SIMULACIÓN CON CÓDIGOS NUMÉRICOS + 3D

THE EFFECT OF CONSERVATIVE HYPOTHESES OVER 3D AND LUMPED CONTAINMENT EVALUATION MODELS OF ALMARAZ

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Licensing process of the nuclear power plants are supported by computational analysis. The large and complex geometry of the containment building, along with a wide spectrum of phenomena, create a demanding scenario for thermal-hydraulics calculation. Over the last decades, this complexity has been addressed with the Lumped Parameters (LP) approach. During the licensing process, where the containment is modelled with a single or few computational cells, the calculation uncertainties and inaccuracies are compensated by the addition of conservative assumptions. Thanks to the computer resources increase, 3D best estimate calculations have become more popular due to their higher accuracy and resolution. However, when accomplishing conservative calculations to obtain maximum containment pressure/temperature values, the LP approach is still the preferred method.

In this paper, two GOTHIC best estimate Evaluation Models (EM) of Almaraz NPP containment are compared: a single-node LP EM and a three-dimensional porous media EM. The first step to assess the differences between the LP and 3D approaches was a pressure and temperature comparison of both best estimate EMs. In a second step, a sensitivity analysis applying general conservative assumptions was performed. The averaged results obtained from the 3D models and from the LP models using the same conservative hypotheses are similar. Therefore, it will be demonstrated the largest differences come from these hypotheses and not from the modelling approach.

INTRODUCTION

The main objective of nuclear safety is the protection of individuals and the environment, and therefore the confinement of radioactive materials inside the Nuclear Power Plants (NPP) containment is mandatory. In accordance with the defence in depth principle, this fundamental safety function is achieved by adding several barriers and levels of defence (OCDE/NEA, 2014). The last physical barrier is the containment building. In the early years, the licensing process of NPP containments was based on major accidents denominated “maximum credible accidents”, subsequently named “Design-Basis Accidents” (DBA) (U.S. AEC, 1962). Therefore, containments were designed to maintain their integrity during the peak pressure associated with all DBA, limiting the release of radionuclides to the environment at a specified design leak rate established in the regulatory guides (U.S. NRC, 2002).

The containment building is a large structure with several compartments, equipment and components. Furthermore, the extreme Pressure and Temperature (P&T) values that might be reached because of the releases associated with DBA postulated events could build complex Thermal-Hydraulic (TH) scenarios. As conducting full-scale experiments for the different containment designs is not economically feasible, computer codes has become important tools to perform safety analyses.

Regarding the computational analyses of the containment phenomenology, there are also several complexities to face. The spatial discretization selected should allow capturing the synergy effect between phenomena with different characteristic lengths (wall friction, convection, radiation, etc.), in a large volume and with reasonable computational time. The traditional strategy to overcome these difficulties has been the Lumped Parameters (LPs) approach.

Under the LP framework, the spatial distribution of the fluid variables within each region (for example, each containment compartment) is neglected, as they are represented by a single computational cell or Control Volume (CV). The Mass and Energy (M&E) conservation equations are solved in each CV using averaged thermal-hydraulic variables. In order to transport M&E between CVs, a 1D approximation is applied to the momentum equation. However, inside the CV there is no velocity and therefore the flow momentum direction is not conserved in the equations.

The LP approach has been extensively validated and has proved its capability to calculate accurate averaged results with affordable computational effort (OCDE/NEA, 2007). However, its common coarse nodalization and the simplification over the momentum transport do not allow capturing local effects or 3D flow patterns (Wolf et al., 1994).

Due to the potential inaccuracies of the calculation, several conservative hypotheses must be added during the licensing process to establish an acceptable safety margin which bounds all possible results (U.S. NRC, 1983). The LP plus conservatisms approach has been the preferred option to afford the containment licensing along decades (Ofstun et al., 2013; Shepard et al., 1975). Nevertheless, since the approval of the Regulatory Guide 1.157 in 1989, the Best Estimate Plus Uncertainty (BEPU) methodologies could be applied to NPP safety licensing (NRC, 1989). The best estimate EMs are based on realistic assumptions, mechanistic models and analytical criteria, and their use is complemented by uncertainty analysis and quantification. The 3D containment codes meet these characteristics defined for the best estimate approach.

On contrary than the LP approach, the 3D codes can consider the local spatial distribution of fluid properties within a much finer discretization of the calculation domain. Improvements in the numerical methods and a steady increase in computer power have allowed applying Containment 3D codes to the containment THs analyses, modelling complex flows in a realistic geometry with a relatively high spatial resolution. This approach has the potential to provide more accurate results in return of a large computational effort (OCDE/NEA, 2014).

Despite the 3D EMs are usually associated to BE calculations, it is important to note that the results of an EM developed using 3D approach could be also conservative, as the conservatism may come from hypothesis in the boundary conditions or the simulation parameters. The main goal of this conference proceeding is to sum up the work presented the last edition of the International Congress on Advances in nuclear Power Plants (ICAPP) (Vázquez-Rodríguez et al., 2019), where the possibility of combining the advantages of 3D EMs and traditional conservative hypotheses to ensure the pressure and temperature safety margin was deeply assessed. In the next section, the LP and 3D EMs developed for Almaraz NPP and GOTHIC, the computational code selected to perform the analysis, are depicted. As a first step to assess the differences between the LP and 3D approaches, the P&T resolution provided for both models is evaluated. Then, a sensitivity analysis applying general conservative assumptions was accomplished, assessing their influence in the averaged P&T results of both approaches. Finally, the main conclusions are summarized.

LUMPED EM AND 3D EM COMPARISONS WITH THE GOTHIC CODE

The code selected to develop Almaraz NPP containment EMs is GOTHIC 8.2 (QA) (EPRI, 2016). GOTHIC is an integrated, general purpose thermal-hydraulics software package for design, licensing, safety and operating analysis of NPP containments, confinement buildings and system components. Its thermal-hydraulics module is based on a two-phase, multi-fluid formulation, and solves separate conservation equations for mass, momentum and energy for three fields: vapor, continuous liquid, and droplets. The vapor phase can be a mixture of steam and non-condensable gases, and a separate mass balance is solved for each component of the vapor mixture. The phase balance equations are coupled by mechanistic models for interfacial mass, energy and momentum transfer. The code includes a full treatment of the momentum transport terms, with optional models for turbulent shear, and for turbulent mass and energy diffusion (EPRI, 2016).

The thermal-hydraulic calculations of GOTHIC are based on a single CV or a network of CVs connected by flow paths or 3D connectors. The code offers the possibility of subdividing the CVs using a 3D Cartesian mesh, so both LP and 3D containment analyses can be performed with GOTHIC. Within the subdivided CVs, the containment geometry can be represented blocking groups of cells using simple shapes (cuboids, wedges, cups and cylinders) exposed in Figure 1 – blocked cells are represented in grey. As can be seen in the figure, solid and fluid can coexist in the computational cells, and the code uses a porosity factor in the conservation equations.

In contrast to commercial Computational Fluid Dynamic (CFD) codes, GOTHIC uses empirical correlations for friction and heat transfer between the fluid and the solid structures, rather than attempting to model the boundary layers in detail. This feature gives the possibility of using almost identical physical models for the LP and 3D EMs developed.

The relevance of this code characteristic is proved in comparisons available in the literature as the one shown in (Beeny et al., 2015), where two twin models developed with different LP codes and the same boundary conditions give different results due to their distinct physical models. In addition, there are some valuable analyses comparing the LP and 3D approaches for the same transient but using different codes, and a good example is the work of Royl et al. (Royl et al., 2000). In this comparison, the differences between the physical models of the 3D containment field code (GASFLOW) and the fast-running integral code (MAAP) may influence some outcomes of the comparison. Therefore, the use of the same physical models makes GOTHIC an adequate tool to perform comparisons focused on the different spatial discretization and conservation equations formulation of the LP and 3D approach.

The most different approaches regarding the spatial discretization are those that use a single calculation node or a fully three-dimensional mesh. The single node LP EMs are considered the best option to obtain conservative pressure values in the short-term (Tills et al., 2008). In fact, they have been extensively used by the nuclear industry, and

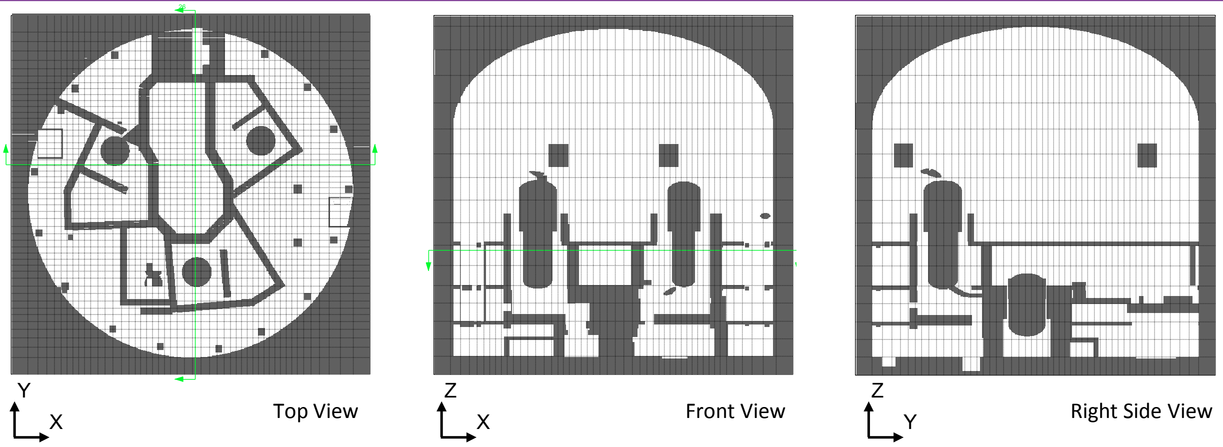

Figure 1. Section views of the 3D EM developed for the Almaraz NPP containment.

the licensing methodologies already developed can be employed as modelling guidelines (Knee and Gharakhanian, 2006; Ofstun et al., 2013). However, LP EMs may be not adequate if the simulation goal is to obtain the local maximum temperature (Jimenez et al., 2017). Furthermore, in spite of LP EMs with advanced nodalizations have proved their capability to capture complex patterns for light gases (OCDE/NEA, 2007), they cannot reach the required local detail to predict hydrogen management systems performance accurately (Royl et al., 2000).

Therefore, 3D EMs are necessary to obtain local maximum temperatures and to calculate several containment scenarios correctly, and the sensitivity analysis presented in this work is focused on finding whether they also have the capability to obtain the conservative pressure values usually calculated with the single node LP EMs.

Best estimate EMs development

The GOTHIC 3D EM has been developed from a detailed Computer Aid Design (CAD) model of the Almaraz NPP containment following a methodology developed in the UPM (Bocanegra et al., 2016). Based on the detailed CAD, the containment geometry is rebuilt using the geometric shapes available in GOTHIC to block groups of cells (cuboids, wedges, cups and cylinders). The coordinates of these simple shapes, called *blockages*, are extracted form CAD and introduced in GOTHIC using an in-house script.

The second step of the 3D EM development is the cartesian mesh definition. In contrast to commercial CFD codes, GOTHIC does not have a body-fitted coordinates capability, so fluid and solid can coexist in the same computational cell. In order to avoid the mass transport between two adjacent cells, their common cell face has to be completely blocked by the *blockages*. Therefore, the mesh is adapted to the implemented geometry in order to assure the hydraulic independence between different compartments. Additionally, the mesh homogeneity is a key characteristic to optimise the code efficiency. The importance of the homogeneity and the methodology developed to get the final mesh (27.000 active cells – with porosities larger than 3%), was deeply explained in the previous annual meeting (Bocanegra et al., 2018; Vázquez-Rodríguez et al., 2018).

RESULTS & DISCUSSION

In this section, a summary of the resulted discussed on (Vázquez-Rodríguez et al., 2019) are presented. First, a P&T comparison of both best estimate EMs were performed, starting by comparing the results for the whole containment and then assessing the different local detail offered by each EM. In order to compare the single P&T value calculated by the LP EM with the values by cell of the 3D EM an averaged value is needed for the latter. With this objective, the P&T values of the 3D EM were weighted multiplying the P&T value obtained for each cell by its free volume and dividing it by the total free volume of the 3D EM. The sum of all the cell values determines the P&T averaged value of the 3D EM. The weighting was performed using ProTON, an in-house UPM Python script specifically developed for this aim. After discussing the outcomes of both best estimate EMs, a sensitivity analysis applying general conservative assump-

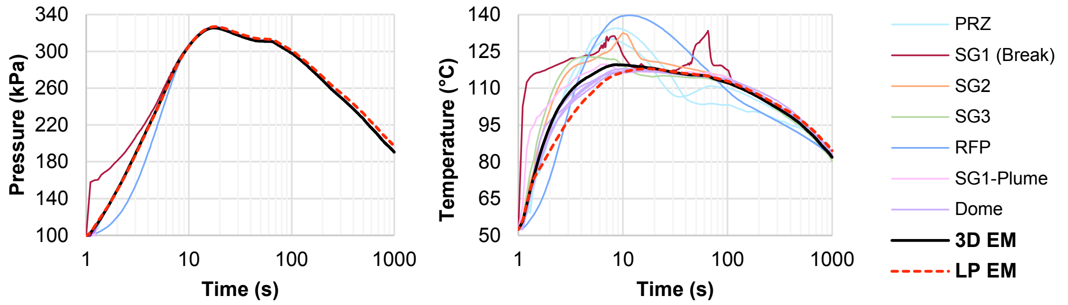

Figure 2. P&T comparison of LP EM and averaged 3D EM (including several compartments).

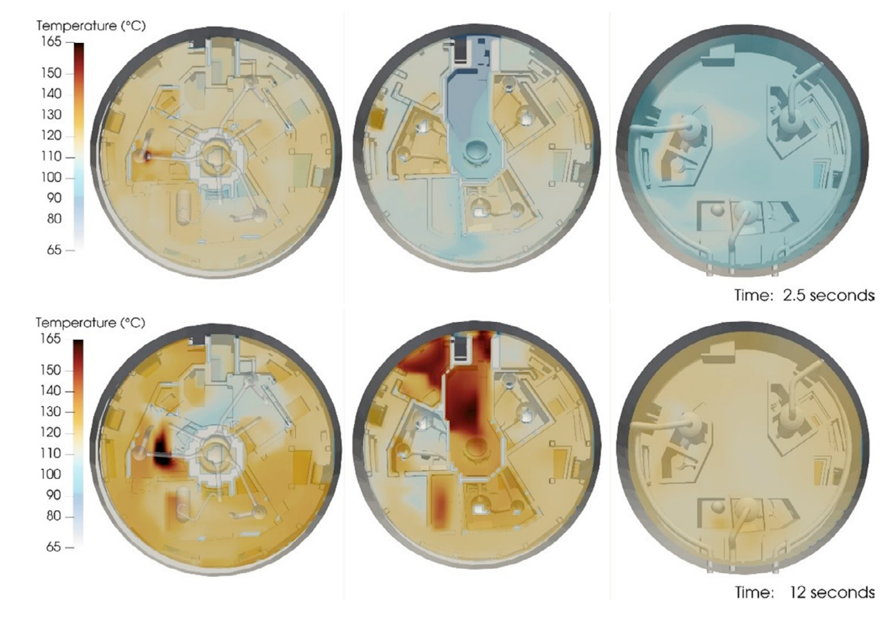

Figure 3. Temperature local analysis using Paraview with the 3D EM.

tions was performed. The aim of this analysis was to assess whether the conservatism affects the LP and 3D EMs to the same extent. The transient time of all the simulations are 1000 seconds and each took approximately seventeen hours using three cores (Intel i7-8700) of 3.2 GHz for the 3D EM and less than five minutes for the LP EM.

Best estimate cases comparison

The comparison of the averaged P&T values of the 3D EM (black line) and the P&T values of the LP EM (red dashed line) are shown in Figure 2. The M&E released during the first seconds from the reactor coolant system caused a sharp P&T increase until their maximum value was reached. The pressure peak values were almost identical in both EMs, 326.9 kPa for the LP EM and 325.4 kPa for the 3D EM. The maximum temperatures were also similar, but the value for the 3D EM (119.6 °C) was larger than the value for the LP EM (118.0 °C) and the relative difference of both temperature peaks was slightly higher than the pressure ones. After these P&T maximums, the condensation of the steam on the containment structures relaxed the pressure and temperature conditions. The P&T tendencies during the containment cooling were similar in both EMs, nevertheless, the P&T differences at the end of the transient were slightly larger (196.7 kPa and 84.6 °C for the LP EM and 190.3 kPa and 81.8 °C for the 3D EM) than the differences of the peak values.

The different temperature tendency observed during the first seconds is due to the single node LP EM inability to capture the superheated vapor state. When the M&E is released to the containment in the LP EM, it becomes immediately in contact with all the heat structure surfaces. Hence, the temperature evolution follows the saturation curve of the containment pressure driven by the condensation process. On the contrary, in the 3D EM may exist a time delay between the M&E release and the contact of the vapor phase with the containment surfaces, thus, the superheated state of the vapor can be captured faithfully.

In addition to the averaged P&T values for the whole containment calculated by the 3D EM, averaged P&T values for different containment compartments are exposed in Figure 2. There are separate results for the Steam Generator (SG) 1, SG2, SG3 compartments; for the pressurizer (PRZ) compartment; and for the Refuelling Pool (RFP). The lines of the *Dome* series correspond to different axial levels of the containment open space and the SG1 *Plume* results shows the specific thermal-hydraulic state of the steam plume over the compartment where the break is located. The Figure 2 allows reflecting in a glance the different behaviour of pressure and temperature within the containment. On the one hand, pressure homogeneity is a result of its characteristic transmission at

Sensitivity Cases	Spray Droplet Size (μm)	Spray Temperature (C)	Spray Flow Rate (kg/s)	Total Surface All THs (m²)	Air gap (cm)	Paint Thickness (cm)
v0	700	30	227.11	31284.0	0.0305	0.0152
v1	1000	30	227.11	31284.0	0.0305	0.0152
v2	1000	48.89	227.11	31284.0	0.0305	0.0152
v3	1000	48.89	181.69	31284.0	0.0305	0.0152
v4	1000	48.89	181.69	25027.2	0.0305	0.0152
v5	1000	48.89	181.69	25027.2	0.305	0.0152
v6	1000	48.89	181.69	25027.2	0.305	0.152

Table 1. Sensitivity cases parameters.

Sensitivity Cases	Pressure				Temperature			
	Peak value		End of transient value		Peak value		End of transient value	
	LP	3D	LP	3D	LP	3D	LP	3D
v0	326.9	325.4	196.7	190.3	118.0	119.6	84.6	81.8
v1	326.9	325.4	196.7	190.5	118.0	119.6	84.6	81.9
v2	326.9	325.4	208.1	202.5	118.0	119.6	88.7	86.5
v3	326.9	325.4	213.3	208.2	118.0	119.6	90.4	88.5
v4	329.8	328.7	223.9	218.8	118.4	120.0	93.7	91.9
v5	329.8	328.8	228.7	223.4	118.4	120.0	95.1	93.3
v6	333.1	333.7	229.9	224.2	118.9	120.6	95.4	93.5

Table 2. Peak and end of the transient pressure and temperature values.

the speed of sound. On the other hand, the temperature heterogeneity is due to the slower convective-diffusive process responsible for the temperature transport. Therefore, the average pressure obtained from the LP EM is a faithful representation of the overall containment value whereas the temperature heterogeneity cannot be reproduced by the single node LP approach.

The looking at the Figure 3, obtained using Paraview, evidences one of the strongest point of the 3D EMs, the thermal hydraulic resolution. The maximum temperatures close to the break position are clearly observed at 2.5 seconds (left side). Then, the 3D EMs capabilities allows calculating local maximum temperatures within the RFP compartment and close to the break at 12 seconds (central image). The temperature heterogeneity is also evident in both time steps.

Conservatism sensitivity analysis

A sensitivity study consists of a systematic variation of code input and modelling parameters and it is commonly used to identify which parameters are the most influential for the target variables. In this particular case, different conservative hypotheses are added successively to the EMs, as can be seen in Table 1. Some of these hypotheses, such as the decreases of the spray system mass flow and the heat structures total surface, are selected to assess their impact on the results.

The P&T results for the 14 EMs (7 LP EMs and 7 3D EMs) used for the Almaraz NPP EMs sensitivity analysis are shown in Figure 4 and Figure 5. The results obtained from the 3D EMs are averaged for the whole containment volume.

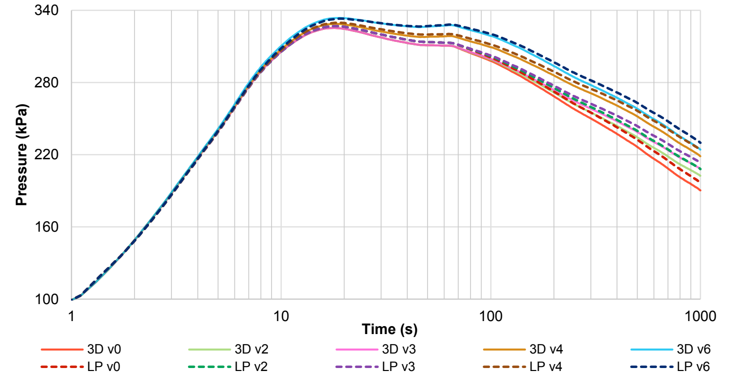

Figure 4. Sesitivity analysis results for the LP EM and averaged 3D EM containment pressures.

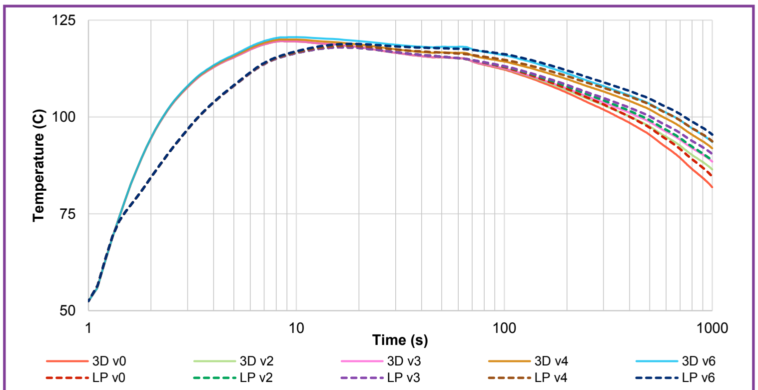

Figure 4. Sesitivity analysis results for the LP EM and averaged 3D EM containment temperatures.

In order to facilitate the results assessment, the maximum and the final P&T values for each sensitivity case are shown in Table 2 and only ten of the fourteen series are plotted in the figures.

The similarity of the LP EMs and the averaged 3D EMs results, already proven by the best estimate models (*v0*), was kept throughout the whole sensitivity analysis. From a quantitative point of view, the pressure results were more sensitive to the tested hypotheses than the temperature ones. The maximum pressure of the best estimate EMs was 325.4 kPa for the 3D EM and 326.9 kPa for the LP EM. In the most conservative case, these values increased to 333.7 kPa and 333.1 kPa respectively, an increase of 8.3 kPa for the 3D EM and 6.2 kPa for the LP EM. In the case of temperature, the initial best estimate maximums were 119.6 °C for the 3D EM and 118.0 °C for the LP EM, with a final increase of 1.0 °C for the first and 0.8 °C for the second. Considering these facts, the P&T results obtained by the 3D EM have shown to be more sensitive to the conservative hypothesis. In fact, the highest P&T peak values of the analysis were obtained from it.

The larger effect of the conservative hypotheses at long-term led to higher changes in the end of transient values. These differences between the best estimate and the most conservative cases (v0 vs. v6) were 33.9 kPa and 11.7 °C in the 3D EM, and 33.2 kPa and 10.8 °C in the LP EM.

CONCLUSIONS

The GOTHIC code ability to perform thermal-hydraulic analyses under the lumped parameters and 3D approaches makes it an adequate tool to assess the differences of both modelling strategies. An evaluation model of Almaraz NPP containment has been developed for each approach. The both evaluation models have the same free volume; total surface of heat structures; boundary conditions; and physical models selected to simulate the containment phenomena. Therefore, the analysis is focused on the differences induced by the different spatial discretization and conservation equations formulation of the LP and 3D approaches.

The aim of the performed comparison is not to present both approaches as competitive solution methods. In fact, the agreement of the averaged results obtained from the seven sensitivity cases provides robustness to both approaches and allows arguing for their combined use. The lumped parameter evaluation model should be used as a fast-running tool to obtain averaged results for the huge number of transients accomplished during the licensing process. Then, the larger thermal-hydraulic resolution showed by 3D models could be used give further insight in a group of critical accidents and address the hypothetical inaccuracies induced by lumped parameters limitations.

The main outcome of the sensitivity analysis has been to verify that the conservative hypotheses affect to same extent to the models developed under the LP and 3D approaches. Despite of single node lumped parameters evaluation models are still the preferred method for the design calculations, where the objective is to obtain conservative values, the highest P&T values of this sensitivity analyses are calculated by the 3D evaluation model. Therefore, the use of the 3D approach, usually applied to best estimate calculations, has the potential to improve the designs basis calculations.

As future works, the effect of the conservatism in both approaches will be assessed in more detail using statistical methods. In order to take advantage of the thermal-hydraulic resolution of the 3D evaluation model, the variation of the P&T local values induced by the conservatism will be also studied.

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