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Probability safety assessment of typical 900 MWE French nuclear containment

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ABSTRACT

The Probability Safety Assessment (PSA) of a typical French Nuclear containment of the 900 MWe type (single prestressed concrete containment with steel liner) has been carried out on the plant of Blayais 3, chosen as the most representative of the 34 other plants of this type owned by EDF. In this paper, we present the main results obtained in terms of median and 95% confidence values of the resistance and leakage capacity of this NPP.

1. INTRODUCTION

The goal of a Probability Safety Assessment (PSA) is to evaluate the probability that a plant, here a Nuclear Power Plant (NPP), might be at the origin of severe consequences (precisely described and quantified), in terms of radioactivity release in the environment.

In support to the level 2 PSA in progress at EDF, the potential failure modes of the containment due to temperature and pressure loadings, well beyond the design basis conditions were studied. In this evaluation, the failure was defined either as incipient leakage or gross structural failures. This evaluation has been carried out using the plans and the data gathered at the time of erection of the NPP of Blayais 3 (near Bordeaux), chosen as the most representative of the 34 other 900 MWe plants of this type owned by EDF

The EDF 900 MWe containment is a prestressed and reinforced concrete cylindrical containment capped by a torospherical dome (figure 1). The containment has an interior diameter of 37 m and a thickness of 0.9 m while the dome is only 0.8 m thick. The containment is designed to withstand an internal absolute pressure of 0.5 bars and a temperature of 140°C corresponding to a LOCA. The mechanical resistance of the containment is ensured by bonded post-tensioned 19T15 tendons ensuring a biaxial prestressing of the cylindrical wall. For the dome, the biaxial prestressing is obtained by a 60° grid (figure 1). The basemat is a 3 m thick conventional reinforced concrete foundation mat. The leaktigthness of the containment is ensured by a 6 mm thick mild and ductile steel liner.

In this paper, we present and analyse the main results obtained in terms of median and 95% confidence values of the resistance and leakage capacity of this kind of NPP and we present our feedback experience on the evaluation of the variabilities associated with the determination of the median pressure capacities.

2. METHODOLOGY

The methodology used to perform this probabilistic evaluation of the containment capacity is based on the American experience of PLG Inc. and EQE International [2], two engineering consultant offices specialised in the conducting of Level 2 PSA. The results presented below have been obtained by EDF with assistance from COYNE ET BELLIER, the French design and engineering consultant office responsible for the design of the prestressed and reinforced concrete containment of the 900 MWe NPP (called the "CP 1-2" series).

The failure modes studied below consist either in an incipient leakage ("Leak"), corresponding generally to deformation induced failure mode resulting in a liner tear, or in gross structural failures ("Break") corresponding to a direct pressure induced failure assumed to lead to large leak areas and rapid depressurisation of the containment, like for example following the rupture of the prestressing cables. The different calculations performed in our analysis are based on the following assumptions :

- the rise of the internal pressure is supposed to be quasi-static ; in particular, no dynamic amplification factor are applied to the pressure loading. This implies a maximum pressure rise time higher than 1 second.
- in a conservative way, the determination of the pressure capacity is performed for 3 temperature levels, 40°C, 140°C and 200°C corresponding respectively to the normal operating conditions, to the temperature of the LOCA and to the maximum expected temperature in the containment in severe accident conditions. For intermediate temperatures, the pressure capacity is obtained by linear interpolation.
- the temperature conditions correspond to steady state field. The temperature has two effects, a gradient effect inducing a moment, as long as the concrete remains uncracked, and a reduction in the mechanical properties of the materials.
- the pressure capacities P(T) are supposed to be lognormally distributed random variables described by a median pressure $P_m(T)$ and a variability $\beta(T)$ corresponding to the standard deviation of the random variable ln(P).

The median pressure $P_m(T)$, calculated without any security factors and with abstraction to codes, national standards and regulations, takes into account the real characteristics of the materials at the temperature T by applying a correcting factor F(T) to the material characteristics (table 1). The logarithmic standard deviation β represents the uncertainty in the value of P_m related both to the variability in the material strength and to the variability associated with the modelling of the structure and the way the calculations are performed.

Therefore, in order to be easily treated mathematically, the random variable P is written in the following way :

$$P(T) = P_m(T).S(T).M \qquad (1)$$

S Lognormally distributed random variable taking into account the variability due to the material Strength with a median value of $S_m = 1$ and a variability β^S

M Lognormally distributed random variable taking into account the variability due to the Modelling with a median value of $M_m = 1$ and a variability β^M

Whereas the variability β^S is rather clear mathematically speaking, the variability β^M is evaluated to take into account the following effect :

- simplifications in the modelling of the structure together with the geometrical position of the different materials,
- simplifications in the description of the failure mode,
- simplifications in the modelling of the behaviour of the materials and in the way the calculations are treated numerically,

- choice of the level of precision in the calculations (simple hand calculations *vs* finite element computations).

Therefore, when the rupture is reached, the way the total load/force applied to the structure, $L(P_m(T))$ is carried by the different materials of the structure can be expressed in the following way :

$$L(P_m(T)) = \sum_{i=1}^{n\ \text{materials}} S_i\sigma_i \qquad (2)$$

where S_i is the section of material "i" and σ_i its stress at the time of rupture. Then, α_i is defined by :

$$\alpha_i = \frac{S_i\sigma_i}{L(P_m(T))} \ ; \ \sum_{i=1}^{n\ \text{materials}} \alpha_i = 1 \qquad (3)$$

The variability β^s can then be computed by taking into account the variability of the materials at the reference temperature (T = 20°C), β_0^S, and the variability induced by the effect of the temperature on the reduction of the material characteristics, β^T (supposed independent of T):

$$\beta^S = \sqrt{\sum_{i=1}^{n\ \text{materials}} \left(\alpha_i\beta_i^S\right)^2} \qquad \text{where :} \qquad \beta_i^S = \sqrt{\beta_{0i}^{S\,2} + \beta_i^{T2}} \qquad (4)$$

Afterwards, the global variability of the failure mode, β, is obtained by combining the above value with the variability due to the modelling β^M in the following way :

$$\beta = \sqrt{\beta^{S2} + \beta^{M2}} \qquad (5)$$

Then, the 95% confidence pressure capacity is calculated in the following way :

$$P_{95\%}(T) = P_m(T).\exp(-1.646 \cdot \beta) \qquad (6)$$

The different characteristics and variabilities of the materials taken into account in the calculations (concrete, prestressing cables, liner & steel rebars) are presented in table 1. These where calculated by using the data gathered at the time of erection of the plant and some values found in the literature especially for the characteristics at high temperature.

3. RESULTS

The results in terms of median pressure, variability and 95% confident pressure capacity, are presented in table 2 for the 3 ranges of temperature studied. The position of each failure mode is presented in figure 2. The different modes studied are listed below with a letter B for Break and L for Leak :

- B1 : Rupture of the hoop cylinder membrane (always less than in the vertical direction)
- B2 : Rupture of the dome membrane
- B3 : Rupture of the roof of the tendon gallery
- B4 : Rupture of the base of the cylinder wall
- B5 : Rupture at the dome and cylinder junction
- B6 : Rupture of the prestressing cables around the equipment hatch
- B7 : Rupture of the sleeve anchors of the equipment hatch
- L1 : Pipe penetration leak capacity
- L2 : Roof of the tendon gallery leak capacity
- L3 : Personnel airlock leak capacity

The transfer tube leak capacity (L4), the electrical penetration leak capacity (L5) and the purge and vent valves leak capacities (L6) have been also studied and are not reported on the tables below. This is due to the fact that their median pressure capacity was found to be much higher than the other failure modes, therefore, the calculations of β and $P_{95\%}$ have not been performed.

Table 1 : Synthesis of the characteristics and variabilities of the materials.

Concrete	X_m	β_x^S	F(140°C)	F(200°C)	β_x^T
- E (GPa)	38.0	0.05	0.68	0.55	0.01
- R_c (MPa)	48.5	0.1	0.88	0.83	0.02
- R_t (MPa)	3.3	0.07	0.7	0.5	0.03
- ν	0.2	0.07			
- $\varepsilon_{b,c}^{rupt}$ (%)	0.02	0.1			
- $\varepsilon_{b,t}^{rupt}$ (%)	0.01	0.1			

Prestressing cables	X_m	β_x^S	F(140°C)	F(200°C)	β_x^T
- E (GPa)	193	0.01	0.96	0.94	0.02
- σ_r (MPa)	1888	0.0175	0.96	0.93	0.02
- σ_y (MPa)	1545	0.0175	0.94	0.87	0.02
- ε_a^{rupt} (%)	3.0				
- ε_a^y (%)	0.8				

Liner	X_m	β_x^S	F(140°C)	F(200°C)	β_x^T
- E (GPa)	200	0.01	0.96	0.94	0.025
- σ_r (MPa)	445	0.027	1	1.1	0.025
- σ_y (MPa)	325	0.037	1.5	1.5	0.025
- ν	0.3	0.02			
- ε_a^{rupt} (%)	> 5		≥ 3	≥ 3	
- ε_a^y (%)	0.2				

Steel rebars	X_m	β_x^S	F(140°C)	F(200°C)	β_x^T
- E (GPa)	200	0.01	0.96	0.94	0.02
- σ_r (MPa)	475	0.05	0.96	0.96	0.05
- σ_y (MPa)	392	0.05	1	0.96	0.07
- ε_a^{rupt} (%)	13.0				
- ε_a^y (%)	0.2				

Furthermore, it is interesting to note that 4 different kinds of failure modes, in the scope of interest of the pressure level studied here, have been identified for the equipment hatch :

- rupture of the prestressing cables around the equipment hatch (B6) ;
- rupture of the sleeve anchors of the equipment hatch by shear failure due to the internal pressure, inducing a radial displacement of the hatch towards the exterior (B7) ;
- together with these 2 Break failure modes, the equipment hatch leak capacity requires to study two other failure modes due to the complex displacement field of the equipment hatch (at high pressure) presenting both an ovalisation in its plan together with a twisting inducing potential liner tears (L7). Furthermore, the twisting of the sleeve tends to open the elastomeric seals ensuring the leaktightness of the junction between the steel annular collar and the torospherical cap (L8). These two last failure modes are still in progress at EDF

since the first calculations of the displacement of the hatch will be checked in the near future to the displacement measured during a containment pressure test at 0.5 MPa.

Finally, for the leak modes, is was interesting to evaluate the leakage surface, or better, the surface characteristics in terms of length, width and thickness of the wall (since the leak rate is very sensitive to the width of the liner tear (*cf.* Poiseuille law to evaluate the leak rate through concrete cracks [3])). This is simply done by evaluating the number of potential cracks, k, depending on the failure mode, and the distance "l" where the elastic strain of the material who has failed should be spread : $\varepsilon_{\text{elastic}} = \varepsilon - \varepsilon_{\text{plastic}} = \frac{k.\Delta l}{l}$ (7)

where ε is the mean strain of the zone and Δl the width of the crack (liner tear or concrete cracks).

4. ANALYSIS OF THE RESULTS

From the feedback experience we now have, several things should be pointed out.

The variability in strength β^s of the materials is, in most of the cases we faced, much lower than the variability β^M due to modelling assumptions. Therefore, in equation (4) the computed value of β is most of the time very close to β^M. To our opinion, this is due to the high level of QA imposed during the construction for the casting of concrete and reception of the steel materials. Therefore, in a first approximation, we may consider that $\beta \approx 1.1 \cdot \beta^M$.

The value of the variability due to the modelling and calculations assumptions, β^M, is sometimes difficult to assess due to the poor references on this subject and the difficulty to really evaluate this variability on a scientific basis. On a first approach, one may consider that β^M relies a lot on the experience and "modesty" of the engineer who performs the calculations. This is only partly true for two reasons. First of all, a certain scale can be kept in mind with all the values of β^M used in the different failure modes. β^M will be close to 0.1 when the loads are easy to evaluate and when the failure process can be precisely described, β^M will be close to 1.5 when shear stress and bending moments occur and can reach 0.2 when strong simplifications are performed in the calculations or when large unknowns are forecast.

This range of values have been checked on the benchmark calculations performed by 10 organisations before the testing of the SANDIA mock-up [1]. As can be seen on the results, the value of the variability β^M is between 0.15 and 0.25 for the prediction of cracking in the concrete and between 0.1 and 0.25 for the prediction of the onset of liner yielding depending of the zone studied. On the contrary, β^M is a lot smaller, around 0.1, for the yielding capacity of the steel rebars and the crushing of the basemat. In our case, as long as the leaktightness of the containment is ensured by a steel liner, the rupture occurs mainly just after reaching the tensile strength of the steel rebars or of the prestressing cables. For these cases, the variability chosen in our calculations (table 2) is in the same order of magnitude as for the SANDIA predictive calculations.

4. CONCLUSIONS

The Probability Safety Assessment (PSA) of the 900 MWe type French Nuclear containment has been carried out, based on the American experience. Up to now, 7 Break failure modes and 8 Leak failure modes (with 2 modes still in progress) have been studied in detail. The ratio of lower pressure capacity to the design pressure at 140°C is obtained for mode B6, a Break failure mode, and is equal to 1.74. This good result confirms the ability of this containment design to remain leaktight during severe accident scenarios. This analysis reveals finally the weakest point of this design, the equipment hatch, with 4 different kinds of failure modes, in the scope of interest for the level of pressure studied here.

Table 2 : Synthesis of the results at T = 40°, 140° and 200°C (capacity pressures in MPa) for the different failure modes (F.M.).

F.M. at 40°C	β^S	β^M	P_m	β	$P_{95\%}$
B1	0.016	0.10	1.17	0.102	0.99
B2	0.026	0.10	1.51	0.103	1.27
B3	0.05	0.15	1.46	0.158	1.20
B4	0.054	0.16	1.51	0.169	1.14
B5	0.083	0.12	1.34	0.146	1.15
B6	0.022	0.20	1.30	0.201	0.93
B7	0.050	0.15	1.35	0.158	0.96
L1	0.115	0.15	1.30	0.189	0.98
L2	0.050	0.15	1.26	0.158	1.04
L3	0.11	0.18	1.42	0.21	1.01

F.M. at 140°C	β^S	β^M	P_m	β	$P_{95\%}$
B1	0.022	0.12	1.15	0.122	0.95
B2	0.027	0.12	1.48	0.123	1.21
B3	0.050	0.15	1.46	0.158	1.20
B4	0.054	0.16	1.49	0.169	1.14
B5	0.089	0.14	1.28	0.166	0.97
B6	0.022	0.22	1.25	0.221	0.87
B7	0.070	0.15	1.35	0.166	0.95
L1	0.121	0.15	1.22	0.193	0.89
L2	0.050	0.15	1.26	0.158	1.04
L3	0.12	0.18	1.29	0.21	0.91

F.M. at 200°C	β^S	β^M	P_m	β	$P_{95\%}$
B1	0.023	0.12	1.14	0.122	0.93
B2	0.028	0.12	1.46	0.123	1.12
B3	0.050	0.15	1.46	0.158	1.20
B4	0.056	0.17	1.36	0.179	1.01
B5	0.095	0.14	1.27	0.169	0.96
B6	0.023	0.22	1.24	0.221	0.87
B7	0.070	0.15	1.32	0.166	0.93
L1	0.130	0.15	1.17	0.198	0.85
L2	0.050	0.15	1.26	0.158	1.04
L3	0.13	0.18	1.22	0.22	0.85

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Figure 1 : Presentation of the 900 MWe French NPP containment - geometry and prestressing.

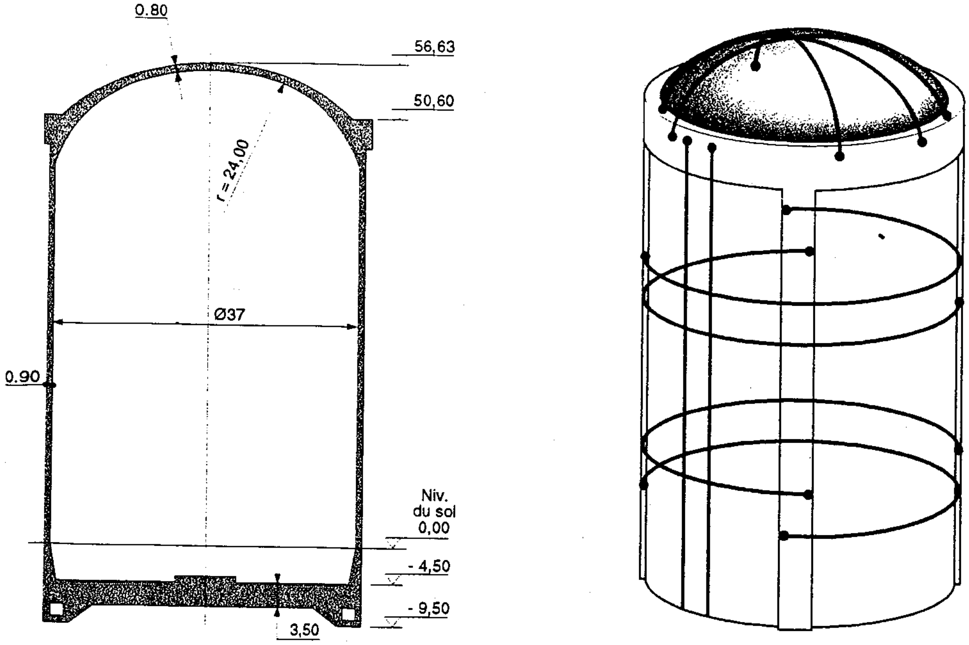

Figure 2 : Overview of the failure modes studied in this level 2 PSA analysis.