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Challenge for the validation of high-fidelity multi-physics LWR modeling and simulation: Development of new experiments in research reactors

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Current approaches to validate multi-physics coupling mainly rely upon experimental data from the operation of the current reactor fleet. These data allow global experimental validation based on Light Water Reactor (LWR) macroscopic physical parameters of interest. However, they are insufficient for validating detailed coupling at the assembly and pin level. The use of well-controlled experimental data provided by research reactors is essential to implement a rigorous and consistent step-wise validation process of high-fidelity multi-physics coupling. That is why experimental data, such as the core power evolution in a transient-state coming from the SPERT-III experimental program and the CABRI research reactor, are analyzed as a first step towards this objective for the simulation of LWR transients initiated by reactivity insertion. The analysis of the state-of-the-art shows no existing experimental benchmark available worldwide for LWRs to consistently and rigorously validate advanced reactor physics/thermal-hydraulics/fuel performance coupling at the pin- or sub-channel scale. In this context, a discussion is therefore initiated in this paper on the perspective of developing new experiments dedicated to high-fidelity multi-physics tools, focusing on a first application: the validation of reactivity feedback effects. Very few existing light-water experimental reactors containing UO_2 fuel could today have the capacity to host these experiments. The development of a new validation experiment could only be achievable by considering a two-stage process for the experiment realization: a first stage involving a distributed network of sensors in the reactor core using instrumentation commonly used in research reactors, and a second stage implementing an instrumented fuel pin and innovative experimental techniques, in the longer term. Even if the OECD/NEA activities in the Expert Group on Multi-Physics Experimental Data, Benchmarks and Validation (EGMPEBV) (currently merged in the Expert Group on Multi-Physics of Reactor Systems – EGMUP) have started to pave the way for the development of such a high-fidelity multi-physics experiment, most of the work is still ahead of us.

KEYWORDS

multi-physics, high-fidelity, coupling, validation, experiment, research reactors, reactivity feedback effects

1 Introduction

The development of multi-physics modeling and simulation (M&S) capabilities makes the assessment of the behavior of nuclear power reactors in normal and accident situations gradually evolve from a conservative approach to a Best-Estimate Plus Uncertainties (BEPU) approach. The implementation of the BEPU approach is of primary importance to accurately quantify the gains brought by innovations (e.g., passive systems or accident-tolerant fuels) for the nuclear power light-water reactors (LWRs). Indeed, high-fidelity multi-physics simulation tools are being developed to be utilized for nuclear reactor safety analyses and advanced reactor design and have shown great promise in their abilities to reproduce observed phenomena for some reactor applications. These simulation tools enable rigorous modeling of coupled behaviours including among other things reactor physics, thermal hydraulics, fuel performance, structural mechanics, and materials chemistry. Even with the increasing fidelity and sophistication of coupled multi-physics tools, the underpinning models and data still need to be validated against experiments. Thus, the development of advanced multi-physics simulation must be associated with the experimentation, which is essential to the model validation.

The established approach to validate LWR multi-physics modeling and simulation is mainly based on measurement data coming from the operation of the current reactor fleet. The Virtual Environment for Reactor Applications (VERA), developed by the US Consortium for Advanced Simulation of Light Water Reactors (CASL) project is successfully benchmarked against measured data from startups and hundreds of PWR cycles (Godfrey, 2022). The French CORPUS multi-physics platform[1] (Le Pallec, 2016), developed by CEA, is being validated in steady-state using the OECD/NEA Tennessee Valley Authority Watts Bar Unit 1 benchmark (Albagami, 2022), including data from startup tests and irradiation cycles 1 through 3. In transient M&S, the CORPUS platform validation relies on the analysis of a House Load Operation (HLO) for a French 4-loop PWR (Olita, 2022).

These data allow a global experimental validation of the coupled multi-physics simulation tools on macroscopic physical quantities of interest, such as total core power, neutron flux at the center of some assemblies, and critical soluble boron concentration during irradiation. However, they are insufficient for the validation of the novel detailed multi-physics coupling currently under development at the assembly and pin and sub-pin levels. Moreover, the simulation of these configurations can be tainted by uncertainties, in particular resulting from the control of technological parameters, the knowledge of the initial state of the reactor and of the boundary conditions in the configurations, and the tool capacity to model the reactor regulations. The impact of these uncertainties is often very difficult to quantify and challenging to consistently propagate to final quantities of interest (QoI).

The use of well-controlled experimental data provided by highly-instrumented research reactors has now become essential to implement a rigorous and consistent step-wise validation process of multi-physics coupling. This paper describes below this general process of a rigorous validation protocol based on series of progression validation experiments to assess the impact of individual physics on multi-physics simulations. Focusing on the validation of a specific application, reactivity feedback effects, existing experiments that can be used to initiate this process are presented, along with their limitations. A discussion is then initiated on the perspective of developing new experiments.

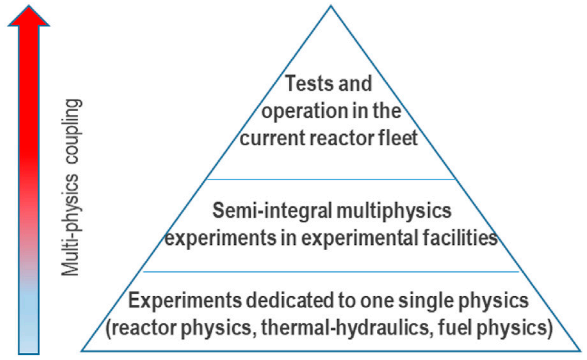

FIGURE 1
Experimental validation pyramid for multi-physics tools.

2 General process of experimental validation to implement for high-fidelity multi-physics tools

The general process to implement for the experimental validation of high-fidelity multi-physics tools is summarized in Figure 1. It can be split into three different levels of validation. The top level corresponds to the traditional approach to multi-physics tool validation. This level is based on the use of data coming from tests or operation in the current reactor fleet. The tests are mainly performed for reactor startup. Reactors contain the instrumentation required to monitor depletion cycles, and usually cannot not be instrumented further. They enable to validate the implementation of physics models from industry practice[2]; they are not sufficient for the validation of advanced physical-based models developed at the pin/sub-pin level. In this case, the experimental validation strategy requires shifting most of the effort to the local scale with the analysis of experiments; at the same time, this enables to get the information needed for a validation at macroscopic scales.

Two different experimental categories must be involved in the validation process of multi-physics coupling. The first category concerns experiments dedicated to the validation of single physics tools. The experimental validation test set for each single physics modeling and simulation tool used in stand-alone is based on these experiments. It is today quite exhaustive: it can be completed over time according to the needs associated with the design of new reactors and fuels. In most cases, the definition of new experiments in this category, even if they may require innovative instrumentation and efforts to

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[1] https://sourceforge.net/projects/cea-c3po/.

[2] e.g., for neutron transport, use of the 3D core diffusion solver with few energy groups with homogenized assemblies; for thermal-hydraulics, use of 1D assembly-averaged modeling.

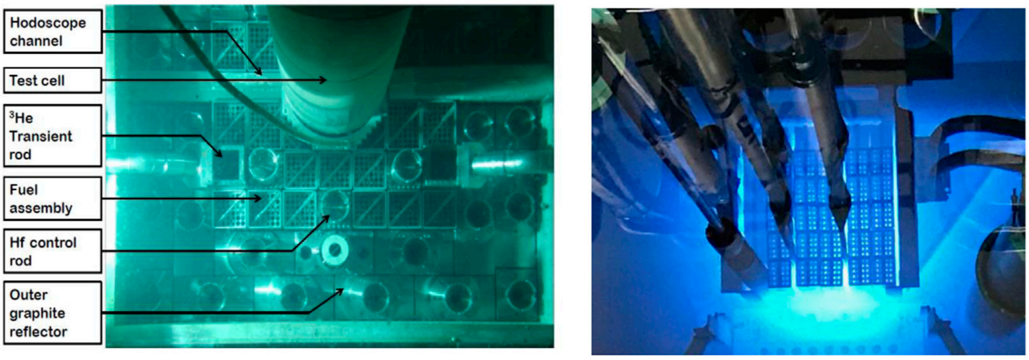

FIGURE 2
Photos of the CABRI core on the left and the PULSTAR core on the right.

reduce experimental uncertainties, no longer represents a challenge in itself. The physical quantities and characteristics of the phenomena to be studied and measured are well identified.

The second category of experiments concerns semi-integral multi-physics experiments. They focus on reproducing, in experimental facilities, a certain number of multi-physics phenomena, related to reactor physics, thermal-hydraulics and/or fuel behavior, and observed during LWR normal or off-normal/accidental conditions. There are few experiments of this category available worldwide. The following LWR experiments can be cited as the main illustration:

✓ Experiments dedicated to the Reactivity Insertion Accident (RIA) phenomenology: the SPERT (Special Power Excursion Reactor Test) program in the 1960's and the power transients of the CABRI reactor,
✓ Experiments dedicated to the Loss of Coolant Accident (LOCA) phenomenology: the LOFT[3] (Loss-Of-Fluid Test) program and the PHEBUS-LOCA program (Granjean, 2005), both in the 1980s,
✓ Experiments dedicated to the Pellet-Cladding Interaction (PCI) phenomenology: the MPCMIV (Multi-physics Pellet Cladding Mechanical Interaction Validation) benchmark[4] that has been defined within the OECD/NEA framework. It relies on experimental data provided by the Studsvik R2 reactor in 2005, during power ramping tests on a fuel sample in a test loop at cold BWR operating conditions

In general terms, these experiments are often quite old, and they were not carried out in order to validate high-fidelity multi-physics coupling at the local scale. They are insufficiently instrumented for this purpose and may show limitations in the description of experimental conditions. Nevertheless, they can be used today for the validation of multi-physics modeling and simulation with their limitations.

A focus on the semi-integral experiments dedicated to reactivity feedback effects is proposed in the rest of the paper. We describe the state-of-the-art for existing experiments and stress the needs of developing new experiments. Indeed, reactivity feedback effects are of primary importance since they are observed in LWR normal situations (steady states, power transients) and reactivity accident situations (such as rod ejection, boron dilution and main steam line break accidents).

3 Existing experiments to validate multi-physics simulation tools for LWR reactivity feedback effects

In steady-state LWR operating conditions, the radial fuel temperature profile is known to be nearly a quadratic function of spatial position within a fuel pin. A flat fuel temperature profile is currently assumed in standard lattice physics and implies the use of a model for the determination of a mean effective fuel pin temperature with the objective to conserve the pellet-integrated ^{238}U neutron capture reaction rate. This model is usually calibrated against reference Monte Carlo calculations. Moreover, a unique fuel temperature is usually considered for the whole assembly in routine industry and regulatory evaluations. Such approximations are often quite accurate because pins within each fuel assembly are physically very similar, and they are exposed to a very similar set of historical conditions. However, the development of high-fidelity modeling makes possible to consider a mesh that resolves each fuel pin, and each ring of each fuel pellet to provide information for the fuel pin/fluid sub-channel models (considering local feedback coefficients and local temperatures). Today, no experimental data is available to validate such high-fidelity modeling.

In transient M&S, the coupling between reactor physics, thermal-hydraulics, and fuel physics phenomena induces reactivity feedback effects. Several zero-power mock-up experiments, such as the MINERVE and EOLE experiments (Santamarina, 2013) at CEA Cadarache, made possible the validation of Doppler coefficient and isothermal moderator coefficient. In these experiments, the fuel thermal-mechanics and hydraulics experimental conditions are well-controlled and imposed as boundary conditions for the validation of reactor physics phenomena modeling and simulation. This validation can be described as a separate effect/single physics validation since it concerns only reactor physics effects.

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[3] https://www.oecd-nea.org/jcms/pl_25963/loss-of-fluid-test-loft-project.

[4] https://www.oecd-nea.org/jcms/pl_32203/multi-physics-pellet-cladding-mechanical-interaction-validation-mpcmiv-benchmark.

Existing semi-integral experiments investigating reactivity feedback effects rely mainly on the SPERT-III and CABRI experiments. The SPERT-III reactor operated at the National Reactor Testing Station in Idaho (United States), with the goal to gather experimental power excursion data. The SPERT-III experiments in the E-core provided open data (McCardell, 1969), that are today widely used. Some illustrations of SPERT-III experiment analysis can be found in references (Aures, 2021) (Dokhane, 2021) (Knebel, 2016) (Downar, 2020). The SPERT-III E-core reactor was an unborated pressurized-water reactor (PWR), containing 60 assemblies (52 fresh UO_2 fuel assemblies and 8 control rod assemblies with fuel followers). Reactor power excursion transients (up to a maximum reactor power of 0.9 GW) were initiated by reactivity insertion (ranging from 0.5 to 1.3 $). Reactivity was inserted by the extraction of a cruciform-shaped transient rod located at the core center. The absorber of the transient rod was made of boron and stainless steel. While the reactor state along with the initial reactivity insertion were reported for each test in the available documentation, the initial axial positions of the transient rod were not specified. The reactivity insertion was deduced from differential control rod worth measurements. The uncertainty associated with the reactivity insertion was estimated to be 4% at one standard deviation in the documentation.

In addition to the reactor power evolution, the variables for which data were recorded during the transient experiments were fuel rod cladding surface temperature, transient pressure, and bulk water temperature. However, pressure and temperature time-dependent values were not shown in the documentation; only the maximum fuel rod cladding temperature, the initial inlet temperature and pressure were provided for the transients.

Different operating conditions were investigated for the transients, including cold-startup, hot-startup, hot-standby and operating-power conditions, with an initial reactor power ranging from 50 W to 20 MW. The performance of Doppler and moderator feedback mechanisms, depending on the reactor power conditions[5], was studied during the SPERT-III transients.

The CABRI research reactor (Biard, 2020) is a pool-type reactor located at CEA Cadarache (France). It is dedicated to the study of fuel behavior during a power pulse transient simulating a reactivity insertion accident in PWRs. The core is composed of about 1500 UO_2 fuel pins moderated by light water. During a transient, the reactivity is inserted – up to 3.9$ in less than 80 ms - by the depressurization of four ^{3}He transient rods. A test cell is placed at the core center. It is composed of a water loop simulating the average thermal-hydraulics conditions representative of PWR cores, i.e., a pressure of 155 bars, a temperature of 300°C, and a flow rate of 5 m/s. A radial voided irradiation channel, the hodoscope channel, passing through the core, allows the observation of the test cell in real time.

The CABRI power pulses provide experimental data valuable for the experimental validation of multi-physics tools, even if the driver core is not instrumented, contrary to the high-instrumented test cell. Only the core power is monitored during a transient thanks to excore B_4C deposition chambers, for a reactor power ranging from a few kW to ~20 GW during the transient. No local measurement is available in the CABRI core. The analysis of the available CABRI power excursions shows that they are essentially limited by Doppler broadening of ^{238}U resonance absorption cross sections, which provided most of the total reactivity compensation.

Two research and development (R&D) multi-physics calculation tools have been developed, gradually improving the modeling of CABRI transients, while relying on simplified models with a point or assembly-scale resolution in the core modeling, SPARTE (Clamens, 2018) and more recently PALANTIR (Labit, 2021). An advanced multi-physics simulation tool (Coissieux, 2023) with a pin-scale resolution is currently under development to model accurately the local three-dimensional (3D) spatial effects in the CABRI core. The tool is based on the reactor physics/thermal-hydraulics coupling between APOLLO3® (Schneider, 2016) and THEDI (Patricot, 2019). A step-wise validation process is implemented in parallel of the tool development using the experimental data provided by the CABRI reactor.

4 Discussion: Perspective for the development of new experiments

Due to the lack of experimental data to validate high-fidelity coupling simulation tools for LWR reactivity feedback effects as shown in the previous section, the development of new highly instrumented semi-integral experiments, dedicated to the validation of high-fidelity multi-physics coupling, appears as a new challenge to handle in the coming years. Discussions have been initiated to define a future experimental program dedicated to the validation of reactivity feedback effects, in steady-state and transient conditions. It will be necessary to identify the most adequate experimental power facilities to perform such experiments. These facilities should be comprised of LWR type fuel pins moderated with light water and have a capacity to perform reactivity insertion and reactivity ramp transients. Very few existing experimental reactors can today meet these requirements; among them are the United States PULSTAR reactor (Hawari, 2021) and the French CABRI reactor (see Figure 2).

A step wise process should be pursued to achieve the desired fidelity in the experiments. First, localized instrumentation would be used to measure profiles of moderator temperature and neutron flux in the assemblies using a distributed network of sensors. Only instrumentation commonly used in research reactors (for neutron flux measurements, fission chambers and activation dosimeters; and for temperature, thermocouples or Bragg grating optical fiber based) would be implemented at this stage. This stage will be completed by an extended experimental characterization of local and global neutron and gamma flux distributions. A second phase of experiments could involve the development of instrumented fuel pins. By using such measurement devices, experimental data could be provided regarding the radial fuel temperature and reaction rate distributions within a pellet for the validation of reactor physics/thermal-hydraulics/fuel physics phenomena coupling at the pin (sub-pin)/sub-channel level/scale. The measurements of fuel pin local parameters will have to be correlated with detailed measurements of surrounding physics parameter variations. It will require the development and qualification of new experimental techniques (indirect measurement of potential state changes of the fuel pin by vibrational analysis, eddy current or acoustic waves propagation, time or spatial correlations

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[5] High-initial-power experiment results showed the effect of initial reactor power on the phenomenology, and in particular the decrease of Doppler coefficient and the increase of moderator coefficient with increasing fuel temperature.

between different local and global measurements,...), relying on innovative instrumentation (miniaturized, distributed or contactless sensors such as fiber optic, eddy current or ultra-sound waves based sensors). One of the most challenging tasks concerns the measurement of fuel centerline (perturbation induced by the replacement of fissile material by the sensor) and external cladding temperatures (miniaturize and contactless measurement system needed) to minimize the impact of the measurement device on the fuel pin. The study performed within the OECD/NEA EGMPEBV- Sub-task 6 (ST6) framework (OECD/NEA, 2021) has identified this task mostly related to the need for online measurement data with an improved spatial and temporal resolution. The preparation of such instrumented fuel pin may likely require a modification of the operating license of the current research reactors, and preliminary tests and qualifications of the instrumentation in out-of-pile and in-pile experiment using mock-up devices. It would be a long-term activity (5 years is expected).

This step-wise experimental approach could be implemented for the analysis of steady-state and transient configurations. Three different types of transients might be studied during the experimental program: transients with no reactivity feedback effects, transients with only Doppler feedback effect and transients with Doppler plus moderator feedback effects building a consistent multi-physics validation pyramid. An analysis of the reactivity insertion rates would be required for these types of feedback to ensure that the insertion rates are within the technical specifications of the reactor operating license. The development of an advanced modeling of the reactor will enable to define/design the configurations for model validation experimentally studies. Efforts have to be carried out all along the program to maintain the uncertainty level as low as possible at least compliant with the target uncertainties defined in the validation protocol.

5 Conclusion

The general validation process/protocol to implement for the validation of multi-physics tools relies on both the traditional validation approach using measurement data coming from the tests and operation of the current reactor fleet, but also on a new proposed approach consisting of using experiments dedicated to the validation of detailed coupling at the assembly and pin level. Thus, the use of well-controlled experimental data provided by highly-instrumented research reactors is essential to build a rigorous and consistent step-wise validation process of high-fidelity multi-physics coupling. However, the analysis of the state-of-the-art shows no existing experimental benchmark available worldwide for LWRs to validate high-fidelity reactor physics/thermal-hydraulics/fuel performance coupling at the pin or sub-channel scale.

In this context, a discussion is therefore initiated in this paper on the perspective of developing new experiments dedicated to validation of high-fidelity multi-physics tools. It is focused on a first application, the investigation of reactivity feedback effects in steady-state and transient conditions. Even if the OECD/NEA activities in the Expert Group on Multi-Physics Experimental Data, Benchmarks and Validation (Valentine, 2021) (currently merged in the Expert Group on Multi-Physics of Reactor Systems – EGMUP) have started to pave the way for the development of such a high-fidelity multi-physics experiment, most of the work is still ahead of us. The most convenient way to achieve it will probably be an international collaborative framework.

For this application (investigation of reactivity feedback effects), it is important to study the neutron flux and fuel profiles between and within fuel assemblies, as well as within fuel pins; that is why the experiment will require the instrumentation of the whole core. For other applications (e.g., related to the phenomenology of the Loss of Coolant Accident or Pellet-Cladding Interaction), other types of experiments could be investigated, implementing a highly instrumented water test-loop, such as in the TREAT reactor and the future Jules Horowitz Reactor (JHR).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

All authors contributed to the conceptualization, methodology and development of research directions presented in the paper. CV-G: first draft. AH, MA, KI, TV, and CD: writing-reviewing. PB and J-PH: reviewing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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