Codes And Methods Improvements for VVER comprehensive safety assessment

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D8.5 – The CAMIVVER VVER Safety Analysis Guidance – Lessons learned & best practices

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Summary

This document corresponds to the Deliverable 8.5: "*The CAMIVVER VVER Safety Analysis Guidance"* of the H2020 CAMIVVER project. The initial title has been updated to *"The CAMIVVER VVER Safety Analysis Guidance – Lessons learned & best practices"*.

In the document, the term "guidance" must be considered as "lessons learned" and "best practices". A list of selected outcomes for each Work Package (WP) is proposed synthetically, leaving more details to the project deliverables listed in the references.

The partners have underlined the points still open, and these will feed possible follow-up activities.

Approval

Version	First Author	WP leader	Project Coordinator
1	B. Vezzoni (Framatome) 28/08/2023	N. Forgione (UNIPI) 29/08/2023	D. Verrier (Framatome) 31/08/2023
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1. Introduction

Within the H2020 CAMIVVER Project [1], Work Package 8 (WP8) aims to ensure that the project objectives, activities, and methodologies are widely promoted and exploited to the target groups defined by the dissemination and communication plan on the European level and beyond [2].

Task 8.4 is dedicated to summing up synthetically the outcomes of each single WP in the form of lessons "learned/best practices" for improved general safety studies on Gen. II and Gen. III LWR and code Verification & Validation (V&V) strategies.

This document corresponds to the Deliverable 8.5: "*The CAMIVVER VVER Safety Analysis Guidance"* of the CAMIVVER project. It summarizes the major outcomes of the project proposed in a synthetic form to the international community and the project's end users. This summary is completed with a list of references to project deliverables and publications where details are provided.

In the present deliverable, the term "guidance" must be considered as "lessons learned" and "best practices". Indeed, massive efforts and consensus are needed to establish nuclear safety guidance on specific methodologies and techniques that imply long-term iterations and the participation of international organizations such as IAEA and OECD/NEA and different member countries. This is not the aim of the CAMIVVER project, and therefore, the name "guidance" will be kept in the title only.

As WP leaders and partner institutions agreed, the following chapters summarize selected lessons learned / best practices for each WP.

Chapter 2 is related to the importance of sharing information at the international level for setting up a common database for code Verification and Validation.

Chapter 3 is dedicated to lessons learned / best practices for developing and validating lattice calculation platforms and schemes.

Chapter 4 is dedicated to best practices for improving neutronics/thermal-hydraulics coupled modeling for steady-state and transient calculations of several reactor types.

Chapter 5 is dedicated to lessons learned about CFD applications on core inlet/outlet flow distribution determination for VVER, and Chapter 6 to system-and-core calculations.

The selected outcomes have been decided in agreement with all the project partners, and some conclusive remarks and perspectives have been summarized in Chapter 7.

2. Common database for codes verification and validation

The following table presents the lessons learned and best practices identified as the outcome of WP3 *"Establishment of a common VVER database for codes verification and validation"*. WP3's main activity was carried out during the first half of the project, but iterations with partners to consolidate data have been foreseen during the whole project.

WP3 has been integrated into the project to collect input data made available to all the partners. This has allowed to make comparisons between data from different partners and to build a shared database used for setting up boundary conditions of the benchmarks exercises at WP4, WP5, WP6, and WP7. In addition, to feed verification and validation (V&V) activities concerning safety assessment codes and methods, an extensive collection of international publications has been created (see Deliverable 3.1, [3]) and made available to the international community.

#	Best Practices	Comment
WP3-1	A comprehensive review of the available VVER data for verification and validation of neutronics and thermal-hydraulics codes	To develop correct input models of investigated objects and for further V&V of the models developed, the data gathering and their organization for the different parts of the calculation chain is mandatory to plan and perform analyses. The priority was to classify the experimental data (neutronics and thermal-hydraulics data) shared by the consortium.
WP3-2	The development of a definition report specifically for NPP with VVER 1000 reactor with respect to project objectives such as the development of neutron physics libraries and the performance of selected specific analyses.	Important for developing or updating the existing input models from previous code versions. Important to extend existing input models with new models in correspondence to the goals set. To fill in missing information important for the correct modeling of the components, structures, and systems of the studied object. Important to provide the range of parameters space used in the library generation as the fuel assembly configurations in nominal and accidental situations comprising fuel and water temperature range, soluble boron content, moderator density, power density, burnup range, type of control rods, etc.
WP3-3	The development of a scenario for an NPP accident including specific processes and phenomena important for the plant's safety, such as SB LOCA combined with an SBO (Station BlackOut) and PRISE (Primary to Secondary Leakage).	The objective is to prepare plant-specific scenarios for the VVER-1000 and to provide information on all equipment and systems expected to be initiated during the progression of an accident [4]. The chosen set of initiating events allows one to simulate various important phenomena and processes and check the code's capabilities through code-to-code comparisons.

3. Innovative methodologies for multi-parametric neutron data libraries

The following table presents the lessons learned and best practices identified as outcomes of WP4 *"Innovative methodologies to generate VVER multi-parametric neutron data libraries"*. WP4 activities have been carried out during the project with several exchanges among the Tasks and other WPs (WP5 and WP7).

WP4 aims to make a step forward in the framework of multi-parameter neutron data libraries generation for Gen II and Gen III LWR (in particular for VVER) using the new-generation EU codes, such as APOLLO3® [5].

A step forward in using new-generation EU codes has been achieved, as presented by the project's final deliverables. This has been possible by the activity carried out in the several tasks proposed for considering all the possible aspects that have to be considered in the "lab to industry" process.

APOLLO3® code has been selected not only for its capability of natively treating hexagonal geometries (specific of VVER) but also for the possibility of using the code to improve lattice calculation schemes for Gen II and Gen III LWR (PWR and VVER) concepts via e.g., 3D models options for axial treatment or 2D core modeling.

Competences in systems engineering and code development [6], calculation schemes definition and validation [7][8] and advanced physics modeling [9] have been included in this WP and coordinated to fulfill the goals foreseen:

- a proof of concept (PoC) of a multi-parameter neutron data library generator based on advanced lattice codes has been developed. The PoC has been called NEMESI [10][11].
- 2D assembly calculations have been carried out with NEMESI and compared against APOLLO2, SERPENT2, and TRIPOLI-4® computed results using an automatic comparison tool developed for this specific purpose [8].
- PWR and VVER MPOs for WP5 and WP7 activities have been produced via NEMESI [11][12] using different output homogenizations.
- VVER assembly calculation schemes have been proposed [7]. These actions aim at answering an additional industrial need: the reduction of calculation time without the degradation of the results' quality, improving the platform computational performances.
- Analyzing the advanced features (new self-shielding model, new neutronic data, 2D vs. 3D treatment, etc.) available in the APOLLO3® lattice code. Results obtained on 2D and 3D configurations have open discussions on improved reflector models and axial interfaces, respectively.

#	Best Practices	Comment
WP4-1	Including systems engineering and code developments practices (Figure 1) since the PoC	A subsequent categorization and analysis of user needs for a lattice calculation platform has been performed as the first step of the multi-parameter neutron data library PoC definition and development. The user needs are written as formal requirements and allowed for defining a unified approach to design an effective, industrial-grade, and future-proof calculation platform [6][10].

		This systematic analysis has allowed to classify use cases (UCs) and requirements with respect to all the software layers of a lattice calculation platform, i.e., the frontend, the interfaces, the backend, and the system in general. This classification mainly aims to separate responsibilities for developing the various identified functionalities and share the efforts among the partners. This approach, defined as generic as possible [6], has allowed to set up a rigorous process for developing and testing the platform. Dependencies have been identified clearly. The remaining work to achieve a complete industrialized platform has been quantified [8].
WP4-2	V&V approach to determine comparisons among different codes	Validation-oriented results are also produced to support the platform and calculation scheme developments. Special attention has been devoted to clearly indicating the specifications of the assembly configurations and input data (isotopic composition, temperature, dimensions), identified as the first step and shared by the partners [13]. Comparisons have clearly indicated what must be done to improve the results.
WP4-3	VVER lattice calculation schemes	These actions aim to answer an additional industrial need: reducing calculation time without degrading the results' quality while improving performances. The definition of the calculation scheme and optimized options for the assembly configurations to calculate is one of the ways to improve the performances together with an analysis of the possibilities offered by the machine evolution and HPC [14].
WP4-4	2D reflector modeling	Improve 2D lattice reference calculations applications may allow to provide reference deterministic calculations for V&V and improve radial reflector XSs data to be used in core diffusion/transport calculations.
WP4-5	APOLLO3® lattice 3D applications	The MOC 3D applications may allow to solve axial heterogeneities (grids, fuel/reflector interfaces, etc.) with more details, provide reference deterministic calculations and improve XSs data to be used in core diffusion/transport calculations.
WP4-6	Management aspects	To ensure the fulfillment of the WP4 objectives, in particular, to guide the "lab to industry" process, an important point has been the choice of the management structure adopted. The leadership of the technical tasks has been shared among the partners. In particular, the industrial partners (FRA and EDF) have led the Tasks

		more related to the industrialization process, and CEA, with its central role in the development of APOLLO3® and APOLLO2 codes, has maintained the lead of the tasks more oriented to the physics. The presence of the KIT as technical contributor has allowed to facilitate exchanges in the benchmark analyses carried out at WP5 and WP7.

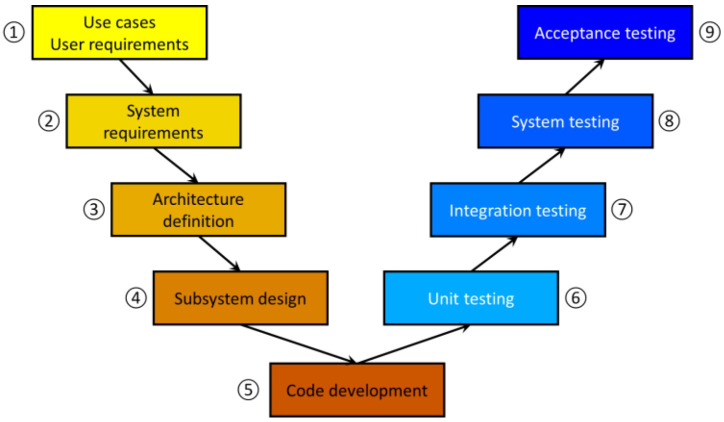

FIGURE 1: SYSTEMS ENGINEERING APPROACH [6][15]

4. Improved neutronics-thermal-hydraulics coupled modelling on core calculations

The following table presents the lessons learned and best practices identified as outcomes of WP5 *"VVER core simulations by improved neutronics-thermal-hydraulics coupled modelling"*. WP5 activities have been carried out during the project with several exchanges among the Tasks and other WPs (WP4 and WP7).

WP5 aims to open the discussion, at the industrial level, on a core multi-physics approach based on neutronics and thermal-hydraulics coupled Best-Estimate simulations. Discussions on multi-physics resolutions are internationally available. The activities carried out in WP5 allowed to bring the industrial view and needs to the international level [17].

The actions proposed aim at providing test cases representative of PWR and VVER configurations and boundary conditions to assess:

- performances of APOLLO3® core solvers using its internal multi-1D thermo-hydraulic library (THEDI) and comparing its results against other state-of-the-art closed channel neutronic/thermo-hydraulic codes [5][19];
- a newly proposed APOLLO3®/CATHARE3 coupling and benchmarking against existing 3D multi-physic High Fidelity models based on Serpent/SCF coupling [18][19];
- the suitability of a framework for verifying the multi-parameter neutron data libraries generated in WP4 for different VVER and PWR configurations and homogenizations.

APOLLO3® code has been selected in the WP5 activity for testing the capabilities of core solvers for solving hexagonal geometries (specific of VVER) [5] and identifying points of improvement for a possible long-term industrialization.

Considerable work has been done on the definition and the assessment of the reference test cases and core boundary conditions. A simplified core geometry definition has been selected and made available to the international community [20][12]. The selected sizes are small enough to reduce the calculation time and allow to test several options as a first step toward a full core calculation [18][21][22][12]. The choice of a simplified geometry aligns with ongoing studies in the PWR framework (i.e., OECD/NEA activities), where multi-physics approaches are tested on cluster cases (e.g., 3x3 assemblies or a full core fraction).

The selected configuration types have allowed further testing of high-fidelity resolutions (Serpent/SCF couplings) developed in previous EU projects (e.g., the H2020 McSAFE project). If no experimental data is available, these high-order solutions may be used to check the prediction accuracy of low-order solutions based on diffusion and simplified transport approximations.

#	Best Practices	Comment
WP5-1	The development of coupling approaches based on deterministic codes	APOLLO3® code has been selected for testing the capabilities of core solvers on treating hexagonal geometries and identifying points of improvement for a possible industrialization in the long term. Two couplings have been tested and compared against high-fidelity solutions: - APOLLO3®/THEDI coupling where THEDI is a closed channel TH model included in APOLLO3® and based on four equations for two-phase flow simulations. This first coupling

		has allowed to verify neutronics data libraries generated in WP4 and provided the first elements to analyze the thermal-hydraulics (TH) feedback on the cores selected - APOLLO3®/CATHARE3 coupling based on the C3PO engine has been developed to improve the 3D capabilities of the CATHARE3 code in comparison to the multi-1D approach. This coupling has been tested under RIA transient within WP5 for small core configurations to investigate the 3D core capabilities of the CATHARE3 code.
WP5-2	Contribution of high-fidelity resolutions to Verification and Validation (V&V) activities	High-fidelity resolutions (Serpent/SCF couplings) allow, if no experimental data is available, to check the prediction accuracy of low-order solutions based on diffusion and simplified transport approximations. Having access to high-fidelity solutions allows to investigate and quantify the approximations introduced.
WP5-3	Boundary Conditions definitions for core benchmark exercises	Considerable work has been done on the definition and the assessment of the reference test cases and core boundary conditions (Figure 2). This work is fundamental to set benchmarks, identify discrepancies and sources of bias among the different codes. Among multiple ones, some boundary conditions to be defined are the geometry, the thermo-physical properties, the temperatures, the flow rate, etc. The work done on small configurations has allowed to set up the models and identify possible discrepancies to be considered in preparation for full core calculations.
WP5-4	Accuracy of XS preparation used in typical two-level scheme calculations	The accuracy of cross-sections (XS) used in core calculation remains fundamental for core-level comparisons. The work done in WP5 via static comparisons has provided a good framework for verifying the multi-parameter neutron data libraries generated in WP4 for different configurations and homogenization (including pin-by-pin) of VVER and PWR. See the iteration process represented in Figure 3.

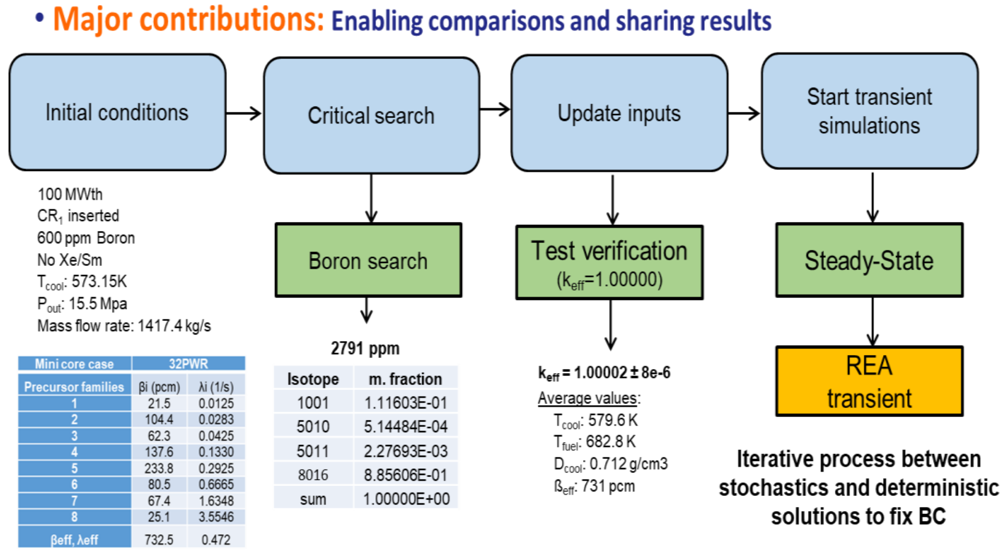

FIGURE 2: EXAMPLE OF BOUNDARY CONDITIONS DEFINITION

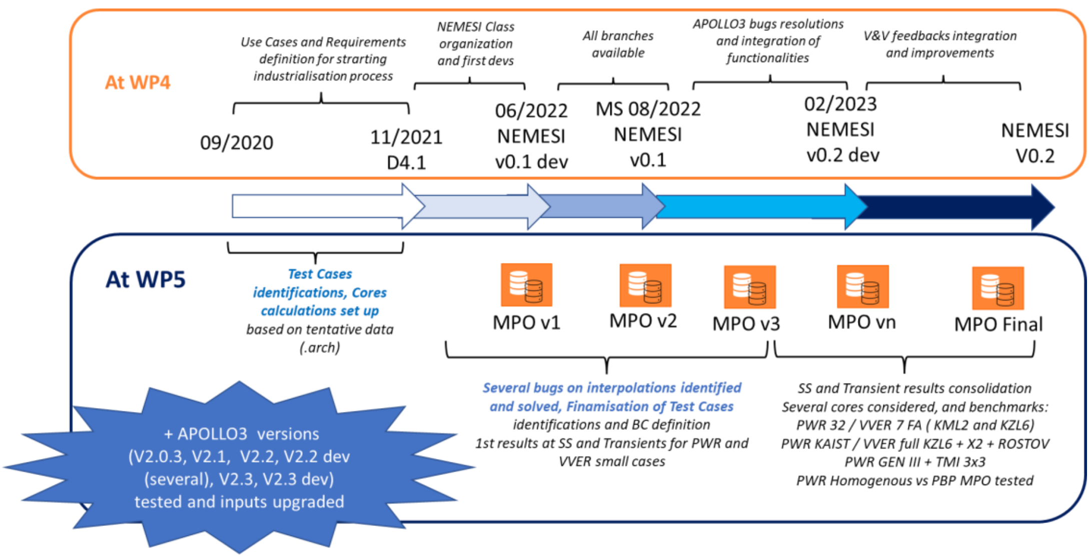

FIGURE 3: ITERATIONS CARRIED OUT AT WP5 FOR VERIFYING THE MULTI-PARAMETRIC NEUTRON DATA LIBRARIES

5. CFD analysis for VVER core-outlet flow distribution

In the following table the lessons learned, and best practices identified as outcome of WP6 *"CFD analysis of VVER core-outlet flow distribution"* are recalled.

WP6 has the objective to improve CFD modelling and validation for VVER applications, especially mixing in primary vessel. It consists in three tasks, each serving as a steppingstone for the next: the first one was dedicated to building a CFD model of the primary vessel of Kozloduy-6; the second to perform a CFD transient calculation of a mixing experiment; and finally, to run multiple times this transient with different inlet conditions to assess the propagation of their uncertainties through the model.

Thanks to the high-performance capabilities of calculations available, one of the goals in WP6 was to model as precisely as reasonably achievable the primary vessel of a VVER-1000. Indeed, several progresses in the CFD codes used in WP6 over the last years allowed to improve the models. The mesh could be refined further than what had been done in the previous studies conducted on this experiment. By increasing the number of cells in the models, it is possible to refine the boundary layers or model fine geometric elements otherwise treated with a simplified geometry. Even for the complex elements still represented with a simplified geometry, the associated physical models have been improved in the codes and ensure a better accuracy than before.

Besides the initial improvements while setting up the calculation, a benchmark was conducted over the 3 tasks of the work package to ensure the consistency between several CFD codes and methods. The aim was to demonstrate the robustness of CFD models and the high fidelity of the results they provide despite their complexity. In the first two tasks, the benchmark of the codes consisted in comparing the results to actual data – whether the operating point of Kozloduy-6 for task 1, or experimental measures in task 2 – and code-to-code comparisons. In the last task, the propagation of the uncertainties through the CFD models was estimated.

Throughout the three tasks, each partner of WP6 was able to set up a calculation with their own methods and practices and provide results comparable to the reference data. Moreover, the code-to-code comparison of the results has been satisfying for every task:

- In the first task, the results among the partners were close to one another and gave confidence in the consistency between the different models for the upcoming tasks;
- In the second task, the transient calculations of a mixing experiment were compared to on-site measures. The prediction of the increase in temperature in the hot legs and the mixing in the vessel were well predicted. Ways to improve the results were also highlighted such as adding swirl at the inlet of the model and representing as explicitly as possible the structures responsible for flow distribution when possible.
- Finally, the third task showed that even though the different models used have their own response to the input signals, the trends between them remain very similar. For all partners, the correlation of the temperature in the core and in hot legs to mixing was highlighted. One model was found to show more variability of the mixing maps which impacted the temperature field which was shown to have an increased variance. The other models all showed identical behavior with slight variations of the mixing maps in the core. Also, the deterministic sampling (DS) method used to propagate uncertainty was found to be effective to assess behavior of the different models regarding the inputs. Whether the variability of the model was chaotic or correlated to inputs, DS enables to distinguish between these two behaviors and yields statistical moments representative of the variability of the output.

#	Best Practices	Comment
WP6-1	1. General improvement of the codes 2. Meshing Modelling explicitly the structures responsible for flow distribution when possible	1. CFD codes have been improved over the last years and the models are now more precise and more stable. For instance, it is now possible to use a 2nd order model without risking divergence. The turbulence models also allow to have a realistic diffusion. 2. The HPC capabilities enabled to use more refined meshes in the models. Notably, the boundary layer mesh could be refined and using inflation is a good way to resolve properly the velocity field near the walls and ensuring a smooth transition with the rest of the mesh. 3. To ensure a good distribution of the mass flow in the core, it is important to represent as explicitly as possible the structures involved in the repartition such as the elliptical plate, the support columns. The head loss in the fuel assemblies can also be set up differently depending on the zone the assembly is in.
WP6-2	1. Meshes capabilities 2. Swirl at the inlet	1. The results were compared between the different CFD codes and models to assess the accuracy and consistency of the simulations with the available experimental data. The simplified model was found to be sufficient for predicting the overall coolant mixing patterns observed in the reactor vessel, provided additional insights into the local flow structures and mixing characteristics [23]. 2. Adding the swirl caused by the pumps in the cold legs improves the results and bring them closer to the experiment by angularly shifting the mass flow in the downcomer.
WP6-3	1. Evaluation of uncertainty with different DS ensembles. 2. Realization of sensitivity analysis with DS/POD Benchmark with different models	1. The evaluation of uncertainties with different DS ensembles was performed with different CFD models. The resulting uncertainty reflects the sensitivity of the CFD model. When the CFD model response is smooth with visible correlation of the output to the input variations, the different DS ensembles responses are consistent with low discrepancy. The evaluated uncertainty is in this case representative of the impact of the input parameters detected by the model. In contrast, if the CFD outputs are noisy with more chaotic behavior, the DS ensembles will show more variability in their results. In this case, the resulting variance reflects correctly the noise observed between the outputs even though it might miss correlation between outputs and inputs. Moreover, some hybrid ensembles built for this study were shown to perform better than other due to their properties. Finally, the benefit of enforcing the fourth

		order moment in ensembles for the evaluation of quantiles with the Metalog distribution has been shown. 2. The evaluation of the sensitivity of 2D data in the core to inputs has been performed with POD (Proper Orthogonal Decomposition). The use of POD brought up modes of fluctuations that could be correlated to physical quantities in the core such as the mixing maps, the flowrate and power distribution. In addition, POD modes can be used from a model to another to compare their sensitivity to inputs. This process enabled the comparison of noisy data to smooth data on a common POD base which showed consistency of the results obtained from the different CFD models. 3. The benchmark of the different models showed a range of behavior that was quite consistent: confidence intervals were assessed on the CFD response with quantiles, with good agreement between the model. Also, this study showed the benefit of testing different turbulence models, as they have their own advantages/disadvantages: $k-\epsilon$ model present smoother values that enables to correlate easily outputs variations to the input variations while the $k-\omega$ models seem to be more precise regarding mixing but are more numerically sensitive to variations of the inputs, which can make difficult the evaluation of correlations, and increase the evaluated variance.

6. Primary-circuit thermal-hydraulic modeling

The following table presents the lessons learned and best practices identified as outcomes of WP7 *"Primary-circuit thermal-hydraulic modelling"*.

WP7 objectives are to improve thermal-hydraulics modelling of VVER plants, especially:

- Challenge robustness and validation of CATHARE3 in the context of VVER reactors.
- Perform significant upgrades of RELAP5 models, including switching to TRACE models.

The "French nuclear network" released and continuously develops the CATHARE3 code, which includes advanced capabilities for 3D modeling and is based on three-field equations that allow a better simulation of two-phase flows. CATHARE3 relies on a strong validation regarding Western PWR, but before the CAMIVVER project has not been tested to VVER specificities.

To improve the models' descriptions, the WP7 activity has been organized in several phases with increased complexity: 1) development of thermal-hydraulics-code models of VVER primary and secondary circuits and performing steady-state benchmarks to check models consistency; 2) simulation of Kozloduy-6 Main Coolant Pump start-up transient (exercise derived from OECD/NEA VVER-1000 Coolant Transient Benchmark); 3) modeling and comparing results over an "SB LOCA + SG line break" transient; and 4) modeling and comparing results of a main steam line break (MSLB) transient typical chosen for evaluating 3D methods between thermal-hydraulics and neutronics codes.

#	Best Practices	Comment
WP7-1	Development of thermal-hydraulics code models of VVER primary and secondary circuits; Perform steady-state benchmark to check models' consistency.	After building new input models or updating existing ones to the requirements of new code versions, achieving good steady-state conditions is important before going further with transient simulations [24].
WP7-2	Simulation of the plant-specific test, based on existing plant data, such as switching-on one MCP (Main Coolant Pump) to the other three MCPs in operation.	The simulation of the actual plant test behavior is important for increasing the fidelity of computer codes for simulating plant accidents. The simulation of such tests allows to reproduce the asymmetrical insertion of positive reactivity, achieving a spatial effect in the reactor core as well as simulating the reverse flow rate in an affected loop. This allows making simulations of the entire plant response [25][26].
WP7-3	Simulation of multiple failures transient such as SB LOCA simultaneously with an SBO and PRISE.	The investigation of codes' capabilities of simulating the plant response in case of multiple failures. Code-to-code comparisons are used when simulating specific phenomena and processes during the accident evolution as a tool for increasing code fidelities. The simulation of the plant integral response in case of multiple failures [27][28].

WP7-4	Coupling System-core (MSLB) -> opening to the 3D coupled analyses	The simulation of selected scenarios is important for investigating coupling capabilities between thermal–hydraulics (T/H) and neutronics codes (NCs). Simulating such tests allows to reproduce and investigate the behavior of plant parameters in case of positive reactivity insertion in asymmetrical feeding of the vessel. Comparison of plant parameters predictions calculated by 1D T/H with point kinetics vs. coupled 3D T/H with 3D NC analyses. The first attempt of application for the APOLLO3-CATHARE3 coupling is provided after having selected specific boundary conditions (KZL6 cycle 1 BOL state) [13].

7. Conclusions and Perspectives

The present document corresponds to Deliverable 8.5, entitled "*The CAMIVVER VVER Safety Analysis Guidance"* of the CAMIVVER project, and it collects the major outcomes of the project proposed in a synthetic form to the international community and the end users of the CAMIVVER project.

In the present deliverable, the term "guidance" must be considered as "lessons learned" and "best practices". Indeed, huge efforts and consensus are needed to establish formal nuclear safety guidance on specific methodologies and techniques that imply long-term collaborations and the participation of international organizations such as the IAEA and OECD/NEA. This is not the aim of the CAMIVVER project and therefore, the name "guidance" will be kept in the title only.

A list of selected lessons learned / best practices for each WP has been summarized as well as the references for more details.

The best practices concern code development practices, numerical and experimental benchmark definitions, V&V practices, and uncertainties approaches. Some of the lessons learned are common to the different WPs and recalled in the following items:

- consider as an important step the definition of well-established and completed boundary conditions and input data for benchmarks exercises at the lattice, core, components (CFD), and system levels.
- give space and time for iterative approaches to consolidate benchmarks analysis and comparisons.
- promote the use of sensitivity studies and uncertainties analysis tools to identify dominant parameters in a specific physic resolution.
- encourage a global approach for guiding the "single physics" treatment and codes developments,
- do not neglect to identify clear roles in the project construction to guide technical choices in the process from lab to industry management.

The practices identified by the CAMIVVER consortium will be applied to codes industrialization and to prepare future R&D works.

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