up, in the standard section and close to the penetration.

The first step of this phase consisted in a purely elastic calculation of the mock-up with imposed materail parameters, subjected to dead loads, prestressing, internal pressure of 0.5 Mpa abs. and a permanent temperature gradient of 120°C. A deformed mesh is presented in figure 4. The comparison between the stresses in the tanagential direction obtained by the different partners are presented in figure 5. The small differences are only due to the modelling hypotheses taken into account by the partners.

- *Leakrate evaluation :*

Using the information obtained on cracking, the organisations must propose (in coherence with stage 1) a method of modelling and calculating the air and steam leakrates through the concrete cracks (number of cracks, length, spacing, thickness).

Stage 3 : Results analysis [08/97 → 12/98]

This stage has two main goals :

- a final comparison of the theoretical results of the stage 2 Benchmark with the experimental results from stage 3. This comparison will therefore make it possible to validate and/or reject certain choices made by the different organisations taking part in the predictive calculations.
- an in-depth analysis of the results using the experience feedback from the first two phases of the project.

This last phase is being piloted by EDF and will be jointly handled by EDF, SIEMENS, ENEL and IPSN. During this phase, AEA/NNC and CEA will provide direct technical assistance, as will the Benchmark participants.

5. CONCLUSIONS

All these results will provide a clearer idea of the safety of existing containments and place in perspective the various theoretical studies on their severe-accident behaviour launched by Utilities world-wide.

Lastly, protecting the environment and the population depends on how well a containment traps radioactive products, even in accident conditions more severe than the design-basis conditions. The experimental results acquired and the calculations carried out will enhance our knowledge and allow better analysis of reactor-related risks and the measures taken to control them.

In addition, beyond the nuclear sphere, the analysis of the predictive calculations will also be highly instructive for other fields such as mechanics and hydraulics, where research also focuses on structural breaking, leaktightness and high-temperature behaviour.

This project also has the advantage of bringing together people from different cultures and backgrounds, (different countries, different job sectors and objectives). This rich mix of participants is, we hope, the face of things to come.

ACKNOWLEDGEMENTS

The MAEVA mock-up is the result of a joint effort of several EDF units : SEPTEN, CNEN, DTG and also DEPT. The contribution of the partners of the CESA project : AEA, CEA, Coyne & Bellier, ENEL, ENS de Cachan, IPSN, ISMES, LCPC, GRS, NNC, SIEMENS, Stangenberg & Partners and the financial support of the European Commission (DG XII - R&TD *Nuclear Reactor Safety*) is greatly acknowledged.

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Figure 2 : Diagram of the mock-up design.

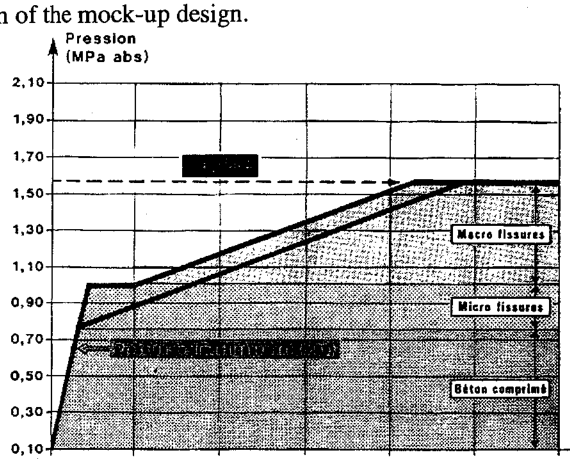

Figure 1: General diagram of the MAEVA mock-up.

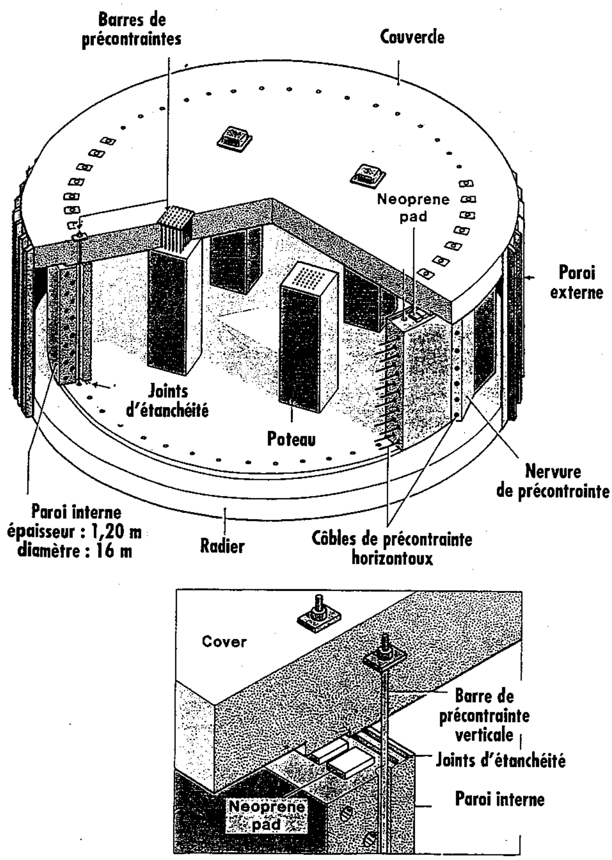

Figure 3 : Diagram of the mock-up test protocol.

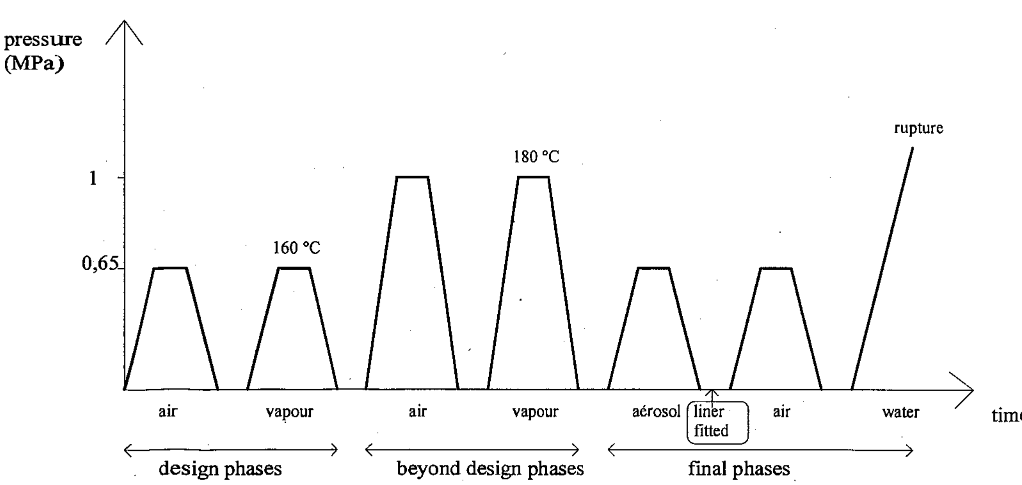

Figure 4 : Tangential stresses in the cylinder wall - Elastic calculations.

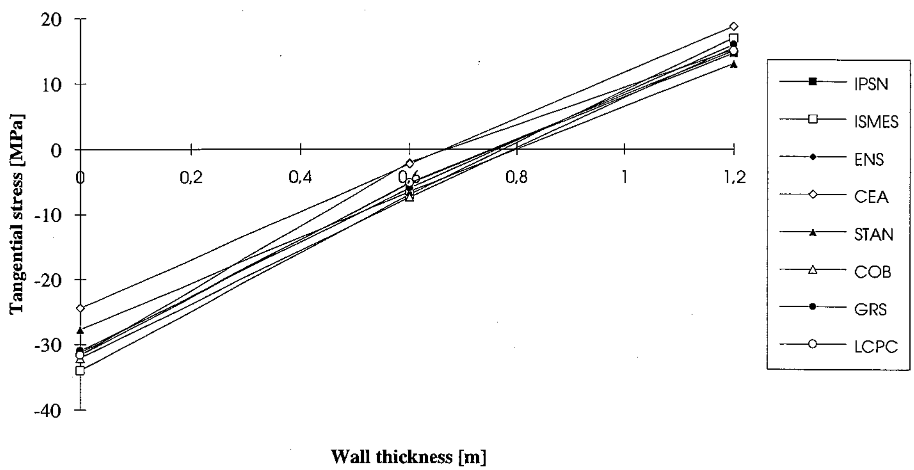

Figure 5 : Deformed mesh of the mock-up - Elastic calculations.