Multiphysics Analysis of CABRI Power Transients through APOLLO3®–CATHARE3 Coupling via the C3PO Platform

Heesang Yoo[a], Jonathan Debove[a*], Claire Vaglio-Gaudard[a], Jean-Marc Labit[b]
[a] *CEA, DES, IRESNE, DER, SESI, Cadarache, 13108 Saint Paul lez Durance, France*
[b] *CEA, DES, ISAS, DM2S, STMF, Saclay F-91191 Gif-sur-Yvette, France*
[*]Corresponding author: jonathan.debove@cea.fr

Keywords : Multiphysics, C3PO, Reactivity Initiated Accident (RIA), CABRI research reactor

1. Introduction

The growing demand for high-fidelity predictive tools in nuclear engineering has driven the development of multiphysics frameworks that consistently couple reactor physics, thermal-hydraulics (TH), fuel behavior, and structural mechanics. These frameworks generally rely on two key elements: coupling infrastructures for code-to-code communication and application-oriented workflows supported by experimental validation [1].

Within this context, building on its previous European collaborative projects, CEA developed the C3PO (Collaborative Code Coupling Platform) to couple next-generation CEA simulation codes and support multiphysics reactor analyses [2].

Despite these developments, validation of fully coupled applications, implementing modeling with a pin-scale resolution, remains limited because well-instrumented integral experiments involving strong feedback effects are scarce, while obtaining such data from current Nuclear Power Plants (NPPs) is not possible. The CABRI reactor was originally designed to perform fuel performance tests under PWR-representative reactivity-initiated accident conditions. In addition, its controlled power transients, characterized by rapid power excursions and mainly Doppler feedback, provide valuable data for multiphysics validation [3].

This study applies the C3PO-based APOLLO3®–CATHARE3 coupling to CABRI transients. The results are compared with experimental data, and previous studies including APOLLO3®–THEDI calculations [4,5], and stand-alone CATHARE2 simulations [6] to assess the benefits of a more consistent integration of neutronics and system thermal-hydraulics.

2. CABRI Transients

This section briefly introduces the CABRI facility and summarizes the main characteristics of CABRI RIA (Reactivity Initiated Accident) transients.

2.1 CABRI Facility

The CABRI facility is a pool-type research reactor dedicated to nuclear safety studies and was originally developed for RIA experiments carried out in a test loop located at the core center and containing a sample of irradiated PWR fuel rods. The core consists of stainless-steel-clad UO_2 fuel rods enriched to 6 wt% ^{235}U and can operate at a maximum steady-state power of 25 MW. Core reactivity is controlled by six bundles, each composed of 23 hafnium control and safety rods. A distinctive feature of CABRI is its rapid reactivity insertion system, which comprises four transient assemblies equipped with 24 ^{3}He-filled tubes each. These tubes can be pressurized up to 15 bar and rapidly depressurized to produce a controlled reactivity insertion (since ^{3}He is a stong absorber), enabling highly reproducible power transients [7].

2.2 Transient Scenarios

CABRI RIA transients involve tightly coupled neutronic and thermal-hydraulic phenomena initiated by rapid ^{3}He depressurization. The resulting positive reactivity insertion causes a sharp power rise, which is rapidly suppressed by negative fuel Doppler feedback. Because heat transfer to the cladding and coolant occurs more slowly, structural expansion and coolant feedback remain limited during the short power pulse. In high-energy transients, however, heat released by neutron capture in ^{3}He-filled tubes can further reduce the absorber density and generate a secondary power bump, known as the TOP effect. Previous event-tree and QPIRT analyses provide guidance for identifying and ranking these dominant phenomena [6].

3. Methodology

For the analysis of CABRI RIA transients, the French reference codes APOLLO3® [8] and CATHARE3 [9] are coupled through the C3PO platform [2]. This section briefly introduces the C3PO platform and describes the coupling strategy implemented between the two codes.

3.1 C3PO Platform

C3PO is an open-source Python-based platform developed at CEA to support standardized multiphysics coupling [2]. It relies on the ICoCo (Interface for Code Coupling) standard [10] for solver communication and the SALOME MEDCoupling library [11] for mesh and field data exchanges. By providing a generic structure

for coupling workflows, C3PO enables different simulation codes to be integrated flexibly without modifications of the original solvers.

The platform is built around three main capabilities: standardized solver interactions through ICoCo, consistent mesh and field exchanges using the MED data format, and a time-management module that coordinates the coupled solvers. **Figure 1** presents the overall coupling philosophy, including the ICoCo interface on the left and the mesh-mapping procedure on the right.

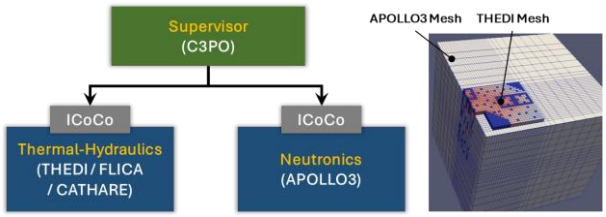


Fig. 1. Key features of the C3PO platform: standardized code coupling through the ICoCo API (*left*) and mesh mapping using SALOME MEDCoupling (*right*) for LWR simulation.

3.2 APOLLO3®/CATHARE3 coupling strategy

As illustrated in **Fig. 2**, APOLLO3® performs the quarter-core neutronics calculation, while CATHARE3 simulates the entire CABRI system. The two models are coupled through the core region, where the spatial power distribution and thermal-hydraulic feedback variables are exchanged.

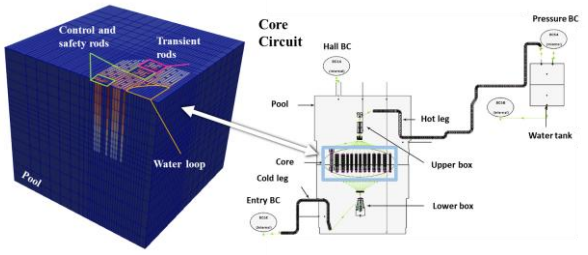


Fig. 2. APOLLO3® quarter-core mesh (*left*) and CATHARE3 system-level nodalization (*right*)

APOLLO3®: Neutronics simulation relies on a two-step calculation scheme. Lattice calculations based on the European JEFF-3.1.1 nuclear data library generate the input data for the core calculation in the form of MPOs (Multi-Parameter Outputs). The MPOs contain pin-wise nuclear data collapsed in space and energy and parameterized by fuel temperature, coolant conditions, ^{3}He density, and control-rod state. These data are then used in eight-energy group, quarter-core SP_3 calculations [4].

CATHARE3: CABRI is modeled with PALANTIR, adapted from the original CATHARE2 model. It represents both the core and the transient-rod depressurization system responsible for reactivity insertion [6].

Coupling strategy: APOLLO3® and CATHARE3 are coupled through C3PO. Steady state is obtained by fixed-point iterations, while transients use an explicit Gauss–Seidel sequence. APOLLO3® provides the power distribution, and CATHARE3 returns the thermal-hydraulic feedback and ^{3}He density.

4. Results

This section presents the results obtained using the coupled APOLLO3®–CATHARE3 model through comparisons with previous numerical studies and available experimental data. The previous numerical studies include 1/ standalone CATHARE2 calculations, in which the entire CABRI system is represented using a one-dimensional model [6], and 2/ the coupled APOLLO3®–THEDI model [5], in which only the core region is modeled for thermal-hydraulics with one-dimensional code THEDI [12]. In the APOLLO3®–THEDI coupling, the depressurization history is imposed as a spatially uniform boundary condition derived from the standalone CATHARE2 calculation.

4.1 Steady-state Calculations

The coupled APOLLO3®–CATHARE3 model was first verified under steady-state conditions through comparison with the previously developed APOLLO3®–THEDI model. The calculations were performed at the same core power of 25 MW while varying the ^{3}He pressure.

Figure 3(a) compares the effective multiplication factors (k_{eff}) calculated by the two models. The results show very good agreement over the entire ^{3}He pressure range. The corresponding reactivity difference remains between 37.5 and 55 pcm, confirming the consistency of the coupled APOLLO3®–CATHARE3 model with the previous APOLLO3®–THEDI model.

Figure 3(b) presents the core-averaged fuel temperatures calculated by the two models. Because the total core power was fixed at 25 MW, variations in the ^{3}He pressure had only a limited effect on the core-averaged temperatures. The fuel temperature differences with the two models remained below approximately 0.8% over the investigated pressure range.

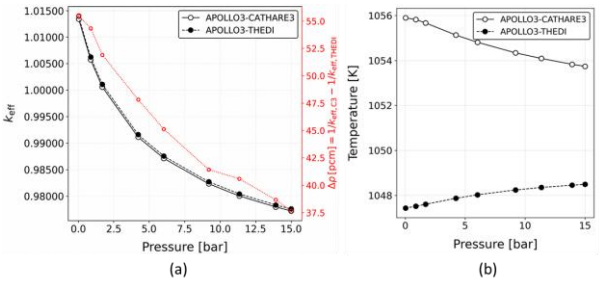


Fig. 3. Steady-state comparison between the APOLLO3®–CATHARE3 and APOLLO3®–THEDI models as a function of ^{3}He pressure: (a) k_{eff} and reactivity difference, and (b) core-

averaged fuel temperature.

4.2 Transient-state Calculations

Various power-pulse transients were investigated. Four representative cases are presented in this paper.

- **Case 1**: Reactivity Insertion without Feedback

In Case 1, approximately 0.6$ of reactivity was inserted gradually within 0.1 s, and the resulting Doppler feedback had only a negligible effect on the transient behavior. **Figure 4(a)** shows that APOLLO3®–CATHARE3 predicts the pressure evolution consistently with standalone CATHARE2. The calculated power histories also agree well with the experimental data as in **Fig.4(b)**. The coupled APOLLO3®–THEDI and APOLLO3®–CATHARE3 results are only slightly lower than the standalone APOLLO3®, confirming that the influence of Doppler feedback is very limited in this case. The deposited energy predicted by APOLLO3®–CATHARE3 during the first 1 s differs from the experimental value by approximately 1.5%.

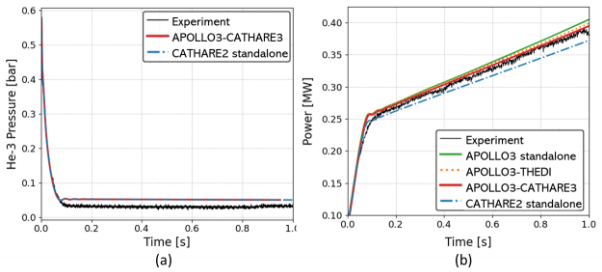


Fig4. Comparison of the simulated and experimental time histories of (a) ^{3}He pressure and (b) reactor power for Case 1.

- **Case 2**: Reactivity Insertion with Feedback

In this case, approximately 1.8$ of reactivity is inserted within 0.1 s. As shown in **Fig. 5(a)**, the predicted pressure evolution agrees well with the experimental data. **Figure 5(b)** shows that strong feedback suppresses the power increase, with the power peaking near 0.09 s. APOLLO3®–CATHARE3 agrees better with the experiment than previous APOLLO3®–THEDI result, with peak-power errors of approximately 35% and 50%, respectively. APOLLO3®–CATHARE3 also predicts the peak timing more accurately because its full-system modeling captures local helium-pressure variations, while APOLLO3®–THEDI uses a simplified, spatially uniform helium-pressure boundary condition derived from the standalone CATHARE2 calculation.

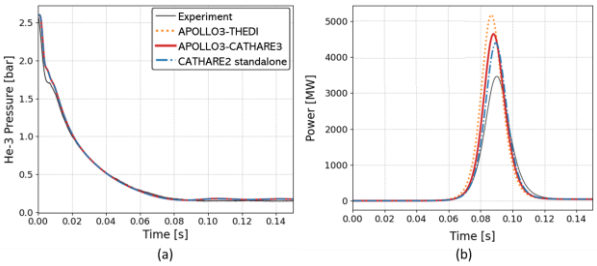


Fig5. Comparison of the simulated and experimental time histories of (a) ^{3}He pressure and (b) reactor power for Case 2.

- **Case 3**: Reactivity Insertion with Feedback and TOP Effect

In this case, approximately 3.3$ of reactivity is inserted within 0.1 s. Owing to the high deposited energy, a transient overpressure (TOP) effect appears as a noticeable pressure bump in **Fig. 6(a)**, while the corresponding power evolution is shown in **Fig. 6(b)**. All three approaches reproduce the power-peak timing within approximately 4% error. The peak-power errors are approximately 23% for APOLLO3®–THEDI, 13% for PALANTIR, and 9% for APOLLO3®–CATHARE3. As in **Case 2**, the better agreement of PALANTIR and APOLLO3®–CATHARE3 is attributed to full-system modeling, which captures local helium-pressure variations.

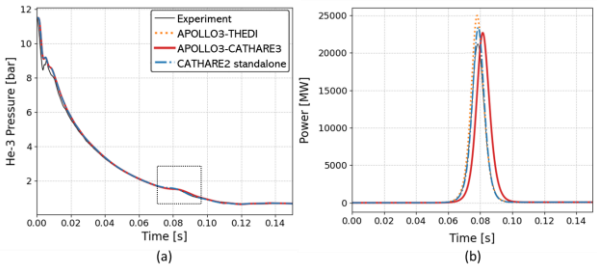


Fig6. Comparison of the simulated and experimental time histories of (a) ^{3}He pressure and (b) reactor power for Case 3.

- **Case 4**: Slower Reactivity Insertion with Feedback and TOP Effect

In Case 4, approximately 2.7$ of reactivity is inserted within 0.4 s. As shown in **Fig. 7(a)**, the predicted pressure evolution agrees well with the experimental data. **Figure 7(b)** compares the power histories obtained using standalone CATHARE2 and APOLLO3®–CATHARE3. The standalone CATHARE2 calculation shows a peak-power error of approximately 50%, whereas APOLLO3®–CATHARE3 significantly improves the prediction, with an error of about −15%. This improvement arises because the power distribution is fixed in the standalone CATHARE2 calculation, while it changes considerably during the relatively long reactivity-insertion period. APOLLO3®–CATHARE3 accounts for this behavior by calculating the evolving spatial power distribution with APOLLO3®.

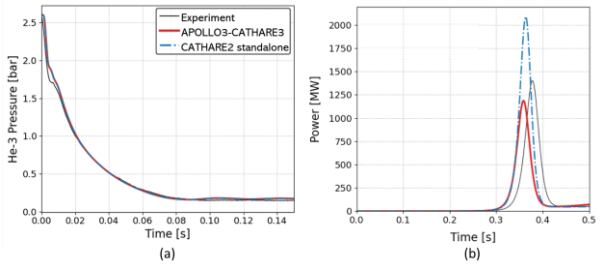


Fig7. Comparison of the simulated and experimental time histories of (a) ^{3}He pressure and (b) reactor power for Case 4.

5. Conclusions

This study coupled APOLLO3® neutronics with CATHARE3 system thermal-hydraulics through the C3PO platform to simulate CABRI transients. The coupled model was assessed against standalone CATHARE2 calculations, the previous APOLLO3®–THEDI model, and available experimental data.

The steady-state calculations and Case 1 confirmed the consistency of the coupling through both code-to-code and code-to-experiment comparisons. For the rapid transients in Cases 2 and 3, APOLLO3®–CATHARE3 produced results comparable to standalone CATHARE2 while providing improved predictions relative to APOLLO3®–THEDI. This improvement is attributed to the full-system representation in CATHARE3, which captures local helium-pressure variations instead of imposing a spatially uniform pressure boundary condition.

For the relatively slower reactivity insertion in Case 4, APOLLO3®–CATHARE3 showed a clear improvement over standalone CATHARE2. Because the standalone calculation uses a prescribed power distribution, it produced a large peak-power error. In contrast, APOLLO3®–CATHARE3 consistently updated the spatial power distribution through neutronic–thermal-hydraulic feedback, resulting in much better agreement with the experimental data.

Overall, by combining the respective strengths of APOLLO3® and CATHARE3, the coupled model provides a more consistent description of CABRI transients, particularly when local thermal-hydraulic conditions and spatial power distributions evolve significantly over time.

REFERENCES

[1] C. Vaglio-Gaudard *et al.*, “Challenge for the validation of high-fidelity multi-physics LWR modeling and simulation: Development of new experiments in research reactors,” *Front Energy Res*, vol. 11, Jan. 2023
[2] C3PO platform, https://sourceforge.net/projects/cea-c3po.
[3] C. Vaglio-Gaudard, I. Ramière, and N. Seiler, “Overview of multiphysics R&D activities at the CEA/IRESNE institute,” *Ann Nucl Energy*, vol. 192, p. 109957, Nov. 2023.
[4] T. Coissieux, J. Politello, C. Vaglio-Gaudard, and K. Ammar, “Development of a 3D APOLLO3® Neutron Deterministic Calculation Scheme for the CABRI Experimental Reactor,” *Nuclear Science and Engineering*, vol. 197, no. 8, pp. 1717–1732, Aug. 2023.
[5] C. Vaglio-Gaudard, J. Politello, T. Coissieux, and K. Ammar, “Analysis of power transients in the CABRI experimental reactor with a multi-physics APOLLO3®/THEDI coupling,” *Ann Nucl Energy*, vol. 204, p. 110551, Sep. 2024.
[6] J.-M. Labit, N. Marie, O. Clamens, and E. Merle, “Multiphysics CATHARE2 modeling and experimental validation methodology against CABRI transients,” *Nuclear Engineering and Design*, vol. 373, p. 110836, Mar. 2021.
[7] Hudelot, J.P., Fontanay, E., Molin, C., Moreau, A., Pantera, L., Lecerf, J., Garnier, Y. and Duc, B., 2016. "CABRI facility upgrade, refurbishment, recommissioning and experimental capacities." PHYSOR 2016: The Physics of Reactors conference. 2016.
[8] Mosca, Pietro, et al. "APOLLO3®: Overview of the new code capabilities for reactor physics analysis." Nuclear Science and Engineering 199.sup1 (2025): S17-S30.
[9] Emonot, Philippe, et al. "CATHARE-3: A new system code for thermal-hydraulics in the context of the NEPTUNE project." Nuclear Engineering and Design 241.11 (2011): 4476-4481.
[10] Icoco API, https://github.com/cea-trust-platform/icoco-coupling.
[11] Salome, https://docs.salome-platform.org.
[12] Patricot, Cyril, Roland Lenain, and Dominic Caron. "Upgrade of apollo3® internal thermohydraulic feedback model with THEDI, and application to a control-rod ejection accident." M&C2019. 2019.