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Development of a detailed 3D CAD model of a generic PWR-KWU containment as a basis for a better assessment of H2/CO combustion risk

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I. INTRODUCTION

In case of a Severe Accident (SA), the Nuclear Power Plant (NPP) reactor containment fulfils an important role acting as the final physical barrier against a release of radioactive material into the environment. Consequently, assuring the integrity of the containment building is a key element of the accident management. Furthermore, the containment geometry and its compartmentalization play an important role in the combustible gas distribution and combustion as it influences notably the thermohydraulic behavior of the gases through the containment. Thus, a comprehensive model of the containment's geometry is the basis of every 3D containment analysis. For this matter, the use of Computational Aided Design (CAD) software as a cornerstone of the modelling process serves as a bridge between the containment layouts and the thermal-hydraulic models [1], [2].

The use of detailed 3D CAD models allows a thorough evaluation of free volumes, flow paths, areas and locations, and wall surfaces. It can be also used as a pre-processing tool to build different nodalization strategies, while storing all the data in the same file, making these models a user-friendly tool to enhance the thermal-hydraulic simulations [3].

This work is being developed under the framework of the AMHYCO project (Euratom 2014-2018, GA No 945057). Its main objective is to improve experimental knowledge and simulation capabilities for the H_2/CO combustion risk management in SAs. The aim is to enhance the accident management strategies; particularly, those related to the mitigation of combustion of heterogeneous gas mixtures. During this project, several models of PWR containments, using different modelling approaches, will be used to simulate the complex scenarios related to SA sequences. Every PWR containment design will have its 3D CAD model, which main application will be to facilitate all the information needed for the creation of all computational models. In this way, the partners of the project using Lumped Parameter (LP), 3D (such as GOTHIC), and Computational Fluid Dynamics (CFD) simulation approaches will build the models on the same basis.

This article is focused on the development of a detailed 3D CAD model for a German PWR-KWU, one of the designs included in AMHYCO, using AutoCAD Autodesk 2021®. Firstly, a description of the methodology which will be used for the PWR-KWU and the other containment designs is given. Then, a process of identification of flow paths and nodalization strategies will be explained, followed by a brief description of the strategy that will be used for modelling the containment geometry into the 3D GOTHIC environment.

II. 3D CAD MODEL METHODOLOGY

The development of the 3D CAD model follows a series of steps: 1. Creation of a fully detailed CAD model, 2. Extraction of relevant information for the creation of lumped models, 3. Extraction of relevant information for the creation of 3D models, 4. Creation of a database with all the relevant information. As stated before, this database will serve as a cornerstone for the development of all numerical models.

This paper will focus on points 1 to 3 for the PWR-KWU. The primary information source this containment model is based on is publicly available in [4]. All floor and elevation layouts have been imported, sized, digitalized, and extruded in the CAD software. The built of the model has been made from bottom to top, using the different plan views as reference for each level construction. Moreover, it has been used to connect concrete and steel structures, accounting for any possible flow paths and junctions within the interior parts of the buildings.

The PWR-KWU containment building is divided into two regions, the spherical inner containment (named UJA) and the outer surrounding region, the annulus (named UJB). The inner region, UJA, contains a missile shield cylinder which allocates the nuclear steam supply systems and the spent fuel pool. The second region, UJB, is enclosed by a thick reinforced concrete wall and protects the inner containment pressure tight steel shell. Furthermore, it houses the emergency cooling and safety injection systems. During the modelling process, this region will be envisaged as a thermal boundary condition for the scenarios addressed in AMHYCO, and the accuracy in its modelling will not be considered as important as the inner compartments.

The different levels of the buildings are mainly built by extrusion (e.g., inner walls or components). This is an advantageous method of 3D construction in a highly compartmentalized containment as the KWU one. The whole containment building, comprised of UJA and UJB regions, has been enclosed by the dome and a horizontal concrete slab (which serves as ground floor at the lowest point). Other structures, e.g., the concrete lower cap that holds the spherical liner, have instead been built by adding and subtracting curved volumes, something either way impracticable with only a vertical snap method [1], as the extrusion one. Moreover, these curved surfaces are important for CFD studies and justify in a way the detail imposed to the construction.

The construction has mainly relied upon five top views at different elevations and two front sections. Elevation 0.0 m corresponds to the bottom of the Reactor Pressure Vessel. Whenever the public information of a certain elevation was incomplete, or detailed geometrical aspects were not available, certain modelling hypotheses were necessary. As an instance, only one of four symmetrical annular rooms stairwells was depicted in the public layouts. Therefore, the building of the other staircases was made using an analogous geometry. Similar hypotheses were needed to model gratings, walking grids, doors, and the nuclear steam supply system.

All these hypotheses have been done maintaining the structural coherence and the isolation of spaces of the two-room containment. An iterative process, supported by several partners of AMHYCO, helped to refine the geometrical details all along the containment to obtain a reliable 3D model of a generic PWR-KWU containment.

Figure 1 shows a sectional cut and an elevation cut of the public available layouts of the PWR-KWU containment from which the CAD model has been built. Figure 2 shows an intermediate stage in the construction of the full model. Walls and floors in a lighter colour belong to the outer containment building (UJB), while the darker ones belong to the inner containment (UJA). The RCS circuit is embedded to show its location.

III. NODALIZATION AND IDENTIFICATION OF JUNCTIONS AND FLOW PATHS

To exemplify one of the applications of the 3D CAD model, this section shows the main steps to define a nodalization for a LP thermal-hydraulic model of the PWR-KWU. The basis for the nodalization of the containment comes from the framework of the Generic Containment (GC) benchmark, which was initially developed within the European NoE SARNET-2 [5] and continued within the framework of the NUGENIA SAMHYCO-NET project, led by IRSN. Taking into consideration the primary containment building, and assuming that the auxiliary building works as boundary conditions in the LP codes, the proposed nodalization is divided in 11 Control Volumes (CV), presented in Figure 3.

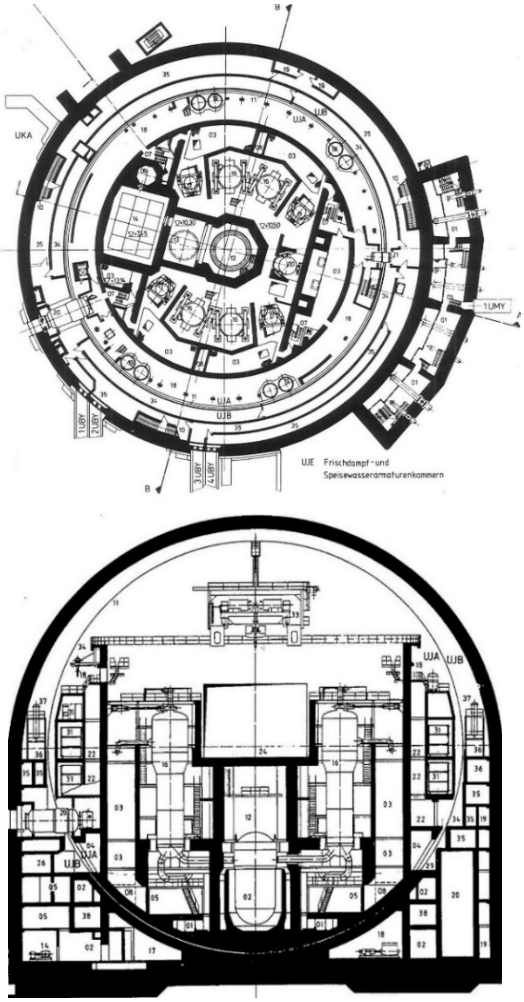

Figure 1. +12 m elevation cut (up) and sectional cut (down) from the public layouts of the PWR-KWU containment. Ref: [4]

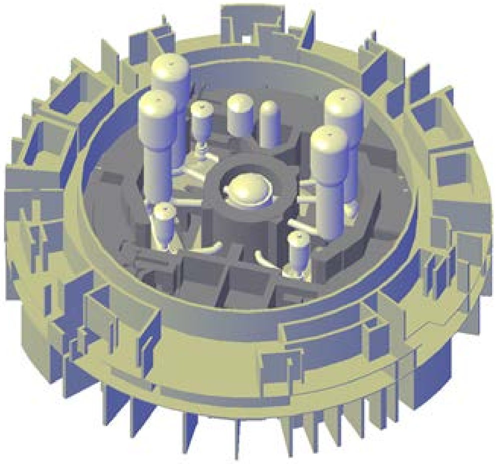

Figure 2. Aerial view of level +6 meters of the KWU 3D containment model with the primary circuit embedded.

The vessel cavity and the SGs compartments have their own CVs in order to study the behavior of gaseous mixtures in detail in postulated transients. Another CV was placed below the SG CVs and surrounding the cavity, which aim to represent the containment sump.

At each side of the SGs, there are two CVs with annular shape. The regions coloured in green, and pink are not directly connected to the open space where the SGs (yellow and red) are located, and thus pressure and temperature differences may be expected in these zones. Equally, the inner cylinder of the containment isolates these zones located inside it (green and pink) from those locate outside (dark blue and purple), precluding the gas flow between them. Thus, those annular spaces should have individual CVs to allow the LP codes to predict certain heterogeneity in these regions. Finally, the last CVs defined are the reactor room, the spent fuel pool (SFP), and the dome. The basic information to model these spaces in LP codes are free volumes and elevations. The free volume values (see Table 1) are easier to obtain from plan layouts thanks to the CAD capabilities.

Table 1. Nodalization CVs with their free volume and elevations.

Zones	Free Volume (m^3)	Base Elev. (m)	Top Elev. (m)
CAVITY	250.31	-1.9	10.55
SUMP	5635.9	-1.9	10.1
DUCT	2698.17	6.2	11.7
SG-N	4371.98	10.1	29.3
SG-S	4311.97	10.1	29.3
ANN-E-int	1709.24	1.84	21.2
ANN-W-int	1206.29	0.35	21.2
ANN-N-ext	4124.09	12	21.2
ANN-S-ext	4178.99	12	21.2
SFP	1326.85	7.45	21.5
R-ROOM	1115.62	10.3	21.2
DOME	43166.59	21.2	50.85

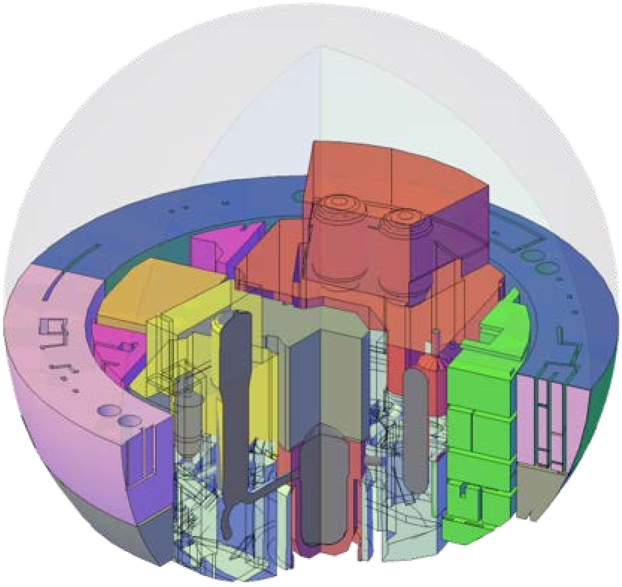

Figure 3. Nodalization of the PWR-KWU Generic Containment

Furthermore, the simulation of the thermal-hydraulic behavior of gaseous mixtures inside the containment requires to define the possible flow paths between the different zones. These connections join CVs of the lumped nodalization and determine the fluid transport between them.

The junctions are defined through an effective area that represent the opening areas between CVs, and other additional variables to approximate friction and form losses. These areas are obtained from the detailed 3D CAD model and are shown in Figure 4, where all identified junctions are displayed under a colored scheme that matches the nodalization representation of Figure 3. Important junctions range from stairwell landings, walking grids, burst foils or open geometrical connections.

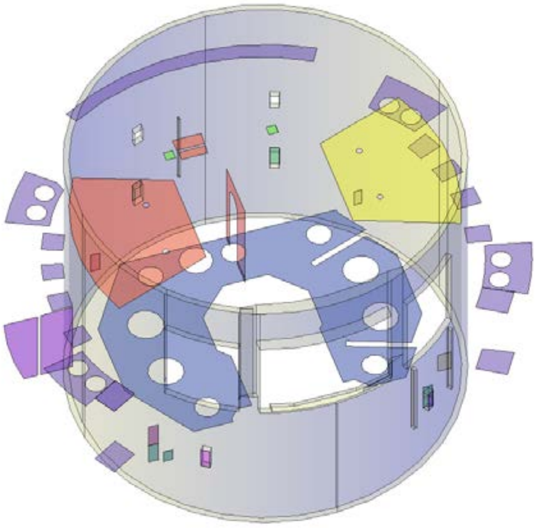

Figure 4. LP junctions between CVs

IV. CREATION OF A SIMPLIFIED MODEL

Some 3D thermal-hydraulic analysis tools, e.g., GOTHIC [6], can import a 3D geometry from external sources. To exploit this capability, the methodology developed at the UPM is based on three stages. The first one is the already depicted creation of a detailed CAD model where all the geometrical relevant data is stored, considerably reducing the required GOTHIC pre-processing time (insight on this matter can be found in [2]). The intermediate stage is the creation of a simplified CAD model which serves as a bridge between the CAD tool and GOTHIC, where the last step, the in-code pre-processing effort, is undertaken.

The simplified CAD model accounts for the geometrical limitations inherent to the analysis code. GOTHIC uses an orthogonal mesh to subdivide volumes into multi-dimensional grids. Also, GOTHIC 3D representation of structures and components relies upon the definition of specific blocks, namely wedges, caps, cones, and cylinders, and on the other hand, in the definition of openings to account for geometrical open connections, flow pathways and 3D local phenomena. To this effect, in the same fashion as the lumped identification of junctions between CVs (see Figure 4), 3D connections are identified by an effective area, e.g., doors, windows, gratings, trapdoors, etc., Thus, the detailed 3D PWR-KWU CAD model needs to be simplified in a further step, by the reconstruction and displacement of walls, floors, openings, etc., to match an adequate and traceable simplified configuration. To this aim, a recently developed methodology is employed [7], which is based on the identification of problematic couplings between the actual geometry and the meshes utilized for the simulations. The implementation of the simplified geometry adapted to the mesh decreases the computational cost up to a 90%. For this reason, it will be used in all AMHYCO GOTHIC models. Figure 5 shows an example of the adaptation of a SG compartment, as part of the preventive simplification basis for pre-processing in the GOTHIC code.

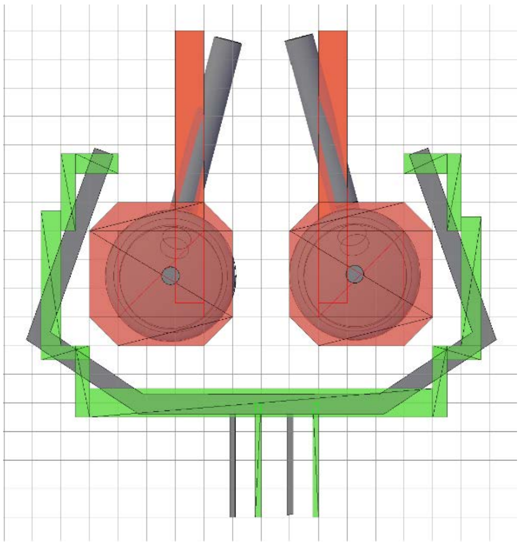

Figure 5. Simplification of KWU SG and its cage and adaptation to a 1x1m mesh

V. CONCLUSIONS

A detailed 3D CAD model of a Generic PWR-KWU containment has been built from publicly available layouts of a 1300 MWe NPP. The model, which can be exported for its use in LP, 3D and CFD codes (under the required adaptations and simplifications) will be used to perform thermal-hydraulic analysis in the AMHYCO project to study the H2/CO combustion risk in the late phases of SAs. The methodology proposed aims to be a cornerstone for the development of other generic PWR 3D detailed models, namely for PWR-W and PWR-VVER containments. Furthermore, to have those generic containments built from the same methodological basis will minimize input data and user effect uncertainties [8] in the various simulations performed by the AMHYCO partners.

The process of 3D modelling a highly compartmentalized containment with CAD tools has brought light to some advantages of the construction methodology presented. The CAD environment is a user-friendly interface where specific data can be traced for further post-processing, e.g., the location of each wall, flow path, thermal surface, etc. Different nodalization strategies can be explored and their free volumes extracted to compare the benefits of each approach or to identify possibly omitted junctions between relevant areas of the containment. Moreover, the CAD model can be simplified to be exported with a geometry usable by thermal-hydraulic analysis codes. This potential is revealed in this case of study in the bridge built between the CAD model and the GOTHIC pre-processing tools. Moreover, the detailed methodology of construction will improve the thermal-hydraulic analysis in both LP code simulations (with accuracy in the definition of free volumes and connections) and 3D containment codes (with the possibility to account for three-dimensional flow paths and sub-compartment interactions) using the CAD as basis for different post-processing tools, such as Paraview.

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References

[1] R. Bocanegra, G. Jiménez and M. K. Fernández-Cosials, "Development of a PWR-W GOTHIC 3D model for containment accident analysis," *Annals of Nuclear Energy,* vol. 87, 2016.

[2] K. Fernández-Cosials, S. Estévez-Albuja, G. Jiménez, R. Bocanegra and C. Vázquez-Rodríguez, "3D containment modelling of PWR-KWU Trillo NPP with the GOTHIC code," *Annals of Nuclear Energy,* vol. 133, 2019.

[3] C. Vázquez-Rodríguez, G. Jiménez, S. Estévez-Albuja and C. Queral, "Nodalization Sensitivity Analysis of the AP1000 Containment with MELCOR 2.1," in *ICAPP 2019*, Juan-les-pins, France, 2019.

[4] SIEMENS, "Dokumentationen SIEMENS / KWU Sicherheitsbericht für die KKW Stendal GmbH 1990," [Online]. Available: http://www.ycdt.de/kkw-stendal/siemens-reaktor-stendal.htm.

[5] S. Kelm, M. Klauck and S. Beck et. al., "Generic Containment: Detailed comparison of containment simulations," *Annals of Nuclear Energy,* vol. 74, 2014.

[6] EPRI, *GOTHIC Thermal Hydraulic Analysis Package, Version 8.3(QA),* Palo Alto, CA, 2018.

[7] S. Arfinengo-del-Carpio, C. Vázquez-Rodríguez and G. Jiménez, "Preventive methodology: beforehand geometric simplifications a priori for containment models optimization with the GOTHIC code," in *ENYGF 2021*, Tarragona, Spain, 2021.

[8] M. Povilaitis, S. Kelm and E. Urbonavicius, "The Generic Containment SB-LOCA accident simulation: comparison of the parameter uncertainties and the user-effect," *Annals of Nuclear Energy,* no. 106, 2017.