Joint Modelling of VVER-1000/320 Containment Specifics for Simulating Pressure Build-Up: A COCOSYS Study

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Abstract:
This study explores a severe accident scenario within a generic VVER-1000/320 containment, highlighting the crucial role of precise geometric modeling, particularly variations in floor elevation levels adjacent to the reactor cavity. Conducted in partnership with technical support organizations ENPRO Consult from Bulgaria and SSTC NRS from Ukraine, the study employs COCOSYS, a thermohydraulic simulation software package developed by GRS. Key elements such as steel door melt-through, residual water volumes, and melt pool spreading are examined, uncovering their complex interactions impacting containment pressure dynamics. The results reveal that even minor design differences in geometric modeling profoundly influence predictions of pressure build-up, the activation of the filtered containment venting system, and severe accident progression. Emphasizing the necessity of precise modeling of VVER containment design specifics and further effort in the validation of melt spreading, this paper calls for continued joint research to attain more realistic and robust results in severe accident analyses.

1 INTRODUCTION

This collaborative study's focal point is COCOSYS (COntainment COde SYStem) [1], an accident analysis code developed by GRS, which serves as an essential tool in comprehensive simulations of severe accidents in light water reactors. COCOSYS integrates a wide range of phenomena, including thermohydraulic behaviour, aerosol physics, and combustion processes, allowing an in-depth analysis of the containment atmosphere's state during severe accidents.

One key component of COCOSYS is the 'CCI' module, based on the MEDICIS model. This module effectively models Molten-Core-Concrete-Interactions (MCCI), a critical aspect during severe accidents. It captures the interaction between molten corium (molten core material) and containment structures, considering diverse melt pool configurations. The CCI module also accounts for the decomposition of concrete, the subsequent release of gases, and their chemical reactions with melt constituents. By incorporating decay heat data, it can simulate temperature shifts in the corium and phase changes, including the stratification into metal and oxide layers, thereby facilitating comprehensive evaluations of concrete ablation and gas production.

In the specific context of the VVER-1000/320 containment, this study leverages the CCI module's ability to simulate scenarios with two and three melt pools, focusing on a Large Break Loss Of Coolant Accident (LB LOCA) scenario coupled with a total Station Blackout (SBO) and Reactor Pressure Vessel (RPV) failure. Due to the unique design of the VVER-1000, In-Vessel Melt Retention (IVMR) is considered improbable, underscoring the need for precise simulation of corium spreading, and its impact on factors such as corium cooling, hydrogen generation, containment pressure build-up, and fission product behaviour.

Containment analyses also serve in analysing whether and when a release might occur in certain accident scenarios, emphasizing target variables such as containment pressure. The insights gathered are essential for Severe Accident Management Guidelines (SAMG) and safety measures such as Passive Autocatalytic Recombiners (PARs) and Filtered Containment Venting System (FCVS), as well as for estimating the source term to the environment. Consequently, the study explores the influence of containment floor geometry on melt-water interaction, containment pressure build-up, and the activation of the FCVS, aligning with the objective of improving simulations of severe accidents.

2 METHODOLOGY

In this study, the COCOSYS code system is utilized in a novel approach to model the impact of specific floor geometries within the containment structure of a generic VVER-1000/320 reactor during severe accident scenarios. The focus of this joint research lies in the complex containment specifics, particularly the investigation and modelling of residual water volumes, the 'step' feature following the reactor cavity, and multiple melt pools. The key elements of this model are derived from research papers and technical notes developed collaboratively with ENPRO Consult and SSTC NRS [2-3], and they are supplemented by the addition of a third melt pool. It's important to note, however, that the model presented in this paper represents a generic plant configuration rather than a specific plant, using the best estimates from collective research and representative values.

2.1 Containment Nodalisation and Accident Scenario

The study utilizes a revised 97-zone containment nodalisation [2], including zone 'c-7a' (room adjacent to the reactor cavity) and 'scrbr' for FCVS implementation. This approach facilitates the modeling of a scenario in which an LB LOCA coincides with an SBO, culminating in RPV failure approximately 3.25 hours into the event. Such projections align with earlier MELCOR integral code analyses [4], which provide the Mass-Energy Release (MER) data incorporated into the model, including decay heat from fission products and corium. Both MER and the nodalisation discussed in this paper is based on collaborative work done with SSTC NRS [2].

Figure 1 depicts this COCOSYS nodalisation, highlighting zones for MER injection and junctions. The symbols indicate the zones with MER (thunderbolt), 184 atmospheric junctions (grey), 6 ATM-FULL (green) and 83 drainage junctions (blue), and the spray system (red), which is not used in the investigated scenario.

In line with VVER-1000/320 construction materials, the CCI module represents containment floors with reinforced siliceous concrete (16.2% Fe), assuming an elevated ablation temperature of 1809 K, as guided by recent MOCKA tests [5].

A core aspect of this study is the collaborative work with ENPRO Consult [2] to estimate residual water volumes on the containment floor post-LOCA. Utilizing detailed plant drawings, these volumes were determined, despite some necessary simplifications that led to certain sections being represented as rectangular plates. The significance of this consideration lies in how the melt-concrete mixture's interaction with residual water in zone c-7a affects containment pressurization and the timing of FCVS activation. The COCOSYS model has been adapted to incorporate this potential for residual water accumulation across specified zones (c-2, c-3, c-4, c-6, c-7).

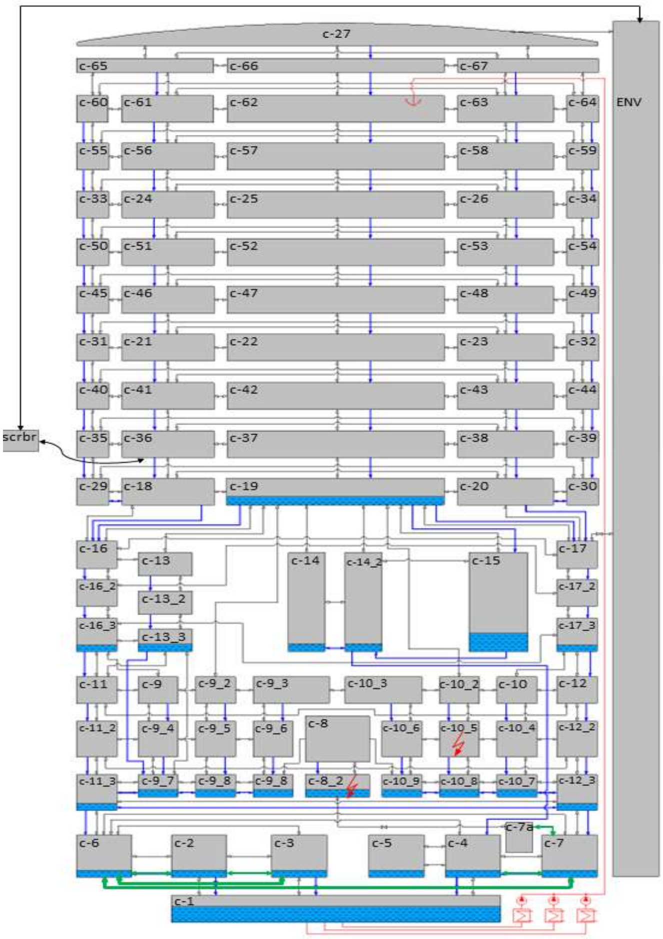

Figure 1: Schematic Representation of the COCOSYS Nodalisation for the VVER-1000/320 Containment [2]

2.2 Core Melt Behaviour and Containment Geometry

In the modified COCOSYS input deck, two molten debris deposition sites, or 'melt pools,' are considered for accurate representation of severe accident scenarios. Melt Pool 1 is referred to the reactor cavity (zones c-8_2 and c-8) and Melt Pool 2 is corresponding to the adjacent room (zone c-7a), with the hermetic steel door typically separating these areas (see Figure 2).

Cavity ionization chambers sealing is assumed in this model, which means that containment bypass after RPV failure is not simulated.

A radial breach of concrete beneath the door is predicted during severe accidents. When erosion reaches a certain depth, a pathway for corium migration is formed, leading to its relocation to c-7a, where interaction with water occurs. This interaction influences the containment's thermal and pressure dynamics, due to the decay heat of the corium. The model also incorporates a detailed representation of the floor geometry in c-7a. The floor of this zone is situated approximately 20 cm higher than the annulus (zone c-7), causing an overflow of water into c-7a when the water level in the annulus exceeds this height. The model confines the spread of corium in Melt Pool 2 to the c-7a floor area, impacting containment pressurization and the timing of FCVS activation.

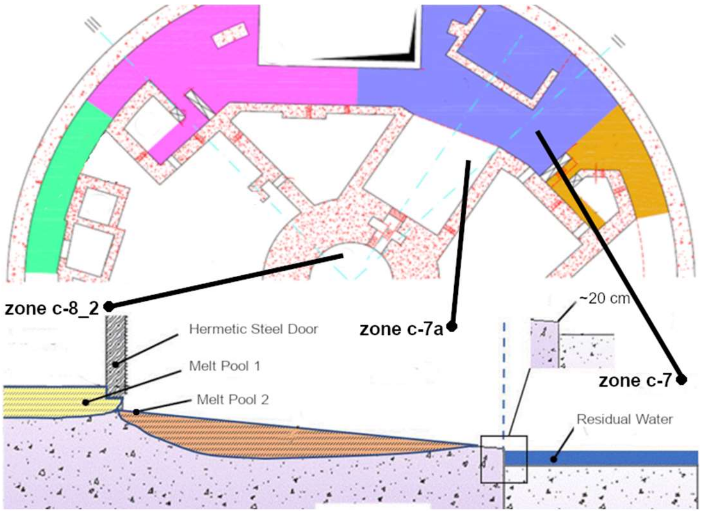

Figure 2: Illustration of Corium Migration and Melt Pool Distribution for a generic VVER-1000 [3]

A third pool, 'Melt Pool 3,' situated in the annulus (zone c-7), is incorporated as a further development of the model for a separate variant analysis in this paper. This permits investigation into the effects of a more realistic melt spreading area and melt layer height on the progression of severe accident scenarios.

The radial erosion depth threshold for the following variant analysis is illustrative, not tied to specific simulations, though comparative analysis with ENPRO Consult suggests similar values [2]. The exact depth is dependent on the corium characteristics and cavity geometry.[1]

3 RESULTS AND DISCUSSION

The impacts of a 20 cm 'step' elevation difference between containment zones c-7 and c-7a in an LB LOCA coupled with an SBO scenario are probed in this study. Two distinct cases are examined: one with the elevation step maintained and another without it. Initially, the effects on containment pressure dynamics using a two-melt-pool model are assessed. Subsequently, a revised model using three melt pools is introduced, and its preliminary findings are presented.

3.1 Impact of Containment Step Geometry on Pressure Dynamics and Melt Behaviour

Two configurations in containment zones c-7 and c-7a are addressed in the context of an LB LOCA combined with an SBO: Variant A, which preserves the 20 cm 'step' elevation, and Variant B, which eliminates this feature.

The accident initiation induces a rise in pressure and water levels in zone c-7 due to steam and aerosol injection from the MER, leading to water level rise in zone c-7a. This overflow is temporarily halted when water levels in the lower compartments rise, filling the Boric Acid Solution Tank (BAST). The overflow recommences once the BAST is full (see Figure 3, left).

Following the RPV failure at approximately 11,700 seconds, core melt enters zone c-8_2, forming Melt Pool 1. Around 13,000 seconds, a radial erosion depth of 25 cm is reached, which meets the predefined criterion for melting through below the steel door. Consequently, the

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[1] SSTC NRS proposed a more conservative approach, suggesting that the door would open in such a scenario to enable an earlier melt-water interaction and pressure build-up.

melt-concrete mixture is discharged into zone c-7a, thereby generating Melt Pool 2. The dynamics of this pool are largely driven by the step elevation in zone c-7a, affecting the water-melt interactions, transitions between wet and dry states on the melt surface, and containment pressure changes.
Heat transfer from the molten core to the water layer is modelled through the CCI module, which simulates the MCCI and considers the crust formation between the melt and water. This approach uses an effective heat transfer coefficient to balance the heat flux through the crust under boiling conditions, determining the crust's external surface interface temperature.
As the molten core transfers heat to the water, the resulting evaporation leads to a reduction in the water level. This dynamic becomes crucial when the water level falls below 1 cm, resulting in the melt pool surface's segregation into wet and dry regions. In Variant A, the emergence of dry regions begins around 25,000 seconds as the water level falls in zone c-7a, progressively reducing the wet surface area. Conversely, in Variant B, wet erosion allows for an expansion of the wet surface area until about 92,000 seconds, with dry regions only appearing when the residual water in the annulus is nearly evaporated. (see Figure 3, right).

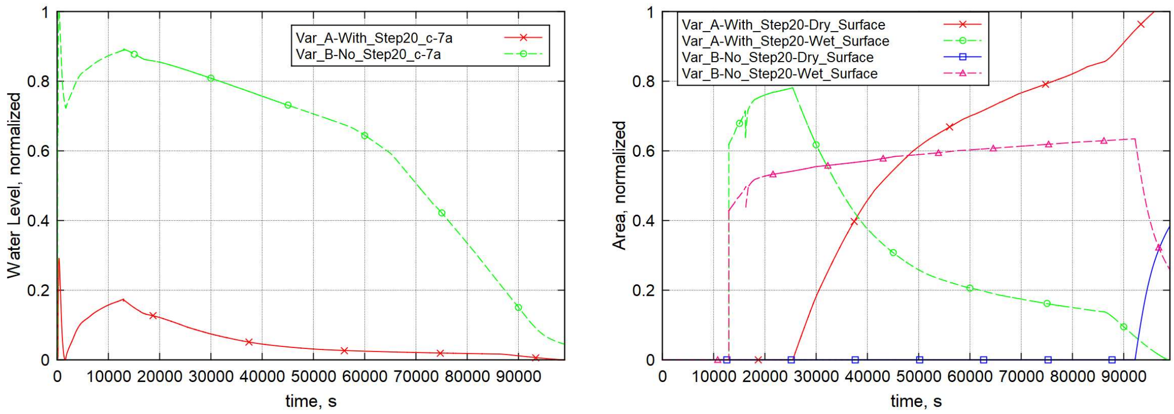

Figure 3: 2-Melt-Pools Model with and without Step in Variants A and B: (Left) Water Level Change in Zone c-7a; (Right) Transition Between the Dry and Wet States of the Melt Surface (The y-axis scale is normalized to maintain data confidentiality.)

This discrepancy in melt behaviour significantly impacts the distribution of decay heat. Variant A transfers a larger portion of decay energy to the containment through dry erosion, whereas Variant B utilizes most of the decay heat to boil the water above the melt, causing a higher steam fraction and pressure rise. The consequences are considerable differences in the timing of FCVS activation. Variant B, experiencing a more intense pressure surge due to the melt being completely submerged in water, triggers FCVS activation at 57,000 seconds. In contrast, in Variant A, FCVS activation is delayed until around 86,000 seconds. The model's limitations, including the neglect of melt layer height in the zones and the simplification of the melt spreading process, are acknowledged, and efforts to refine the model are discussed in subsequent sections.

3.2 Preliminary Results using three Melt Pools to simulate the Melt Spreading

In the pursuit of refining the understanding of severe accident progression, a third melt pool, Melt Pool 3, is introduced (beneath the step, illustrated in Figure 2). This adjustment results in two more scenarios: Variants C/D and E/F. Variants C/D consider the melt spreading across a 230 square meter area, maintaining a melt layer height in zone c-7a of 0.1 meters. Conversely, Variants E/F represent a larger melt spread, encompassing 280 square meters with a reduced melt layer height of 0.03 meters. This portrayal brings the model into alignment with earlier analyses [6-7] conducted by ENPRO Consult and SSTC NRS, utilizing the COCOSYS module for melt spreading simulation LAVA. Each scenario pair (C/D and E/F) either incorporates the containment step between zones c-7 and c-7a (Variants C/E) or omits it (Variants D/F). Furthermore, greater realism is attained in Variants C and E by integrating the melt layer height into the analysis. The step elevation in the COCOSYS zone is adjusted to 0.3 meters in Variant C and 0.23 meters in Variant E, thereby providing a more realistic depiction of melt-water interactions, steam production, and containment pressure dynamics. Notwithstanding, the axial erosion depth and dynamic pool height difference are disregarded since their contribution is an order of magnitude smaller than the layer itself throughout the computation.

These adjustments lead to a more accurate simulation, but it's crucial to remember these scenarios are preliminary and require further validation. The unique LB LOCA scenario, distinguished by an SBO and door melt-through, introduces complex dynamics that require additional exploration. Unmodeled phenomena include the melt spreading from beneath the door to under the water in zone c-7 and the interaction between the melt 'tongue' in zone c-7a and the water in zone c-7. Further research utilizing tools like the LAVA code or comparable methodologies is essential for a better understanding of these interactions.

Within the three-pool variants framework, an increased radial erosion depth of 0.55 m is assumed for the melt-through criterion, delaying the fulfilment of this condition until around 15,000 seconds into the computation. Uniform melt layer heights across all three pools are maintained as well.

Figure 4 elucidates the implications of these assumptions. The right figure contrasts the evolution of the steam fraction within the containment for scenarios with and without the containment step, while the left figure presents the time-dependent pressure dynamics for the variants. The pressure dynamics in all variants align until the melt enters zone c-7a and consequently flows into the annulus (zone c-7) at about the 15,000-second mark. Beyond this point, the dynamics differ.

For Variant C, with an increased effective step height of 0.3 m, the water doesn't overflow into zone c-7a, leading to exclusively dry erosion. In contrast, Variant D submerges the Melt Pools 2 and 3, resulting in a significant pressure rise and an earlier FCVS initiation at roughly 38,000 seconds, as opposed to 50,000 seconds in Variant C. Analogously, the volumetric steam fraction in the annulus escalates to 90% in Variant D and only slightly above 60% in Variant C, when Melt Pool 1 and 2 forms. Despite a brief decrease in Variant D and a continued rise in Variant C (mirrored later by D), an approximately 15% difference in the fraction is maintained until the FCVS initiation.

Despite the reduced melt layer height (and consequently, corium mass in zone c-7a) in Variants E and F, the influence of the containment step is still evident. For Variant E, which includes the containment step, the initiation of the FCVS happens approximately 1,000 seconds later, approximately at 35,400 seconds. Conversely, Variant F, without the containment step, experiences an earlier FCVS initiation, at around 34,400 seconds.

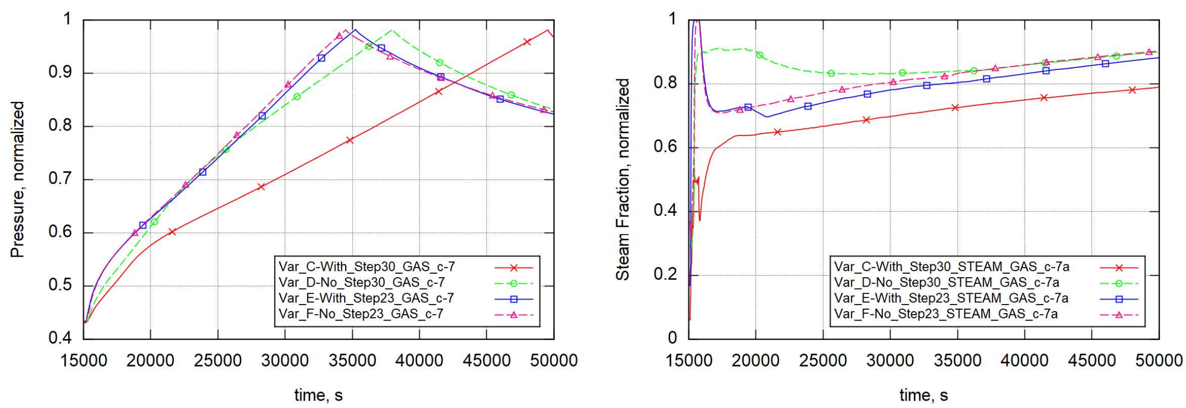

Figure 4: 3-Melt-Pools Model with Melt Layer Heights of 0.1 m (Variants C/D) and 0.03 m (Variants E/F) in Zone c-7a: (Left) Pressure Response in Containment; (Right) Volumetric Steam Fraction (*The y-axis scale is normalized to maintain data confidentiality*.)

In conclusion, the introduction of a third melt pool underscores the substantial influence of the containment step and melt layer height on the progression of severe accidents. The step's impact is particularly pronounced in Variant C, where melt layer height consideration prevents melt-water interaction in zone c-7a, thereby delaying FCVS initiation significantly. Similarly, Variant E mirrors the dynamics of the two-pool variants, with dry erosion in zone c-7a following a decrease in the water level of the annulus. These findings align with those from the two-pool model, underscoring the importance of accurate containment geometry and realistic simulations and validation of melt spreading.

3.3 Conclusions and Outlook

In the conducted study, the emphasis has been placed on the integral role of geometric modelling in understanding the progression of severe accidents within specific containment areas. Central considerations include the precise modelling of multiple melt pools, the unique 'step' elevation difference, and the calculations of residual water volume.

The incorporation of uncertainties, especially through corium relocation, has accentuated the importance of detailed validation and modelling. Critical decisions made in assumptions, ranging from melt-through criteria to melt spreading area and layer height, were found to significantly impact results, highlighting a need for validation through tools such as LAVA.

The examination of the specific methodologies, like the usage of the CCI module in COCOSYS, unveiled areas for improvement. Notably, scenarios involving melt spreading under water and melt-water interaction in adjacent zones called for refinement. Opportunities were also identified for enhancing the dynamic representation of melt layer height within COCOSYS. A salient finding was the pronounced effect of both melt layer height and the specific 'step' elevation in zone c-7a on FCVS initiation timing. Differences ranging from 1,000 to 12,000 seconds were observed in the variants with three melt pools depending on the considered melt layer heights. This disparity underscores the influence of geometric factors on simulation outcomes.

In conclusion, the study emphasizes the importance of precise geometric modelling, residual water volume estimation, and melt pool dynamics in simulating severe accidents. These factors significantly influence outcomes, including FCVS activation timing. Such simulations are vital for Severe Accident Management Guidelines (SAMG), safety measures such as PARs and FCVS, accurate source term estimation, and, in particular, the evaluation of plant design specifics. Thus, this study underscores the need for ongoing collaboration and research to achieve more realistic and robust results in these crucial areas of nuclear safety.

ACKNOWLEDGMENTS

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