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# Functional fragility curves of a French PWR 1300 MWe double walled nuclear containment buildings under severe accident conditions

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## ABSTRACT

As a part of level 2 Probabilistic Safety Assessment (PSA), the Institute for Radiation Protection and Nuclear Safety (IRSN) analyzes the structural and functional behavior of the containment buildings of nuclear reactors (third and final barrier of the in-depth defense system of pressurized water reactors) under severe accident conditions. Several scenarios are considered following a sequence involving the total loss of external electrical power sources and leading to an accidental rise in temperature and pressure inside the building. Under such conditions, the objective of the level 2 PSAs is to quantify the risk of loss of confinement assigned to the CCB and to prioritize the various failure modes. In this paper, we are particularly interested in the fragility calculations (conditional probability of failure at given severe thermomechanical conditions) which are the inputs for PSAs. Thus, this paper presents a general approach for the propagation of uncertainties when predicting the thermomechanical behavior of double-walled containment buildings via non-linear modeling; before then detailing the approach to calculating conditional probabilities of the loss of tightness using meta modeling techniques.

## INTRODUCTION

Large-scale civil engineering structures, especially within the nuclear industry, undergo simultaneous and different loads of chemical, thermal, hydric and mechanical nature. This has an impact on the evolution of their performance over time; this is commonly referred to as ‘’ageing’’ under normal service conditions (Bouhjiti, 2018). On the other hand, these structures are expected to ensure, to some extent, an acceptable functional performance with regards to accidental conditions with a given probability of occurrence. In this work, our interest is geared towards the probabilistic quantification of the functional performance of such structures. In that sense, our aim is to establish a strategy allowing an objective estimation of performance fragility curves at a given condition (normal or accidental) accounting for the inherent spatial and temporal variations of material and structural properties.

One should note that the foreseen strategy is mainly numerical and blindly predictive in the sense that the simulated operational duration (beyond the present age of the structure) along with the accidental conditions (have not taken place luckily so far) can hardly be compared to any in situ measurements (the goal is to provide a methodology allowing to anticipate/predict how the structure behaves if such conditions are met in the future given our best knowledge at the present time). Nonetheless, the used behavior laws and the associated structural model need to be verified and validated to ensure an objective physical representativeness at the foreseen conditions (Heitz, 2022). For the sake of conciseness, hereafter, we assume that one has a verified and valid model (a chained thermos-hydro-mechanical model), knows with a certain confidence the properties of uncertain parameters (expressed in terms of probability density functions) and has identified the conditions of interest (allowing the computation of fragility curves). From there, one follows the scheme shown in Figure 1.

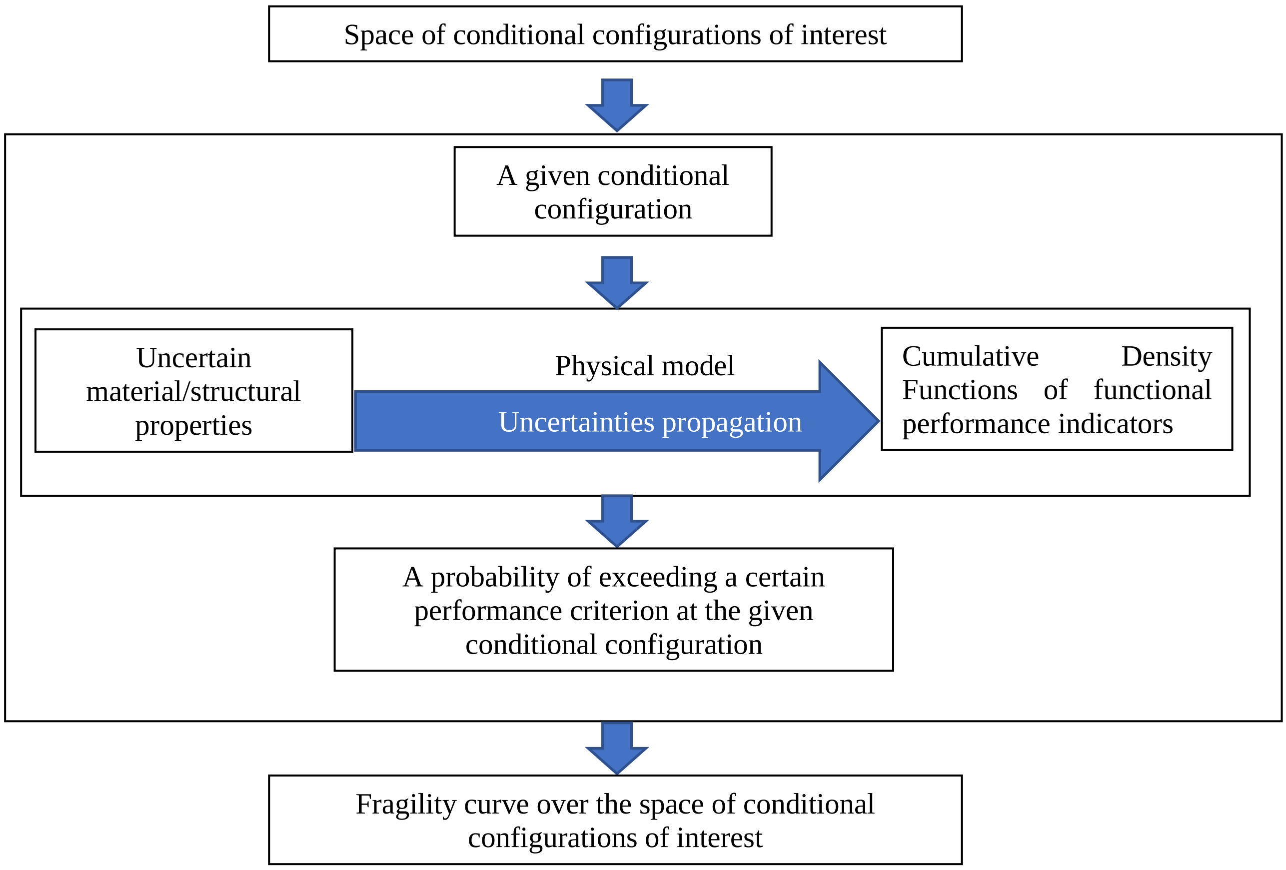


*Figure 1:* A general scheme for fragility curves generation

As the number of the involved inputs is usually important and the computational time is relatively high (especially for nonlinear calculations), the use of Monte Carlo or Quasi Monte Carlo methods remains out of reach. Therefore, it is recommended to construct a metamodel based on a limited number of calculations to obtain an explicit approximation of the model's response over the domain of interest (by selecting adapted fitting mathematical functions). Polynomial chaos methods are a widely used example of such approaches (Baroth et al., 2007). One should note that in the present case metamodeling is applied at two distinct levels, first during the propagation of uncertainties through the physical model at a fixed condition and then, as one goes over the space of conditional configurations of interest.

## THERMO-MECHANICAL MODELLING OF CONCRETE BEHAVIOR

In this work, the modelling accounts for ageing phenomena in normal conditions (young age behavior of concrete, creep and shrinkage, thermal strain, etc.) before considering (by numerical simulation) a severe accident leading to an increase in temperature and the pressure inside the containment. This increase causes increasing damage of concrete in the thickness of the containment wall and ultimately reduces the containment capacity of the nuclear building (degradation of the tightness function). In the present study, numerical calculations are carried out (with Cast3m software, 2022) for double-walled containment buildings without metal liner (inner wall of interest is depicted in Figure 2 – the outer wall is not studied here). The long-term behavior of concrete is calculated according to Eurocode 2 (all formulas have been adapted to in situ measurements to improve the representativeness of the physical model) and is carried out for a predicted service life of 60 years. Accidental conditions (interior temperature and increase in pressure) are applied once this operational duration is reached. Thermal calculations are carried out in a transient regime using a complete 3D model with 472 289 finite elements (20-node solids). In addition, mechanical calculations are carried out according to a fictitious cracking formalism (Ottosen, 1977) using a complete 3D model with 272

508 finite elements (8-node solids). The reinforcement bars and prestressing cables are modeled by 311 637 linear segments with a perfect steel-concrete bond (segments with 2 nodes).

*Figure 2:* 1/4th of the mesh of the internal containment wall of a double-walled containment building (left) relatively coarse mesh intended for mechanical calculations (right) relatively refined mesh intended for transient thermal calculations

### *Transient thermal calculations*

The temperature evolution over time at each nodal position is computed according to the classical heat equation solved within the transient regime. For each accidental scenario, boundary conditions are of Dirichlet nature with applied temperatures on surface nodes. These temperatures are set according to prior calculations using ASTEC (Accident Source Term Evaluation Code) software (Chatelard et al., 2014). These temperatures evolve with time but also with the spatial position that is considered. Generally, for thermomechanical analyses, we consider 5 temperature profiles: one is the temperature in the extrados side of the wall T_EEE, and four zones within the inner side of the wall (dome T_DOME, higher part of the wall T_ANNRBH, lower part of the wall T_ANNRBB and the foundation T_RAD). During such conditions, temperatures can exceed 100° and for fewer scenarios they can go beyond 200°C. For this study around 400 accidental scenarios have been calculated leading to various thermal transients over time.

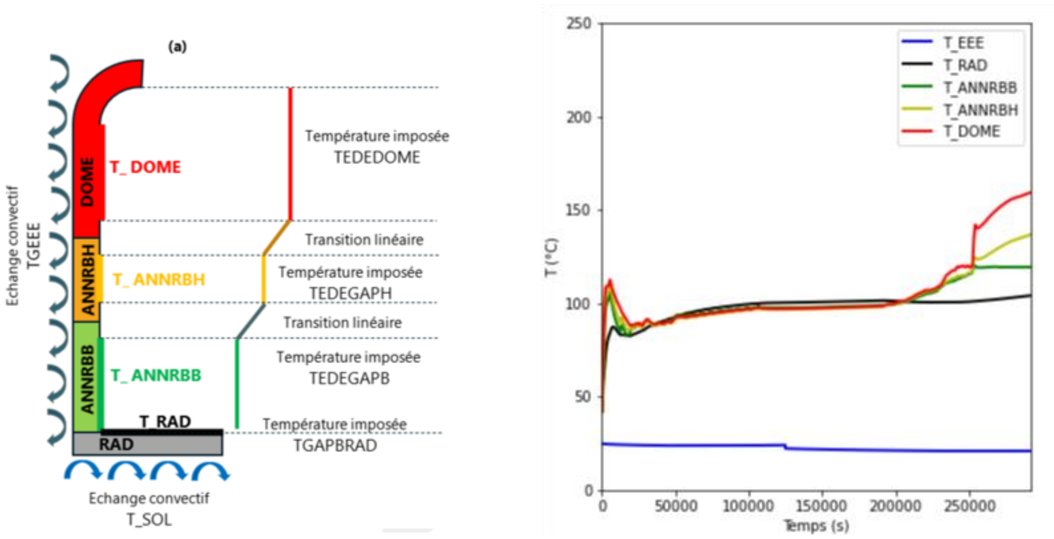


*Figure 3:* Example of evolution of temperature during severe accident

***Mechanical calculations***

The mechanical calculations are conducted based on the principle of strain superposition where the total strain is the sum of the thermal strain, the endogenous shrinkage, the drying shrinkage, the basic creep and the drying creep (see Table 1). The fitting parameters of the formulae of each strain term are identified based on available experimental data at the specimen scale and at the full structural scale (long term monitoring data provided by operators). The considered concrete has a characteristic compressive strength of 45 MPa.

Table 1: Summary of strain components formulae

| Strain component | Formula |
|---|---|
| Thermal strain$\varepsilon_{ts}$ | $$\varepsilon_{ts}(t) = \alpha_{th}\left(\mathrm{T(t)} - \mathrm{T(t_i)}\right)$$<br>$t$ is the time expressed in days<br>$\alpha_{th}$ is the coefficient of thermal expansion (expressed in m/m/°C)<br>T is the temperature value in °C<br>$\mathrm{t_i}$ is the reference time (casting instant) |
| Endogenous shrinkage $\varepsilon_{es}$ According to appendix B of Eurocode 2 | $$\varepsilon_{es}(t) = \beta_{1re}\,(f_{c28} - 20)\left[\beta_{2re}\,2.8\frac{f_{ct}(t)}{f_{c28}} - \beta_{3re}\,1.1\exp\left(-\frac{t}{96\,\beta_{4re}}\right)\right]10^{-6}$$<br>$f_{c28}$ is the characteristic strength under compressive loads at 28 days in MPa<br>$f_{ct}(t)$ is the characteristic strength under compressive loads at a given time t<br>$\beta_{1re}, \beta_{2re}, \beta_{3re}, \beta_{4re}$ are four fitting parameters (without unit) |
| Drying shrinkage $\varepsilon_{ds}$ according to appendix B of Eurocode 2 | $$\varepsilon_{ds}(t) = \beta_{1rd}\frac{K(f_{c28})\,\lvert 72\exp(-0.046\,f_{c28}) + 75 - \rho_h\rvert}{1 + \beta_{2rd}\,8.4\,\frac{r_m^2}{(t - t_0)}}\,10^{-6}$$<br>$t_0$ is the instant when drying strats (in days)<br>$K(f_{c28})$ is a multiplying factor depending on $f_{c28}$ (without unit)<br>$\rho_h$ is the mean degree of saturation in concrete (expressed in %)<br>$r_m$ is the equivalent drying radius defined as following: $2\frac{Area\ exposed\ to\ drying}{Perimeter\ of\ the\ drying\ are}$ (expressed in cm).<br>$\beta_{1rd}$, $\beta_{2rd}$ are two fitting parameters (without unit) |
| Basic creep compliance tensor (Raphael et al., 2002) | $$J = J(t_0) + K_{KV}\left(1 - \exp\left(-\frac{t - t_0}{\tau_{KV}}\right)\right) + K_{Amort}\log_{10}\left(\frac{t}{t_0}\right)$$<br>$t_0$ is the instant when loading starts (in days)<br>$\mathrm{J(t_0)}$ is elastic compliance tensor as a function of the Young's modulus E and the Poisson ratio<br>$K_{KV}, \tau_{KV}$ are two parameters allowing the definition of short term creep (Kelvin-Voigt chain for reversible strains)<br>$K_{Amort}$ a parameter defining long-term creep component (Maxwell chain for irreversible strains) |
| Drying creep $\varepsilon_{dc}$ according to appendix B of Eurocode 2 | $$\Delta\,\varepsilon_{dc} = 3.2\frac{\Delta\,trace(\boldsymbol{\sigma})}{E}\,\Delta\,\varepsilon_{ds}^{*}$$<br>$\boldsymbol{\sigma}$ is the stress tensor (in MPa)<br>$\Delta\,\varepsilon_{ds}^{*}$ is the increment of drying shrinkage using new fitting parameters $\beta_{1rd}^{*}$, $\beta_{2rd}^{*}$. |

Damage in concrete is described using the fictitious cracking model OTTOSEN that is available in Cast3m software. This model shows a softening behavior beyond strain thresholds (under compressive and tensile loads) and accounts for irreversible equivalent cracking strains. The model is regularized based on the Hillerborg energy approach (Hillerborg, 1976). Steel elements in the model are assigned elastoplastic behavior with linear kinematic hardening and with no sliding between concrete and rebars. As for the prestressing loads, they are applied according to the BPEL99 recommendations. In terms of loadings, in addition to the dead load, the prestressing, the thermal strains, an inner pressure is applied on the inner side of the wall. The variation of such pressure depends on the considered accidental scenario. Th range of the absolute pressures varies between 2 bars and 6 bars (see example in Figure 4).


*Figure 4:* Example of the evolution of cracked area based on blind numerical analysis (equivalent cracking strain in m/m) as a function of the absolute pressure (no thermal loads)

The presence of thermal loads redefines stress distribution over time, induces compressive stresses on the inner side of the containment wall and leads to cracking on the extrados side. Depending on the temperature kinetics and the amplitude of accidental temperatures (ranging between 130°C and 230°C), the residual thickness of wall under compression can be as small as 10% of the total thickness. So, the accidental thermal conditions can induce more damage and distribute it differently than in the pressure only case (see Table 2). One should note that there are two main parameters defining such level of damage, first is the pressure of course, then there is the thermal gradient in the thickness of the structure leading to a thermal moment applied to the section of reinforced and prestressed concrete. Such moment is calculated at each time as following: $M_T(t) = \alpha\ E\ \int_0^e \left(T(x,t) - \overline{T(t)}\right)\left(x - \frac{e}{2}\right) dx$ with e the thickness of the wall. In this work, we choose to retain what we call an equivalent thermal gradient $\Delta T_{lin}(t) = \frac{M_T(t)}{\alpha\ E\ \frac{e^2}{12}}$ as the intensity measure of the thermal load. For each accidental scenario, this quantity is strongly correlated to the applied absolute pressure. From Table 2, one can note how the portion of volume under tensile loads rapidly increases with the equivalent thermal gradient: even at pressure values less than the nominal one and especially at the dome area.

Table 2: Effect of temperature on the computed area under tensile loads

| Scenario at 60 years | Absolute Pressure (bars) | Equivalent Thermal gradient (°C) | % of volume in the structural zone under tensile loads | | | | |
|---|---|---|---|---|---|---|---|
| | | | Dome | Raft | Gusset (low part of the wall) | Hatch area | Rest of the containment wall |
| Operational ageing | 0,00 | 11,45 | 0,00 | 1,32 | 0,05 | 0,00 | 0,00 |
| Nominal pressure | 4,00 | 11,45 | 0,36 | 12,04 | 1,34 | 7,88 | 0,05 |
| Accidental pressure + no temperature | 5,00 | 11,45 | 12,41 | 13,70 | 3,87 | 24,99 | 0,49 |
| Accidental pressure + no temperature | 6,00 | 11,45 | 23,87 | 19,37 | 14,95 | 56,34 | 22,89 |
| Accidental pressure + temperature | 2,00 | 51,98 | 24,12 | 8,89 | 4,14 | 3,50 | 0,21 |
| Accidental pressure + temperature | 3,00 | 66,79 | 43,25 | 45,17 | 27,58 | 46,55 | 43,18 |
| Accidental pressure + temperature | 4,00 | 87,23 | 55,70 | 17,76 | 41,10 | 66,11 | 58,44 |
| Accidental pressure + temperature | 5,00 | 123,63 | 62,02 | 27,38 | 53,45 | 73,97 | 67,15 |

***Leakage assessment***

Leakage blind quantification remains a complex and difficult task. Indeed, the complexity of air flow through concrete at the full structural scale is not easy to predict given the unknown precise damage state in the thickness of walls, the possible air flow path along rebars, cables and casting joints, the difficult prediction of water content evolution over time and difficult precise prediction of prestressing losses. In this work, air leakage rates are identified based on the hypothesis of superposition according to which the total leakage is the sum of air flow through cracks (Poiseuille's mode) and the air flow through undamaged concrete's porosity (Darcy's mode) – see (Bouhjiti et al., 2018) for more details. In this work, and in a first attempt, the modelling of the correlation between damage and leakage is strictly based on measurements of dry air leakage that are obtained during the periodic Integrated Leak Rate Tests (ILRT). In the one hand, by numerical means, we know the portion of concrete that is cracked and the one that remains under compressive stresses. On the other hand, by experimental means we know (given certain confidence level that is not very narrow) the air flow going through exiting cracks and the one through the rest of the structure. By combining this two known information, we define an analytical correlation function to estimate the leakage rate depending on the portions of concrete that is damaged and that is compressed. We also, as a first attempt, accept the application of the same correlation function beyond ILRTs and during severe accidents. As leakage information are not public, the correlation function is censored and is not provided in this work. This does not prevent one from understanding the principle upon which we base our analysis.

## FUNCTIONAL FRAGILITY – APPLICATION TO FRENCH PWR 1300 Mwe

In this part, we present the general modelling steps to compute functional fragility curves of nuclear containment buildings under severe conditions.

### *Metamodel of leakage function*

The nonlinear analysis of nuclear containment buildings using full 3D models requires large computational time. To overcome such difficulty, we base here our development on the use of metamodeling techniques. The principle consists of selecting few dozens of accidental scenarios that allow us to cover the physical domain of thermomechanical intensity measures (pressure and thermal gradient). Only those scenarios are used for nonlinear analysis providing us with numerical results of the portion of damaged concrete and the one that is under compressive loads. In this work, we have considered 934 calculation points with different couple values for the absolute pressure and thermal gradient. We achieve then a polynomial fitting $f_{poly}$ according to a given confidence level ($\varepsilon$ fitting error). Eventually, we have an expression that looks like the following:

$$\%volume_{cracked} \approx f_{poly}(P_{abs}, \Delta T) + \varepsilon$$

Then, we use the correlation function $f_{corr}$ (relating the leakage rates to the portion of cracked concrete based on ILRT results), to quantify the resulting dry air leakage $Q_{dry,air}$:

$$Q_{dry,air} \approx f_{corr}(\%volume_{cracked}) \approx f_{corr}\big(f_{poly}(P_{abs}, \Delta T) + \varepsilon\big)$$

The considered metamodel hereafter allows for an accurate fitting with an $R^2$ higher than 95% and an error standard deviation of 10%.

### *Uncertainties and fragility calculations*

Fragility calculations consist of quantifying the probability of failure meaning the probability of having $Q_{dry,air}$ exceeding a given threshold for a fixed thermomechanical intensity measures $(P_{abs}, \Delta T)$. This probability results from the existence of aleatoric uncertainties (such as the intrinsic variations in concrete properties: tensile strength, fracture energy, Young's modulus, etc.) and epistemic uncertainties (the error of fitting using the metamodel mainly). In this work, we quantify:

- the aleatoric variation of the portion of concrete under tensile loads with values around 50%
- the aleatoric variation of the air leakage rates for French PWR 1300 Mwe containment buildings during ILRTs with values around 40%
- the epistemic error due to metamodeling with values around 10%.

As we have now an explicit and analytical model of the dry air leakage under thermomechanical loads, the use of Crude Monte Carlo Method to propagate uncertainties is possible at low cost. As for the air leakage threshold, we consider two:

- one called "DAC" which is the one to be verified during normal ILRTs representing a small breach in the containment wall.
- one called "GB" being 10 times higher that the "DAC" threshold representing a large breach in the containment wall.

For the sake of sensitivity analysis, we also compute the fragility curves according to two methods:

- the first one is analytical assuming a lognormal distribution on inputs and of the fragility curve outputs
- the second one is based on uncertainties propagation without any constraint on the shape of the fragility curve.

Each time, results are presented considering three confidence levels: at 5%, at 50% and at 95%.

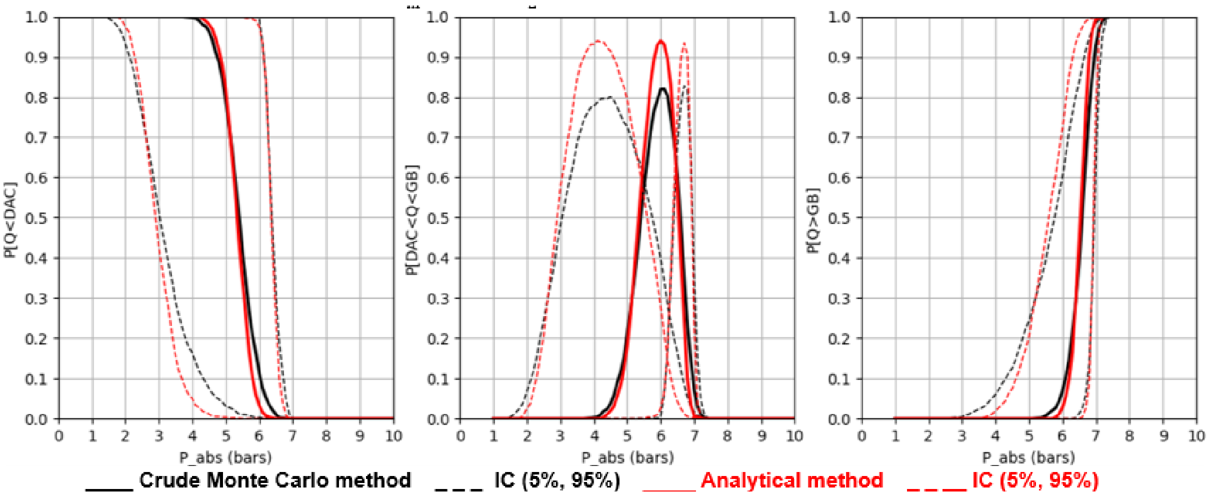


*Figure 5:* Fragility curves computed for pressure only accidental scenarios (with no thermal gradient)

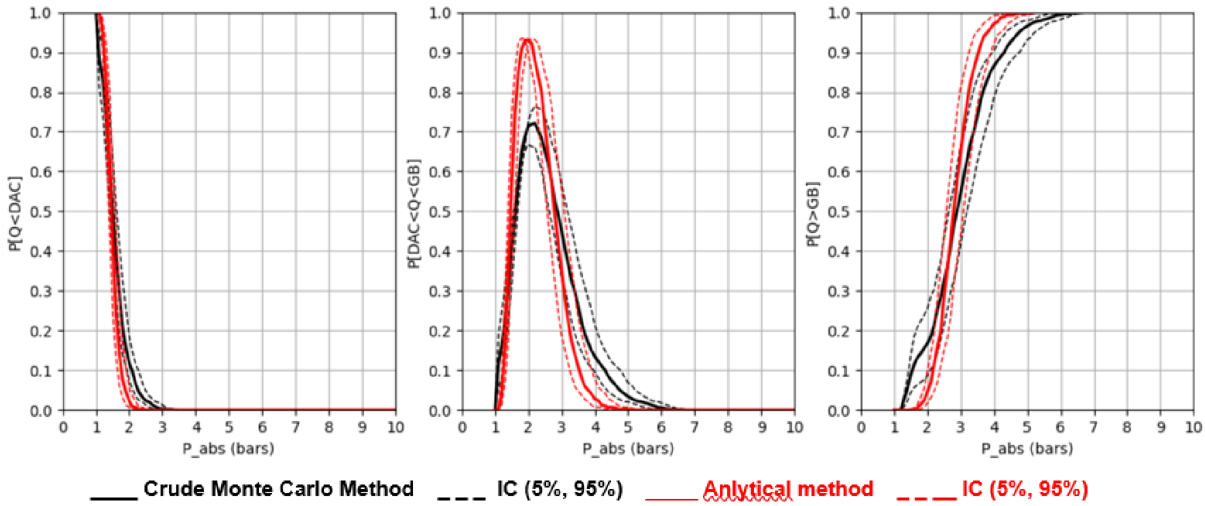


*Figure 6:* Fragility curves computed for accidental scenarios with an increase of pressure given a thermal gradient of 160°C

From Figures 5 and 6, one can see that:

- the analytical and simplified method (assuming a lognormal fragility curve) is not always a good choice and might misestimate the probabilities of failure. The use of Crude Monte Carlo Method without any prior assumption remains the best option not to introduce any additional bias.
- the consideration of thermal effects leads to a decrease (by a factor 2 for severe thermal conditions) of the mean pressure capacity of the containment wall under accidental conditions and to an increase (by a factor 5 for severe thermal conditions) of the coefficient of variation of the fragility curve.

One should note that these calculations do not consider all repair operations that are applied to the containment walls by operators to limit the leakage rate. They aim at demonstrating the importance of considering thermal effects for while computing fragility curves for level 2 PSA. Several improvements are considered for this work, starting from the physical modeling of concrete at high temperature and a more precise quantification of the leakage rate using more advanced approaches. So, the true fragility curves should be different from the ones shown here. Nevertheless, if one has realistic data and proper inputs, one can find here a global methodology that allows for the computation of fragility curves of containment buildings within a reasonable time.

## CONCLUSIONS AND PERSPECTIVES

This paper presents an efficient methodology for establishing thermomechanical fragility curves for the functional capacity (tightness) of the inner containment walls in the French PWR 1300 MWe. These fragility curves are to be used within level 2 PSA and are constructed based on the principles of meta modeling making it possible to optimize the use of non-linear finite element calculations requiring significant calculation times. The numerical experimental plan used to construct the substitution model (or meta model) is composed of more than 900 calculation points with different thermomechanical conditions covering the possible physical domain of interest. At the end of the non-linear thermomechanical calculations, the evolution of the portion of the tensile volumes as a function of the thermomechanical conditions is analyzed. This ultimately makes it possible to retain a direct correlation between the evolution of the diffuse flow (through the porosity of the concrete) and the compressed volume (concrete in compression) then between the evolution of the localized flow (through the existing cracks or newly created) and the volume under tensile loads. Once the metamodel is obtained, one can propagate uncertainties at low cost and get the probabilities of failure at given temperature and pressure values. This work, though being exploratory, shows that the coupling between thermal and pressure loads reduces the tightness of the containment walls and increases the overall coefficient of variation of the fragility curve. This clearly demonstrates the dependency of the failure probability on both the temperature and pressure values during severe accidents and lead to the conclusion it is necessary to take into account the temperature when assessing the behavior of CCBs.

## REFERENCES

Bouhjiti D. 2018. Analyse probabiliste de la fissuration et du confinement des grands ouvrages en béton armé et précontraint. Thèse Communauté Université Grenoble Alpes. Grenoble. France.

Heitz T. 2022. Vérification et validation de modèles non linéaires en génie civil. Techniques de l’ingénieur. Réf : C6006V1.

Baroth J., Bressolette P., Chauviere C., Fogli M. (2007). An efficient SFEM using Lagrange Polynomials: application to nonlinear mechanical problems with uncertain parameters. Comp. Meth. Appl. Mech. 196(46-58): 4419-4429

Cast3m. (2022). http://www-cast3m.cea.fr/

Chatelard P., Reinke N., Arndt S., Belon S., Cantrel L., Carénini L., Chevalier-Jabet K., Cousin F., Eckel J., Jacq F., Marchetto C., Mun C., Piar L., “ASTEC V2 severe accident integral code main features, current V2.0 modelling status, perspectives”, Nuclear Engineering and Design, 272 (June 2014), p.119-135

Raphael W., Kaddah F., Geara F., Favre J.-L., Calgaro J.-A. « Nouveau modèle de calcul pour la prédiction du fluage du béton », annales du bâtiment et des travaux publics, 2002

Eurocode 2, EN 1992-1-1: Eurocode 2: Design of concrete structures.

Hillerborg A., Modeer M., Petersson P.-E. Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. Cement and Concrete Research. Volume 6, Issue 6, November 1976, Pages 773-781

BPEL99, limit states design of prestressed concrete 91 revised 99

Bouhjiti D., Ezzedine El Dandachy M., Dufour F., Dal Pont S., Briffaut M. New continuous strain-based description of concrete’s damage-permeability coupling. International Journal for Numerical and Analytical Methods in Geomechanics, 2018, 42 (14), pp.1671-1697.