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Development of a PWR-W GOTHIC 3D model for containment accident analysis

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ABSTRACT

The confinement of radioactive material in a nuclear power plant, including the discharge control and the release minimization, is a fundamental safety function to be ensured in a design basis accident (DBA).

For plant licensing analysis, the containment is usually modeled with a lumped parameter approach. Inherent to the lumped parameter approach is the assumption that within each region the fluid is well mixed. However, the containment is a large building with a complex configuration and it is distributed in several compartments that avoid the well mixing of the fluid and could have three-dimensional effects that affect the thermal–hydraulic behavior. Therefore, the commonly used lumped parameter approach may not be enough to capture these effects.

In order to study these assumptions, four generic PWR containment models have been developed for Mass and Energy (M&E) release analysis with GOTHIC 8.0 (QA) code, three of them being subdivided and the fourth one is a lumped parameter model. A Large Break LOCA is simulated in order to compare the thermal–hydraulic behavior of the different models. The results show a high dependence on the three-dimensional phenomena, especially the temperature and velocity distribution. In contrast, the pressure evolution is qualitatively similar in all models with small quantitative differences.

1. Introduction

The confinement of radioactive material in a nuclear power plant, is a fundamental safety function to be ensured in a DBA. In accordance with the defense in depth concept, this fundamental safety function is achieved by means of several barriers and levels of defense. In most designs, the third and fourth levels of defence are achieved mainly by the containment building.

For plant licensing analysis, the containment is usually modeled in a single node, like the evaluation containment model for Kewaunee (Westinghouse, 2001) and Prairie Island (Westinghouse, 2004), or Framatome (Framatome, 2004) and Dominion methodologies (Dominion, 2006). However, the containment is a structure with a complex configuration for accommodating the Nuclear Steam Supply System (NSSS), and all the equipment needed for the adequate performance and safety of the plant, Fig. 1. As a result, the containment is distributed in several compartments that are not well mixed and this makes three-dimensional effects on the fluid that affect the thermal–hydraulic (TH) behavior during an accident, thus the traditional lumped parameter approach may not be capable of capturing these effects.

The use of three-dimensional models in containment analysis has mainly been focused on hydrogen distribution, especially after the Fukushima Accident in 2011. Some of these containment analyses have been performed with commercial CFD codes. In the study of hydrogen behavior within PWR containments of Martín-Valdepeñas et al. (2007), some phenomena, such as the steam condensation onto the walls in presence of non-condensable gases were validated by the undertaking of several exercises, demonstrating the capability of the CFX-4 code in simulating these phenomena. Recent hydrogen studies with a three dimensional containment model in commercial CFD codes can be seen in Jiménez et al. (2014) or Prabhudharwadkar et al. (2011).

The GOTHIC code also has the capability to model the containment in detail and to calculate the three-dimensional distribution of a Mass & Energy Release (M&E). There is an extensive literature on the GOTHIC code validation in predicting 3D phenomena under DBAs and severe accidents, see for example (Andreani and Paladino, 2010; Andreani et al., 2010).

There are also simulation for full containments, like the simulations conducted by Grgić et al. for Krsko NPP (Grgić et al., 2012, 2014a,b), with the GOTHIC code predicted the hydrogen distribution in a PWR containment based on a multi-volume lumped

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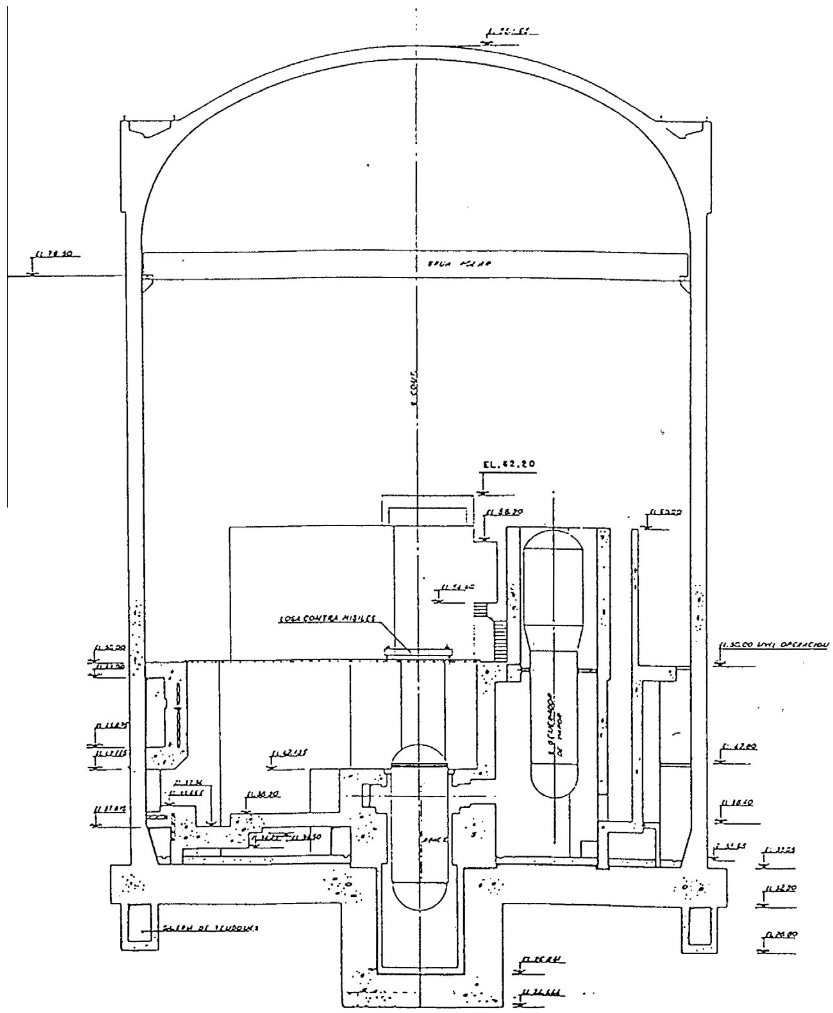

Fig. 1. PWR pre-stressed containment building (Martin-Fuertes et al., 1994).

model, where the volumes, in which the PWR containment was divided, do not present a refined nodalization. The analyses carried out by Jimenez et al. (2015) show the capabilities of the GOTHIC code to capture the hydrogen distribution phenomena through the suppression pool, and the hydrogen flammability in a fully three-dimensional BWR Mark III containment model. Papini et al. (2015) realized a similar study, modeling a PWR-KWU containment. Recently, (Ozdemir et al., 2015) performed a Fukushima Daiichi Unit 1 containment analysis using a GOTHIC 3D model, being successful in capturing the three-dimensional flow patterns in the suppression pool and the variations in the temperature which influence the containment pressurization and hydrogen release.

To assess the impact of subdivided versus lumped parameter modeling in the GOTHIC code, the CVTR tests were simulated with both types of models, as can be seen in the GOTHIC 8.0 (QA) Qualification Report, section 19 (Rahn, 2012b). Moreover, in the analyses conducted by Papini et al. (2010), different models for IRIS containment were used to research on condensation, heat transfer distribution, pressure and temperature within the drywell compartment. The simulations of PANDA large-scale thermal–hydraulic facility within the OECD-SETH project, (Andreani et al., 2010) were successful in predicting gas distribution, wall heat transfer and condensation with a three-dimensional model using a coarse mesh. Another example of the evaluation of a GOTHIC model with a coarse mesh can be found in (Andreani and Paladino, 2010). This study states that GOTHIC can be used for predicting gas distribution in a complex or multi-compartment geometries, with special attention to those regions where phenomena, such as stratification, incoming fluid stream or condensing jet, could appear. The study realized by Papini et al. (2014), compared phenomena focusing on the condensation of steam to remove the decay heat on a PCC (Passive Containment Condenser) in a ALWR (Advance Light Water Reactor) with GOTHIC, resulting in the capability of the code in predicting the heat transfer in case of pure steam and the influence of non-condensable gas on the model.

In the present study, the develop and comparison between three GOTHIC 3D models, with different mesh approaches, has been performed in order to study the impact of three-dimensional effects in the TH behavior of the containment during a DBA. The containment building modeled is a cylindrical pre-stressed concrete structure, covered by a hemispherical dome, with a steel liner in its inner wall, Fig. 1.

In the first section of the paper, the modeling process is summarized, followed by the modeling approaches and assumptions used. A base test is analyzed comparing the different model results. Finally, the simulation results are summarized and some conclusions and recommendations about the different models are discussed.

2. PWR-W containment thermal hydraulic model

GOTHIC (Generation of Thermal–Hydraulic Information for Containments) is an integrated, general purpose thermal–hydraulics