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Synergies in VVER reactor long-term operation and aging: A comprehensive review of CAMIVVER, DELISA-LTO, and EVEREST projects

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Abstract. This paper reviews the synergies between three Euratom projects–CAMIVVER, DELISA-LTO, and EVEREST–focusing on the long-term operation (LTO) and safety assessment of VVER reactors. These projects address challenges associated with extending the lifespan of VVER reactors with implications to Europe's energy infrastructure.
The CAMIVVER project concentrates on the development of VVER specific computational methods to support their safety assessments. Through the development of advanced simulation tools like APOLLO3® and CATHARE3, CAMIVVER aims to refine thermal-hydraulics and neutronics models for the VVER-1000 reactor type, supporting both existing reactor safety analyses and the qualification of alternative fuel sources. DELISA-LTO focuses on understanding and mitigating material degradation in VVER reactors, especially in the context of thermal aging and swelling. This project emphasizes non-destructive testing (NDT) and experimental validation to identify critical components and extend reactor lifespans safely. In parallel, EVEREST investigates advanced multi-physics approaches to improve the accuracy of reactor pressure vessel fluence assessments. By producing high-resolution experimental data, EVEREST seeks to validate these models for improved safety analysis of both VVER and other pressurized water reactors.
A key synergy across these projects is the integration of experimental data and advanced modelling technics. Additionally, the projects share a focus on knowledge dissemination through workshops, training, and collaborative efforts, aimed at aligning regulatory, and industrial stakeholders with modelling and safety aspects associated with LTO of VVER. Together, CAMIVVER, DELISA-LTO, and EVEREST represent complementary approaches to addressing the aging and sustainability of VVER reactors, thereby contributing to Europe's energy security and decarbonization efforts.

1 Introduction

Nuclear energy plays an increasingly important role in achieving Europe's low-carbon energy goals, particularly as many countries seek to reduce their reliance on fossil fuels and integrate more renewable energy sources. Among the various types of nuclear reactors used in Europe, water-water energetic reactors (VVERs) stand out as a critical part of the energy infrastructure, especially in Central and Eastern European countries such as Finland, Bulgaria, Slovakia, Hungary, and the Czech Republic. VVER reactors are a type of pressurized water reactor (PWR) that have been in operation since the 1970s, contributing significantly to these nations' energy security.

As many VVER reactors approach or surpass their original design lifetimes, extending their operational periods through long-term operation (LTO) becomes a strategic priority. However, operating reactors beyond their initially projected lifespans introduces several technical challenges. Some of these challenges are related to material degradation, aging of critical reactor components, and developing advanced modelling techniques for safety analysis. Additionally, there is a growing need to implement

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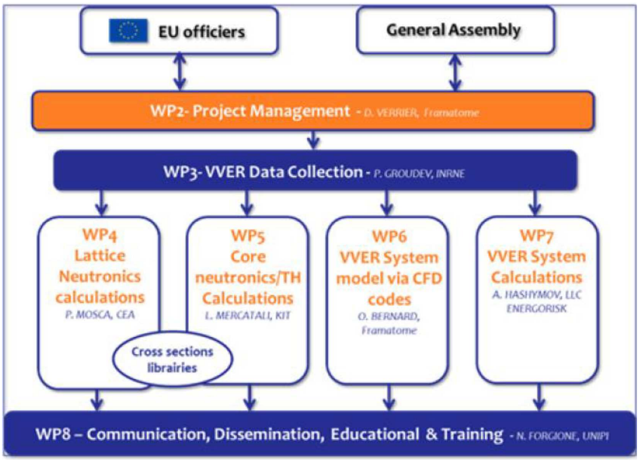

Fig. 1. CAMIVVER project structure.

non-destructive testing (NDT) methods that allow for early detection of material degradation without interrupting reactor operations.

In response to these challenges, the European Union's Horizon 2020 and Europe programs have funded several collaborative projects aimed at long term operation (LTO) of VVER reactors while ensuring their ongoing safety and reliability. This paper provides a detailed overview of three such projects, namely EVEREST, DELISA-LTO and CAMIVVER. These three projects are at various stages of completion, CAMIVVER being over (Sept 2020 – August 2023), DELISA-LTO being at his halfway mark and EVEREST just starting. Each of them focuses on different aspects of VVER reactor operation, safety, and aging management.

The purpose of this paper is to explore the objectives, methodologies, and outputs of each project and to highlight the synergies between them. Special attention will be given to how these projects contribute to LTO aspects of VVER addressing material degradation, implementing advanced multi-physics modelling, and fostering collaboration between industry, regulators, and academic institutions.

2 CAMIVVER

In order to support the development and the qualification of new fuel assembly types and, more generally, to provide the required elements for the safety analysis report (SAR), an important place is reserved to the development, improvement, verification and validation of computer codes and methods used in the VVER safety analysis. The codes and methods continuous update, needed for answering the regulatory requirements for reactors LTO, is the basis of the CAMIVVER project, for the improvement of codes and methods for VVER comprehensive safety assessment in support to other activities carried out concerning VVER fuel development and qualification. CAMIVVER project is oriented to VVER-1000 reactor type.

The CAMIVVER project activities (Fig. 1) have been built to reach four main objectives:

– The improvement of scientific computer codes, models, and methods to be used at an industrial level for the comprehensive safety assessment of Generation II and III reactors.
– The promotion of 3D neutronics-thermal hydraulics coupled calculations to improve the safety assessment by a better representation of the physical phenomena (e.g., accidental transient characterized by strong heterogeneities in power or coolant fields), an important aspect for the LTO upgrade when considering the evolution of margins with respect to safety criteria.
– The promotion of the use of advanced mathematical methods (metamodels, deterministic sampling, etc.) for the assessment of uncertainty propagation within numerical simulations.
– The integration of the VVER context (VVER-1000), slightly different from western PWR but with some common features, to challenge the robustness of codes and methods and their validation strategy.

The project is organized in 8 Work Packages (WP). Each WP is dedicated to a specific part of the safety assessment calculation chain, except WP2 dedicated to Project Management, WP3 dedicated to VVER data collection and WP8 dedicated to Communication, Dissemination, Educational and Training activities. This structure has been chosen following the type of codes used in each technical WP (lattice codes in WP4, core neutronics and thermal-hydraulics codes in WP5, CFD codes in WP6 and systems codes in WP7), the skills to be involved and the dependency between the different actions. This structure allows maintaining an overall consistency through the technical links existing between each WP, as indicated in Figure 1, while keeping separate the implementation of work programs and therefore limiting the risk of strong dependencies that may result in planning fulfillment delays.

2.1 CAMIVVER ambition

CAMIVVER project ambition for reaching its objectives is to push new generation codes and methods towards an industrial use for VVER and PWR safety assessments. The selected new generation codes, namely APOLLO3® [1] and CATHARE3 [2], are still under development at laboratory level. Their industrialization process is ongoing and CAMIVVER is directly contributing to that effort. This laboratory-to-industry process is illustrated in Figure 2. The CAMIVVER project is identified as one step in that process. Post-CAMIVVER steps could be considered in the frame of next EU R&D programs.

To achieve that significant progress, CAMIVVER relies on:

– Performing code development of a neutron data library generator prototype based on APOLLO3® code and of a proof of concept of an innovative coupling based on APOLLO3®/CATHARE3 codes.

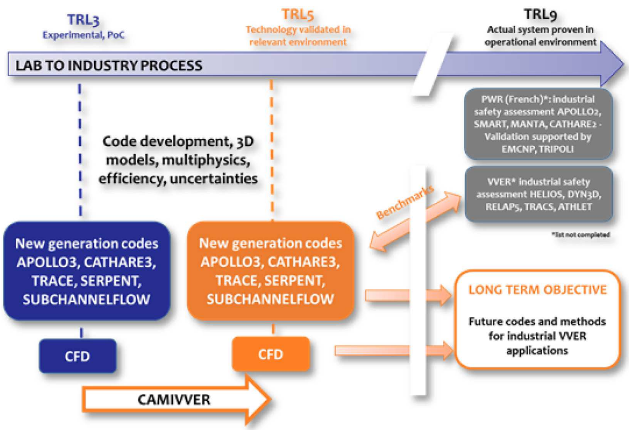

Fig. 2. Codes development within CAMIVVER.

- Benchmarking those new generation codes against codes currently used for VVER and PWR safety assessment (PARCS and RELAP5) and/or high-fidelity calculations (high level of representativity of the 3D geometry and physics with limited modelling simplifications) based on Monte Carlo codes (TRIPOLI-4 and SERPENT, [3–5], coupled with sub channel codes (SUBCHANNELFLOW) for steady state and transient calculations.
- Performing methods development based on 3D-modelling to improve system thermal-hydraulics modelling of VVER plant, especially by challenging the robustness and validation of CATHARE3 against reference RELAP5 and TRACE models.
- Performing methods development based on 3D-modelling and uncertainty propagation in CFD analyses, using partners codes (STARCCM+, CFX, FLUENT, TRIO-CFD). CFD analyses are expected to support the modelling in systems codes when non symmetrical phenomena or thermal stratification are occurring.

Both APOLLO3® and CATHARE3 bring potential advantages and improvements to the safety analysis studies with respect to the codes currently used in France. The developments of these codes have been initiated several years ago and are achieved outside the CAMIVVER framework. Within the CAMIVVER scope, essential adaptations of APOLLO3® required for VVER applications are implemented, in WP4 focusing on the industrialization of the lattice part, and in WP5 by coupling neutronics with thermal-hydraulics models. In that respect, CAMIVVER includes a demonstration of the feasibility of APOLLO3®/CATHARE3 coupling.

CATHARE3 development and validation are also involved regarding VVER plant system thermal-hydraulics. Within CAMIVVER, CATHARE3 is benchmarked with updated RELAP5 and TRACE codes on selected transients, namely: MCP start-up, LOCA and MSLB.

CFD modelling of VVER is addressed in WP6 of CAMIVVER especially as regards to mixing phenomena in the primary vessel. Specific works within CAMIVVER are consisting of calculations based on the Kozloduy-6 mixing experiment: CFD models development and upgrades by contributing partners, benchmarking results of CFD analyses, and performing uncertainty propagation analyses by using Deterministic Sampling method [6]. The ambition is clearly to improve the validation files.

2.2 CAMIVVER main outcomes

The following gives an overview of its main achievements. The vast majority of deliverables can be found at `camivver-h2020.eu`.

First technical activities in CAMIVVER have consisted in collecting all necessary reference data to be used by project partners. That essential task has been conducted within WP3 led by INRNE-BAS from Bulgaria and 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 in 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 and made available to the international community (Deliverable D3-1).

The WP4 aim was 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 codes, such as APOLLO3®. 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 modelling.

Competences in systems engineering and code development [4], calculation schemes definition and validation (Deliverables D4-4 and D4-5) and advanced physics modelling (Deliverable D4-6) 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 (Deliverable D4-2), [5].
- 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 (Deliverable D4-4).
- PWR and VVER MPOs for WP5 and WP7 activities have been produced via NEMESI ([5], Deliverable D5-4) using different output homogenizations.
- VVER assembly calculation schemes have been proposed (Deliverable D4-5). These actions aimed 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,

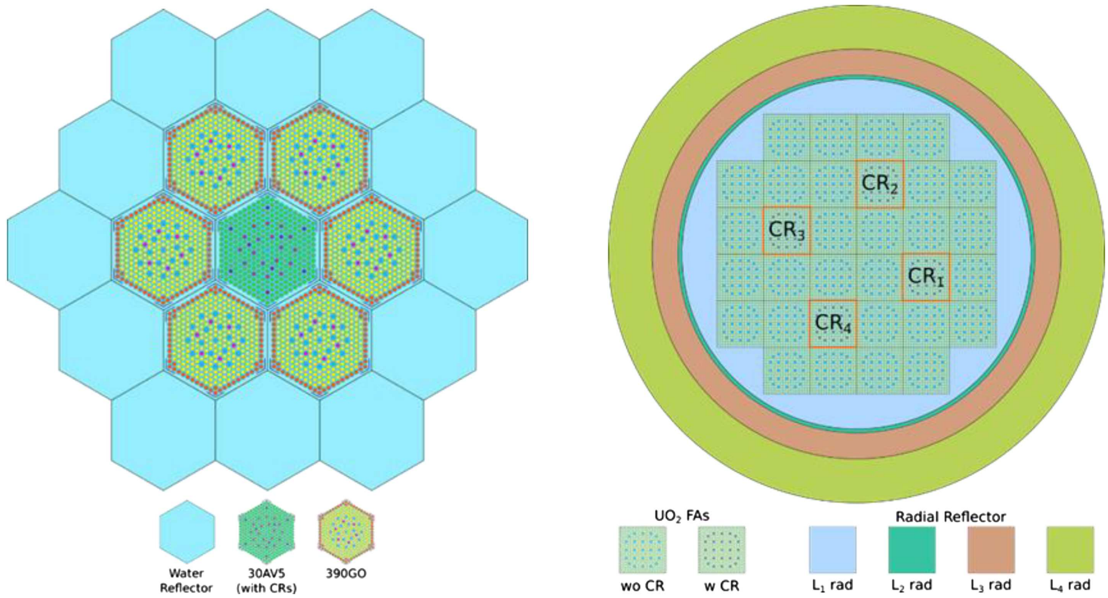

Fig. 3. Selected VVER (left) and PWR (right) mini core geometries.

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.

WP5 aimed 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 [7].

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 [8,9];
- A newly proposed APOLLO3®/CATHARE3 coupling and benchmarking against existing 3D multi-physic High Fidelity models based on Serpent/SCF coupling [6,9];
- 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) [8] 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 in the form of a deliverable [4]. The selected sizes, see Figure 3, are small enough to reduce the calculation time and allow to test several options as a first step toward a full core calculation [6]. 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., 3×3 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.

WP6 had the objective to improve CFD modelling and validation for VVER applications, especially mixing in primary vessel. It consisted in three tasks, each serving as a steppingstone for the next: 1/ building a CFD model of the primary vessel of Kozloduy-6; 2/ perform a CFD transient calculation of a mixing experiment; 3/ run multiple times this transient with different inlet conditions to assess the propagation of their uncertainties through the model.

Thanks to the available high-performance calculation capabilities, one of the goals in WP6 was to model as precisely as reasonably achievable the primary vessel of a VVER-1000 (see Fig. 4 for examples of results obtained during the project). 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

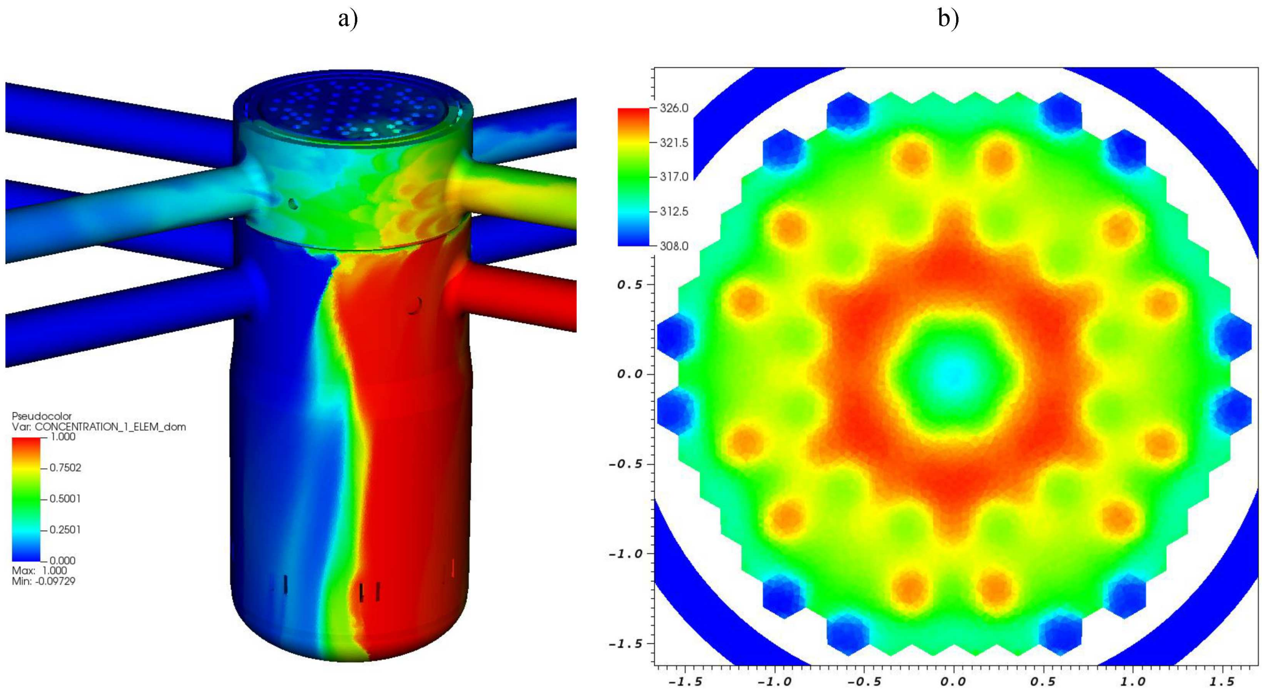

Fig. 4. Concentration of a passive scalar (a) and temperature at the end of the active core (b).

models have been improved in the codes and ensure a better accuracy than before.

Beside 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, despite their complexity, and the high fidelity of the results they provide. 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 [10]. 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 temperature increase 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.
- 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 the 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.

WP7 objectives were defined 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. It includes advanced capabilities for 3D modelling based on three-field equations that allow a better simulation of two-phase flows. CATHARE3 relies on a strong validation regarding Western PWR but had not been tested to VVER specificities prior to CAMIVVER.

The WP7 activity has been organized in several phases with increased complexity:

- Development of thermal-hydraulics-code models of VVER primary and secondary circuits and performing steady-state benchmarks to check models' consistency (Deliverable D7-1) and [11]. As part of the task, based on the data prepared in the Task 3.2 of WP3, all participants developed calculation models of the VVER-1000 reactor plant. The following codes were used in the development of the models: INRNE, using RELAP5, ENERGORISK, using RELAP5, KIT, using TRACE and Framatome, using CATHARE3. The calculation results showed a good consistency of the results of all participants with the characteristics of the Kozloduy-6 NPP.

- Simulation of Kozloduy-6 Main Coolant Pump start-up transient (exercise derived from OECD/NEA VVER-1000 Coolant Transient Benchmark) (Deliverable D7-2) and [12]. The benchmark was performed to improve the thermal-hydraulics modelling of the VVER plant, especially to challenge robustness and validation of CATHARE3 in the context of VVER reactors. The analysis of the results of the benchmark shows that the participant's results for each parameter are in significantly good agreement with some exceptions. As a general conclusion this benchmark shows that all codes can simulate adequately the selected transient. The calculation with the CATHARE3 model must be completed with the required regulations and systems.
- Modelling and comparing results over an "SB LOCA + SG line break" transient (Deliverable D7-3). The results of the comparative analysis showed very similar coincidence in the dynamics of changes in the main parameters. There are deviations in some of the parameters, but the code-to-code comparison demonstrates a reasonable agreement between the obtained results.
- Modelling and comparing results of a main steam line break (MSLB) transient typically chosen for coupling methods between thermal-hydraulics and 3D neutronics codes (Deliverable D7-4) and [13]. The comparison of selected thermal hydraulic parameters predicted by partners for the MSLB-transient have shown that in general the RELAP5 and TRACE/PARCS codes are able to describe the key-physical phenomena taking place during the MSLB-transient e.g. the strong coupling of the thermal hydraulic parameters with the core neutronics. In addition, the fast evaporation and critical flow through the broken steam line are correctly predicted by the codes and their agreement is reasonable. Additional work may be necessary to reduce the differences between the integral plant models developed for TRACE, CATHARE3 and RELAP5. That will allow to lower the discrepancies of the predicted nominal parameters as well as the discrepancies among the trends of selected parameters calculated by the different tools.

Communication, Dissemination and Exploitation activities have been developed all along the project duration as part of WP8. A Workshop took place at KIT premises on 3-5 July 2023. The workshop featured seventeen lectures from members of the CAMIVVER consortium, all sharing their expertise in reactor modelling. The lectures provided a comprehensive overview of all work package achievements, including their work on lattice physics, core physics, CFD and system code analysis (Deliverable D8-4).

2.3 Summary

A step forward in using new-generation European codes has been achieved. CAMIVVER has pushed the development and validation of new generation scientific computer codes as part of a lab to industry process. CAMIVVER allowed improving the robustness and qualification level of these codes for VVER applications but also for LWR in general. Reinforcement of the modelling capabilities of LWR has been obtained using improved physical models in the new codes, and the development of 3D multi-physics coupled methods that provide a better evaluation of local heterogeneities, and allow a more comprehensive assessment of the accidental events. Eventually CAMIVVER has provided recommendations about scientific code development practices, numerical and experimental benchmark definitions, verification & validation practices, and uncertainty quantification approaches.

3 DELISA-LTO

The DELISA-LTO project was initiated in response to the growing need to extend the operational lifetime of nuclear power plants (NPPs), focusing on water-water power reactor (VVER) technology, vital for maintaining energy security, especially in Central Europe countries like the Czech Republic, Slovakia or Hungary. This region faces challenges from several directions, including war in Ukraine, reducing fossil fuel supplies and integrating less stable renewable energy sources [14]. These challenges make it crucial to maintain the output of reliable existing NPPs, allowing them to operate beyond their projected initial lifetime without compromising safety. Besides enhancing energy security, the long-term operation (LTO) of NPPs also contributes significantly to reducing carbon emissions, as it saves the resources required to produce and transport construction materials. Thus, the environmental impact of constructing new power plants is minimized.

One of the most significant challenges in the NPP lifetime extension is managing the degradation of construction materials exposed to radiation, corrosion, and thermomechanical ageing for extended periods, where the final degradation is potentially doubled [15–17]. NPP lifetime extension has already begun at the national levels; in the US, for example, licenses have been extended to 60 years for most NPPs (90% of all US NPPs) [18], with discussions underway for expanding operations to 80 years. However, lifetime extension is closely tied to stringent safety regulations and periodic evaluations of NPP materials and technologies in Probabilistic Safety Assessment reports [19]. Despite plans for LTO, material degradation may require earlier NPP shutdowns, which should be predictable and driven. As NPP constructions and their operational conditions vary between plants, their lifetime extension strategies cannot be universally applied without

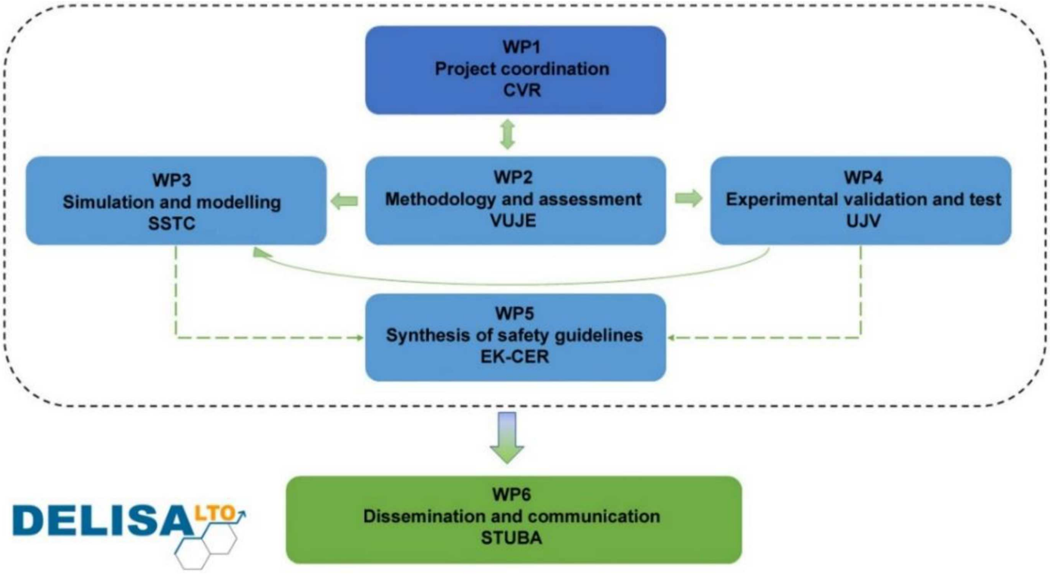

Fig. 5. DELISA-LTO working packages.

consideration of specific conditions. Therefore, the recommendations can be written for specific groups of reactors, as is the DELISA-LTO effort for VVER reactors; otherwise, only general guidance for LTO can be issued.

The DELISA-LTO project addresses these issues through research on the thermal ageing of materials in VVER reactors and by identifying the most critical components from the perspective of LTO. Furthermore, the project aims to develop non-destructive testing (NDT) techniques, simulation tools, and methodologies that can be used for the early prediction of potential failures. The future application of these measures would allow operators to make informed decisions about future operations, ensuring a safe and reliable extension of the NPP's lifetime.

The DELISA-LTO project is organized into six work packages (WPs) focusing on particular works that contribute to extending the safe operational lifetime of NPPs. The WPs and their connections are shown in Figure 5. WP1, led by CVŘ (the Czech Republic), is dedicated to project management, ensuring seamless coordination among partners and monitoring technical progress. WP2, under VUJE's leadership (Slovakia), concentrates on collecting and analyzing data on reactor components' degradation mechanisms and developing robust material testing methodologies. WP3, led by SSTC (Ukraine), focuses on the simulation and modelling of material degradation processes, such as swelling and thermal ageing, providing predictive insights into material behavior during LTO. WP4, managed by UJV (the Czech Republic), is tasked with experimental validation, utilizing materials aged in NPPS to verify the accuracy of the simulation models and NDT methods. WP5, under EK-CER's guidance (Hungary), synthesizes the results from the previous WPs to formulate comprehensive guidelines for safe LTO. Finally, WP6, led by STUBA (Slovakia), emphasizes dissemination, education, and training, ensuring that the project's findings are shared with the broader nuclear community and that the next generation of engineers is well-versed in the newly developed methodologies and technologies. The project also involved other partners: VTT from Finland, IPP from Ukraine and BZN from Hungary.

These nine institutes in the DELISA-LTO project are working to enhance the longevity and safety of VVER nuclear power plants, mainly by applying advanced NDT techniques, simulation tools, and experimental validation to ensure that reactors can operate safely beyond their original design limits. The project contributes to Europe's energy sector's safety, sustainability, and efficiency by addressing key material degradation challenges and can provide clear guidelines for the industry.

3.1 Methodology

The DELISA-LTO project adopts a comprehensive methodology to address the critical challenges of thermal ageing and swelling in VVER components. Through advanced testing, simulations, and planned preparation of guidelines, the project can help predict material failure, ensure components' reliability and integrity, and provide safe LTO of NPP. There are four main parts of the project: thermal ageing, swelling, non-destructive testing and synthesis of guidelines.

3.1.1 Thermal ageing

Thermal ageing and irradiation embrittlement of critical components are central concerns for NPPs operating beyond their intended design lifetime. While irradiation embrittlement can partially be recovered, the effect of thermal ageing is not well known. The DELISA-LTO project aims to predict thermal embrittlement and its trend thanks to planned experimental testing of material exposed to thermal ageing in NPP and observation of thermal ageing simulated in the laboratory. The experimental efforts are designed to comprehensively evaluate changes in material properties due to thermal ageing in components (main circulation piping, pressurizer surge line, heat exchange tubes and collector of steam generator, etc.) from decommissioned NPP V1 Jaslovské Bohunice (Slovakia) after 28 years of operation. Microstructural analysis using high-resolution microscopy (such as TEM and SEM) identifies grain boundary-level changes. At the same time, mechanical testing, including tensile strength and fracture toughness assessments, quantifies the impact of thermal ageing on the structural integrity of reactor materials. The program also employs novel techniques like nano-indentation and the small punch test (SPT) to provide detailed insights into phase changes and mechanical properties on a microscale level.

To enhance understanding of thermal ageing and determine Thermal Ageing Trend Equations (TATE), a laboratory simulation of thermal ageing is planned to predict embrittlement, hardening, and loss of corrosion resistance in steels operated for 60 years. According to the Arrhenius equation, ageing at 295°C for 30 years is equivalent to accelerated annealing at 420°C for 90 days. The similarity of the thermal ageing trends due to laboratory accelerated ageing and natural ageing in NPP can be verified by the experiments with the material in its initial state (without previous thermal strain). The software modelling of thermal ageing is also part of the project and can support experimental results. If the measured and modelled trends agree, further accelerated annealing can reliably indicate the state of the material after 60 years.

3.1.2 Irradiation swelling

Irradiation swelling of reactor internals presents another critical challenge from the view of the LTO of NPP. In particular, the reactor core baffle, exposed to high irradiation levels, is susceptible to deformation due to swelling and creep. The DELISA-LTO project systematically addresses these issues through benchmarking, modelling and experimental validation.

The main objective of swelling research is to develop and validate a detailed finite element model for predicting swelling under actual operating conditions. The model incorporates dose distribution, temperature gradients, and stress-strain interactions to simulate the effects of irradiation over time. This model uses mechanical analysis tools to assess the influence of stress-dependent irradiation swelling and creep on reactor internals, mainly focusing on areas vulnerable to deformation and failure.

3.1.3 Non-destructive testing (NDT)

NDT methods are crucial for evaluating the condition of nuclear components without causing damage. In DELISA-LTO, several advanced NDT techniques are tested and refined to enhance their effectiveness for NPP inspections. The work focuses on developing and optimizing techniques such as Eddy Current Inspection, Ultrasonic Testing, Metal Magnetic Memory Testing, and Non-linear Elastic Wave Spectroscopy. These methods should be validated against known material defects, and their efficacy can be assessed through simulation models. The simulation of Ultrasonic Testing is planned to refine defect detection capabilities, using phase-controlled heads to achieve better precision in identifying material weaknesses. The new NDT technique plans to be tested on the heat exchanger at the Maintenance Training Centre of MVK Paks NPP (Hungary) to demonstrate its functionality and practical applicability.

3.1.4 Synthesis of guidelines

The results gained from WP3 (Simulation and modelling) and WP4 (Experimental validation and test) can be supplemented by knowledge collected from ongoing EC-funded projects and a database of publications relevant to the DELISA-LTO project (Task in WP6). All information is planned to be treated and synthesized into comprehensive guidelines for the safe long-term operation of nuclear reactors. These guidelines should be harmonized with existing national and international standards. By working closely with regulatory bodies and the nuclear industry, DELISA-LTO aims to contribute to developing new safety regulations, ensuring that the lessons learned from the project are implemented in future reactor operations.

3.2 Progress

In WP2, the identification of critical NPP components from the view of LTO was performed through communication with partners and vendors by survey. The critical components were indicated: reactor pressure vessel, reactor internals, heat exchange tubes in the steam generator and welds, mainly dissimilar ones [20] (Deliverables D2.1). Further, the harmonization of methodologies for destructive experimental techniques was performed to consolidate experimental works in WP4 and implement the interlaboratory study. Creating cutting schemes of experimental materials (Fig. 6) within this WP was more time-consuming due to accommodating all partners' requirements for their measurement techniques and the demand for the material amount. Research materials were successfully distributed to partners according to plan in May 2024.

The operational practice investigated within WP2 showed that heat-exchanging tubes in VVER steam generators experience degradation primarily due to increased power output, extended operational periods, secondary water chemistry, and mechanical impacts from repairs. In Slovakia, damage is commonly found at the tube support plates and the tube-collector transition area, with Eddy Current Testing (ECT) techniques such as the MRPC probe used for inspections. Ukraine faces corrosion-related damage, often caused by chlorine ions and oxygen, with periodic ECT inspections identifying wall loss and stress corrosion cracking (SCC). In Hungary, most defects are detected on the outer surfaces of tubes, particularly at the support plates, with SCC as the predominant mechanism. Across these countries, ECT inspections are optimized to prevent premature tube plugging and unplanned reactor shutdowns, focusing on stress corrosion cracking and pitting as the fundamental degradation mechanisms.

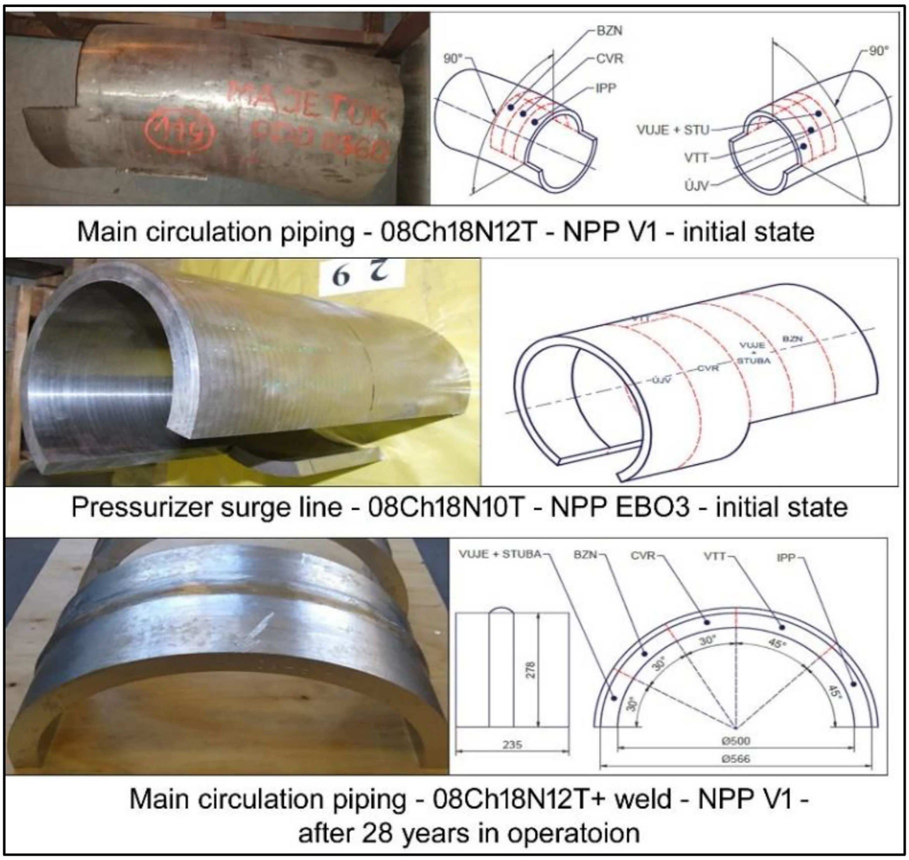

Fig. 6. Example of the NPP aged materials and their cutting schemes.

The NPP V1 Jaslovske Bohunice heat exchange tubes were used to improve non-destructive testing (NDT) methods (Deliverables D2.4). A total of 26 tube fragments from 2 steam generators were examined. Elevated pH and specific chemical treatments helped control corrosion and deposits at NPP V1 Jaslovske Bohunice. In 2004, 39 tubes in one steam generator showed signs of wall thickness reduction, with stress corrosion cracking confirmed (Fig. 7). Most damage occurred on the exterior surfaces due to secondary circuit conditions, while internal defects were linked to manufacturing issues.

In WP3, all participants provided comprehensive and technically reliable results for the 2D simplified benchmark for the modelling of the baffle, with substantial agreement among the outcomes. Several conclusions can be drawn from the analyzed data. The maximum temperature of 385 ° C was reached at the midpoint of the first ligament. The maximum volumetric swelling strain, approximately 6% after the 60th campaign (Fig. 8), also occurred at the midpoint of the first ligament. Creep deformations exhibited an accelerating trend during NPP operation. The maximum equivalent creep strain, around 2.5% after the 60th campaign, was observed at the midpoint of the first ligament. That was attributed to the peak temperature, swelling strain, and the maximum displacements per atom (dpa) occurring at this location.

In the first period of WP4, an experimental matrix was developed from NPP V1 Jaslovské Bohunice (Slovakia) materials, and it was supplemented with materials from NPP Paks (Hungary) and VVER-1000 (Ukraine) as is detailed described in Deliverable D4.4. Within that matrix, experimental methods and partners' responsibility for individual measurement were added according to the broad discussion within the DELISA-LTO project. All partners involved in WP4 received the materials according to the schedule, and the experimental phase of the WP4 commenced.

The first task of WP5, "Collecting guidelines based on the key structures, systems, and components", was performed by a survey attended by all partners (Deliverables D5.2). The primary objective of this task was to gather guidelines, reports, and good practices related to critical components, materials, and monitoring methods for managing swelling and thermal ageing phenomena during the LTO of NPP. According to the provided information, critical components for long-term operation include the steam generator (with heat-exchange tubes), the pressurizer, and primary loop pipes, which are critical regarding thermal ageing. Reactor internals, mainly baffle, are identified as crucial components concerning swelling. These components are incorporated into ageing management programs and related Time-limited ageing analyses to ensure the reliability of LTO across all participating countries.

For good practice in swelling, visual inspections, measurements of the core baffle's geometry, and

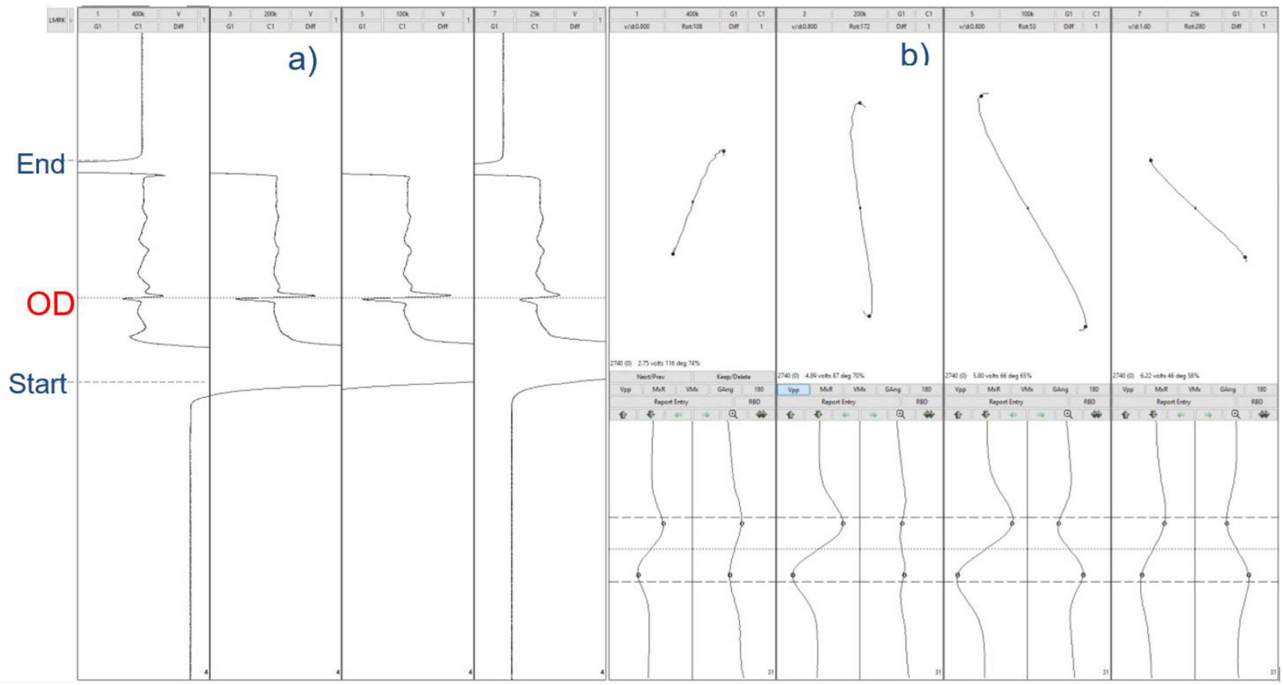

Fig. 7. Data from the Eddy Current testing (ECT) by Bobbin probe at various frequencies (Start-End) show a defect on the outer surface (OD) of the measured steam generator tube from NPP Bohunice V1. The eddy current signal is visualized as: a) a linear progression over time of individual signal components with the axial position of the indication, and b) the display of indication in the $X-Y$ plane (a complex impedance plane). The parameters of indication for the main measurement frequency $f = 200\,\text{kHz}$ are $A = 4.89$ [V], phase = 87 [°], wall thickness loss = 70%. Peak-to-Peak Voltage (Vpp) measurement mode used.

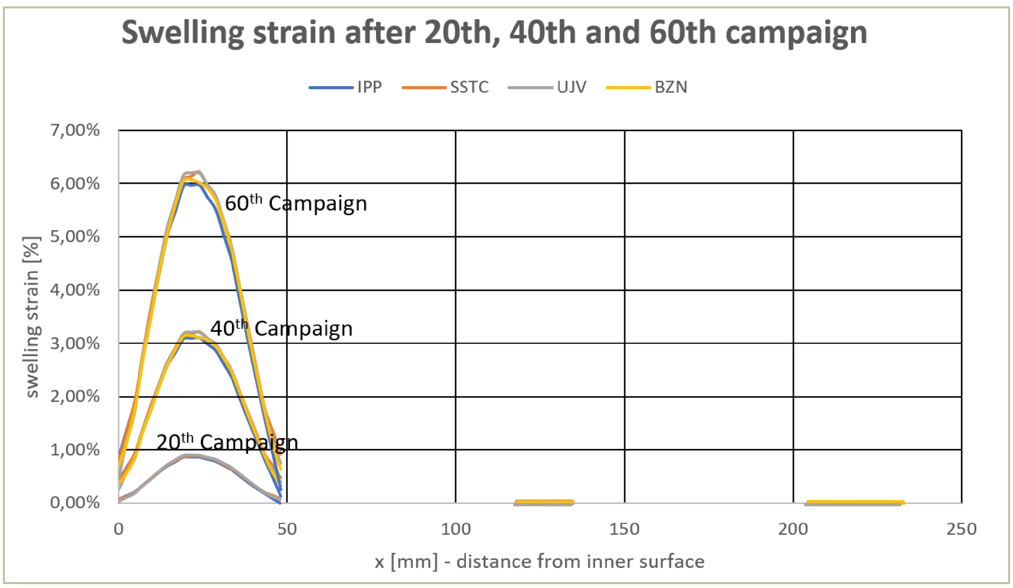

Fig. 8. Comparison of swelling strain profiles in radial cross-section in symmetry plane across 2 channels after 20th, 40th and 60th campaigns calculated by institutions IPP, SSTC, UJV and BZN.

comparisons with calculated estimates are conducted during shutdowns to assess inaccessible areas of the baffle. In monitoring thermal ageing, periodic non-destructive methods, hardness measurements, and defect monitoring in heat exchange tubes are commonly used and supplemented by destructive methods. Visual inspections and standard techniques are not sensitive enough to incipient cracks. Accurate crack characterization and size determination are best achieved through ultrasonic volumetric testing. According to the practice, the components made from 08Kh18N10TL austenitic steel are susceptible to thermal embrittlement and ageing, which should be studied in detail within WP4.

The survey highlights that all participating countries have successfully developed and implemented advanced regulations and guidelines to support licensing and ageing management for long-term operation.

Within WP6, the database of relevant publications to the DELISA-LTO project was formed (Deliverables D6.2) to support other WPs and for knowledge spreading. Communication with vendors and regulatory authorities has started, primarily performed nationally, and the list of contacts for all partner countries is being prepared. The dissemination of knowledge to young professionals and students is regularly through lectures and presentations at the University and by organizing the first Workshop on Integrity Assessment of Main Structural Components Using Decommissioned Bohunice V1-NPP in February 2023 [21].

More information about the DELISA-LTO project and its deliverables can be found at https://delisa-lto.eu/.

3.3 Summary

The DELISA-LTO project focuses on ensuring the safe and reliable LTO of NPPs by addressing signs of material ageing such as thermal embrittlement and swelling. Through collaboration between the EU countries operating VVER reactors, the project aims are to collect and implement best practices, guidelines, prepare a basement for future advanced monitoring methods to manage the ageing of critical components. Supported by the European Union, DELISA-LTO enhances regulatory frameworks and technical assessments essential for nuclear safety during extended plant lifetimes.

4 EVEREST

The EVEREST project (Experiments for Validation and Enhancement of Reactor Pressure Vessel Fluence Assessment) started in September 2024. The essence of the project is to demonstrate the usefulness of advanced multi-physics simulation platforms for core internals and vessel fluence calculation and their trustworthiness through the production of dedicated experimental data. Advanced multi physics simulation tools are neutron transport codes (Monte Carlo and deterministic) coupled to subchannel thermal hydraulic codes. The propagation of the neutron source towards the vessel is carried out using Monte Carlo codes including variance reduction techniques.

Specifically, the project is aimed at:

a) performing a detailed and systematic analysis of the impact of using the advanced multi-physics platforms; instead of a conventional approach for the vessel fluence calculation of three operated PWR cycles, including a VVER-440 plant. This analysis will focus on the computational biases associated with the neutron source determination together with the propagation of input data uncertainty through the neutron source determination and subsequent shielding calculations;
b) producing experimental data relevant for validation of an advanced multi-physics scheme, especially the simulation of local parameters; by doing so addressing the issue of scarcity for this type of measurement data. This experimental data is paramount to using those codes for practical applications, as to this day, it is very unclear if the additional information (improved resolution) obtained with the advanced multi-physics codes can be trusted.

The final goal of this project is to generate relevant knowledge on the topic that can assist the international community in adopting best practices for safety analysis in LTO by ensuring the uptake of the advanced modelling approach by key groups (both industrials and regulators) in Europe; and providing training to them.

Currently, the European NPP fleet has an average age of 36 years, while the NPP considered in the proposal are even older. Those NPP are:

- The Beznau Nuclear Power Plant Unit 1 (Switzerland), a 2-loop PWR with 121 rectangular fuel elements, commissioned in 1969.
- The Grohnde Nuclear Power Plant (Germany), a Vor-Konvoi PWR with 193 rectangular fuel elements, commissioned in 1975 and decommissioned in 2021 after more than 46 years of operation.
- The Paks Nuclear Power Plant Unit 1 (Hungary), a VVER440 PWR with 349 hexagonal fuel elements, commissioned in 1983.

The purpose of the case study for each reactor is to demonstrate unequivocally the impact of using advanced MP tools instead of the conventional approach for core internal and vessel fluence assessment, focusing on two aspects. First, EVEREST will provide a comparison with the core cycle measurements in order to demonstrate the accuracy of both the conventional and advanced MP computational schemes; second, a code-to-code comparison with as consistent as possible specifications in both modelling approaches. The goal is to produce a quantitative assessment of the modelling biases introduced by the conventional approach when computing the neutron source in shielding calculations. The idea is not to discuss the respective merits of damage factors against 1 MeV neutron fluence to estimate the degradation of the pressure vessel under irradiation but to understand better what would change if one would use advanced MP computational schemes instead of the conventional ones.

Two scales of reactors (large and medium-size reactors) were selected to provide insight into the sensitivity of the computational schemes to neutron leakage, increased by smaller core dimensions (the smaller a reactor core, the larger the neutron leakage across the core boundaries and the potential to induce neutron damage).

Tackling point b) is challenging since operating NPPs historically have been the primary provider of experimental data to validate multi-physics simulations. However, these data are not suitable for the validation of the advanced approach as they are limited in spatial resolution. Research reactors offer more flexibility in what could be done in terms of resolution, but they do not offer the same conditions that one will encounter in an NPP. Therefore, the approach applied by EVEREST relies on a staged, modelling- informed experimental design to maximize the value of the produced measurements.

In the first stage, multi-physics measurements will be carried out at each research reactor producing a significant amount of power involved in the consortium. The obtained experimental data are then used to validate a set of multi-physics models based both on conventional and advanced approaches. In a second stage, these models will be used to design new experimental setups at the same research reactors, targeting the following points:

- maximum achievable temperature;
- strongest temperature and neutron flux gradients;
- measurements done at location where the predictions of conventional vs. advanced multi-physics methods differ the most;
- maximization of the representativity metric [22] between the research reactors (usually pool type reactors, functioning at low temperature and atmospheric pressure) and NPPs.

The new instrumentation will be deployed and tested, first in low flux conditions of a zero-power research reactor and then at power conditions in one of the suitable research reactors. All this will be done to increase resolution and reduce the experimental uncertainties. The desired outcome is a set of experimental data suitable, on the one hand, to discriminate between conventional and advanced approaches on equivalent quantities; on the other hand, to assess the accuracy/precision of the advanced model for the local quantities such as the power produced at the fuel rod level. This exercise will also provide a set of advanced multi-physics models for the research reactors allowing safer, more economical and flexible use of those installations (for example, power uprate or life-time extension with extended experimental repertoire of the facilities).

4.1 Methodology

The methodology of the EVEREST project is built around three core pillars: comparison of modelling approaches, experimental validation, and knowledge dissemination. The first research thrust involves comparing conventional and advanced MP approaches through the realization of fluence assessments for three specific pressurized water reactors (PWRs). This includes a VVER-440 reactor, the Paks Nuclear Power Plant in Hungary. The goal is to compare the results of conventional fluence models, with the results produced by advanced MP models that offer subpin level resolution. This allows the project to quantify the computational biases inherent in conventional approaches and assess the added value of high-resolution high-fidelity advanced MP models.

The second research axis of EVEREST seeks to produce dedicated experimental validation with research reactors; data suitable for the validation of the advanced MP models. Within the project, experiments in research reactors will be conducted. at the BME reactor, the Budapest Research Reactor (BRR) and the JSI TRIGA reactor, to generate datasets that mirror the conditions found in full-scale PWRs. These experiments focus on measuring neutron flux and temperature distributions within the core, as well as studying material responses to prolonged neutron exposure. The data collected from these experiments are then used to verify and improve the MP models, ensuring that they accurately reflect real-world conditions.

The third pilar of the project consists in activities related to dissemination and training. A key aspect of the EVEREST project is ensuring that the advancements in fluence assessment techniques are adopted by the wider nuclear community. To this end, the project organizes workshops, summer schools, and training programs that aim to educate nuclear professionals, utility operators, and regulators on the use of MP tools for fluence assessments. By engaging with stakeholders early in the process, EVEREST aims to ensure that its findings are implemented in long-term operation strategies.

The workflow envisioned during the project is shown in Figure 9.

The main expected outcomes of the EVEREST project are the production and validation of advanced multi-physics models of research reactors. Those models are, in turn, used to maximize the potential of the research reactors to produce relevant experimental data for the validation of advanced models of pressurized water type of nuclear power plants. The benefits of using advanced reactor models are then quantified by comparison with the conventional approach for the vessel fluence assessment of three operated PWR cycles, for which data is provided by industrial members of the consortium. The organization of the project follows the logical structure of these concepts: (a) assessment of the impact of using conventional vs advanced multi-physics models for neutron source determination at the fuel rod level; (b) generation of validated advanced multi-physics models of research reactors, (c) production of tailored high-resolution experimental data for validation of the local prediction capabilities of these advanced models. The three areas above represent the three technical Work Packages (WPs) of EVEREST. An Education & training & dissemination WP complement these work packages where the uptake by key groups (regulators, industrials, students and the general public) is pursued to promote the use of such methods.

Besides the data of three operating and operated NPP, the project makes use of four research facilities to achieve these goals: three research reactors producing a significant amount of power to allow observing a multi-physics behavior, as well as a zero-power facility. The Training Reactor (TR) of BME is a light-water moderated and cooled reactor of 100 kW nominal thermal power. The TRIGA Mark II research reactor of JSI is a pool type reactor of 250 kW nominal power. It is well characterized in terms of neutron and gamma fields; it is also capable of pulse mode operation. The Budapest Research Reactor (BRR) is a light water-cooled, light water-moderated reactor of 10MW nominal thermal power. The zero-power facility CROCUS of EPFL will be involved for the purpose of testing the performance of the new instrumentation (neutron flux and temperature measurement) under irradiation.

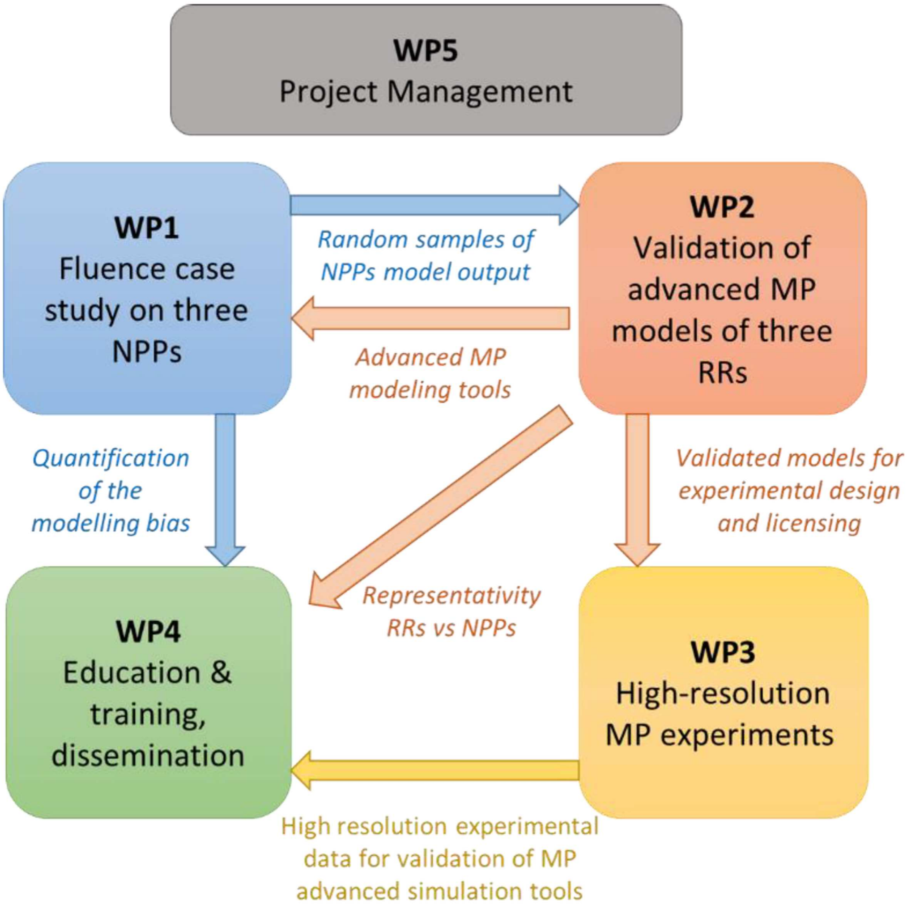

Fig. 9. EVEREST Workflow - Bridging MP Modelling and Validation for RPV Fluence.

As the objective of the project is to demonstrate the usefulness and trustworthiness of advanced MP models of NPPs and research reactors, the definition of pertinent quantities of interest is of paramount importance to the achievement of those goals. EVEREST focuses on local quantities that are relevant to core internals and vessel fluence assessment, namely the neutron source term at the fuel rod level. Concerning the research reactors, the quantities of interest are the distribution of coolant temperature and neutron flux throughout the core and in its vicinity.

EVEREST relies on diversity and redundancy both in terms of modelling (conventional and advanced simulation tools, uncertainty propagation) and measurements (numerous NPPs and research facilities, variety of detectors and experimental techniques) to reach its objectives and mitigate the risks associated with the project. On the modelling side, care is given to reach an acceptable compromise between the costs of redundancy with the benefits of diversity. On the experimental side, the chosen approach is to include as many diverse research reactors as possible as the risks of delay and/or failure to deliver are higher. Moreover, the modeler and experimentalist communities involved in the project agree that more experimental data can only add value to the project, improve robustness and increase the trust in results down the line.

More information about the EVEREST project can be found at https://projecteverest.eu/.

5 Synergies between CAMIVVER, DELISA-LTO and EVEREST

One of the key synergies between the EVEREST, DELISA-LTO, and CAMIVVER projects is their shared focus on VVER reactors. VVER reactors are unique in their design and operational characteristics, and all three projects are tailored to address the specific challenges associated with extending the operational life of these reactors. By focusing on VVER reactors, the projects ensure that their advancements in material aging understanding, experimental data, and high-fidelity simulation tools directly benefit VVER operators in Europe. This shared focus allows the projects to pool their resources and expertise, creating a more comprehensive approach to managing VVER long-term operation and reactor aging.

First, the projects propose complementary approaches to material aging. Both DELISA-LTO and CAMIVVER focus on understanding and mitigating the effects of material aging in VVER reactors, but they approach the problem from different angles. DELISA-LTO takes an experimental approach by studying thermal aging and irradiation effects through direct and non-destructive testing (NDT) techniques. Meanwhile, CAMIVVER and EVEREST complements this work by developing and validating advanced simulation tools that can produce more accurate information about parameters that affect how materials degrade over time. The experimental data generated by DELISA-LTO could be fed into CAMIVVER and EVEREST's models, ensuring that the simulations are based on real-world data. This synergy between experimental testing and simulation modelling creates a more robust framework for managing material aging in VVER reactors, helping operators extend the life of their reactors while maintaining safety.

Additionally, both EVEREST and CAMIVVER share a strong focus on multi-physics modelling, which is essential for accurately predicting the behavior of reactor components under normal and abnormal conditions. EVEREST focuses on applying MP models to improve RPV fluence assessments, while CAMIVVER uses similar tools to model a broader range of reactor behaviors, including fuel cycle management and core monitoring. The data generated by EVEREST's high-resolution experiments provide valuable insights that can be used to validate CAMIVVER's models, particularly in terms of neutron flux and temperature distributions.

Finally, a key synergy between the three projects is their focus on knowledge sharing and collaboration. By organizing workshops, training sessions, and summer schools, the projects ensure that their findings are widely disseminated to the nuclear community. The training programs offered by EVEREST on multi-physics modelling are highly relevant for professionals working on DELISA-LTO's material degradation studies and CAMIVVER's numerical tools development.

The EVEREST, DELISA-LTO, and CAMIVVER projects represent a comprehensive and coordinated effort to address the challenges of long-term operation and material aging in VVER reactors. By focusing on different aspects of reactor safety–such as material degradation, RPV fluence assessment, and advanced simulation tools–these projects collectively provide a robust framework for extending the operational life of VVER reactors.

In this paper, "synergies" does not refer to a sequential relationship in which the output of one project serves as the input for another. Instead, it aligns with its fundamental definition, signifying that the collaboration between two projects yields a combined outcome that exceeds the sum of their individual contributions. For instance, the expertise acquired in advanced VVER modeling during the CAMIVVER project will contribute to a faster and more efficient development of advanced models in the EVEREST project.

6 Conclusions

The EVEREST, DELISA-LTO, and CAMIVVER projects represent a comprehensive and coordinated effort to address the challenges of long-term operation and material aging in VVER reactors. By focusing on different aspects of reactor safety–such as material degradation, RPV fluence assessment, and advanced simulation tools–these projects collectively provide a robust framework for extending the operational life of VVER reactors.

More specifically, the industrial outcome of each project is (or will be) the following:

- CAMIVVER was a step forward in reactor modelling and methods development with industrial application in mind, and was expected to be carried on in the frame of another project with new European partners. The new proposal has not been selected; a new trial will be prepared for the next call.
- The DELISA-LTO project enhances NDT techniques like eddy current testing for defects detecting in SG tubes on time, preventing unexpected shutdowns. It also develops simulation tools to predict material degradation and avoid failures in NPPs due to thermal ageing, core barrel and baffle swelling. The project's results can also lead to updated guidelines and standards for ageing management for VVER technology.
- In EVEREST, neutron fluence estimates for reactor pressure vessels will be produced using advanced methods, improving computational accuracy and reliability for nuclear power plant applications, possibly allowing operating the considered plants longer.

The synergies between the projects, particularly in the areas of multi-physics modelling, and through the production of dedicated experimental data, ensure that advancements made are complementary and produce useful knowledge towards safe lifetime extension of NPPs. Through their shared focus on VVER reactors, these projects contribute to Europe's broader energy security goals by ensuring that its nuclear power plants can continue to operate safely and efficiently for decades to come.

By fostering collaboration between industry, academia, and regulatory bodies, and by training the next generation of nuclear engineers, the EVEREST, DELISA-LTO, and CAMIVVER projects help build a sustainable and secure future for nuclear energy in Europe.

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Conflicts of interest

The authors have nothing to disclose.

Data availability statement

Data associated with this article cannot be disclosed due to legal/ethical/other reason.

Author contribution statement

All authors contributed equally.

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