Requirements for experimental data and associated uncertainties in order to validate multi-physics simulation tools: case of the experiments in the cabri reactor

J.-P. Hudelot, O. Clamens, J. Lecerf, J.-M. Labit, E. Stratta

ANS Best Estimate Plus Uncertainty International Conference (BEPU 2018) BEPU2018-209
Real Collegio, Lucca, Italy, May 13-19, 2018

REQUIREMENTS FOR EXPERIMENTAL DATA AND ASSOCIATED UNCERTAINTIES IN ORDER TO VALIDATE MULTI-PHYSICS SIMULATION TOOLS: CASE OF THE EXPERIMENTS IN THE CABRI REACTOR

J.P. Hudelot[1], O. Clamens[1], J. Lecerf[1], JM. Labit[2], E. Stratta[2]
[1] CEA, DEN, DER/SPESI, Cadarache, F-13108 Saint Paul les Durance, France
[2] CEA, DEN, DER/SESI, Cadarache, F-13108 Saint Paul les Durance, France

jean-pascal.hudelot@cea.fr

ABSTRACT

This paper focuses on the opportunity given by the CABRI experiments to contribute to the validation of High-Fidelity multi-physics computational tools; it does not address the safety demonstration for the CABRI reactor that is based on a robust and conservative approach that does not need the use of high-fidelity multi-physics modelling and simulation tools. The paper first presents a general approach and recommendations to be used to meet the requirements for experimental data and associated uncertainties in order to validate multi-physics modelling and simulation tools. After a short presentation of the CABRI facility, it then provides a review and critical analyses of the multi-physics available experimental data for CABRI. Finally, it addresses the adequacy and completeness of the CABRI experimental datasets for the validation of multiphysics computational tools, as well as promising perspectives in terms of instrumentations that could fill in the gaps in terms of information in the future experiments.

1. INTRODUCTION

High-fidelity, multi-physics modeling and simulation tools are being developed and utilized for a variety of applications in nuclear science and technology with the objective to accurately model and predict complex phenomena for many applications. In spite of their sophistication, the experimental validation of those tools is needed to address the complexity of the physical applications in terms of time, spectral and spatial domains. In this framework, the Expert Group on Multi-Physics Experimental Data, Benchmarks and Validation (MPEBV) of the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) was formed to address the challenges with the validation of such tools [1]. The main goal of the group is to provide guidance for creating validation experimental benchmarks for high-fidelity of multi-physics tools and to define the process for such a validation. However, very few experimental datasets are available to fulfill those ambitious objectives of validation, due to the fact that there are so far few existing experimental facilities available for conducting multi-physics experiments and due to the increasing need of experiments for validating more complex and complete simulation tools. It also appears the fact that in some instances instrumentation and experimental techniques may not exist to validate some models or approximates.

This paper focuses on the opportunity given by the CABRI tests to contribute to the validation of High-Fidelity multi-physics computational tools; it does not address the safety demonstration for the CABRI reactor that is based on a robust and conservative approach that does not need the use of high-fidelity multi-physics modelling and simulation tools.

The paper first presents general approach and recommendations to meet the requirements for experimental data and associated uncertainties in order to validate multi-physics modelling and simulation tools. After a short presentation of the CABRI facility, it then provides a review and critical analyses of the multi-physics available experimental data for CABRI. Finally, it addresses the adequacy and completeness of the CABRI experimental datasets for the validation of multiphysics computational tools, as well as promising perspectives in terms of instrumentations that could fill in the gaps in terms of information in the future experiments.

2. EXPERIMENTAL APPROACH TO MEET THE REQUIREMENTS FOR THE VALIDATION OF MULTI-PHYSICS MODELLING AND SIMULATION TOOLS

The expert group on Multi-Physics Experimental Data, Benchmarks and Validation (MPEBV) of the OECD-NEA was created in 2014 to address the specific challenges with the validation of high-fidelity, multi-physics M&S tools. The aims of the group are to provide the member countries of the OECD-NEA with consensus guidelines and recommendations for validating multi-physics M&S tools, to evaluate legacy and new experiments for validation, and to demonstrate validation principles for specific industry challenge problems [1] [2].

In this framework, validation matrices utilizing the phenomena identification and ranking table (PIRT) process are being developed for specific challenge problems. The main idea of the approach is to identify all the integral and local, time-dependent and steady-state, physical quantities that need to be known for the validation of both individual and coupled codes. Such as PIRT validation matrix is given as an example in Figure 1 for the case of the PCI challenge; it is based on a color chart to emphasize the importance and the level of knowledge for each physical quantity.

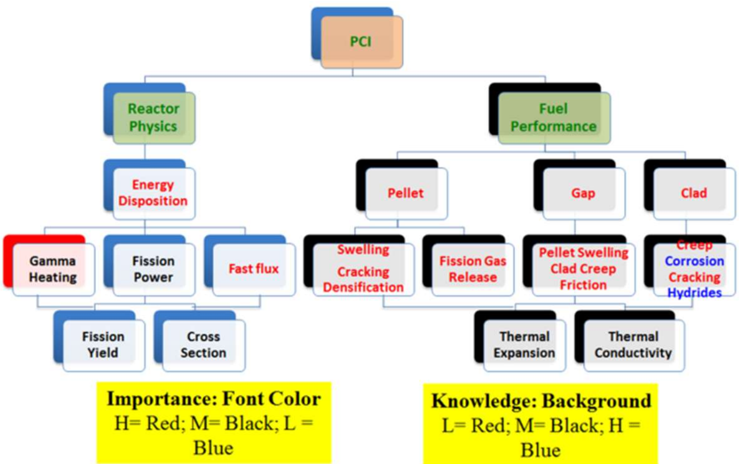

Figure 1 – Example of PIRT validation matrix for the PCI challenge (for reactor physics and fuel performance domains).

Once the target physical quantities of interest have been identified, it is important to establish the concrete process for reaching the multi-physics code validation. This complex iterative process between simulation and experimentation can be summarized and schemed as shown in Figure 2.

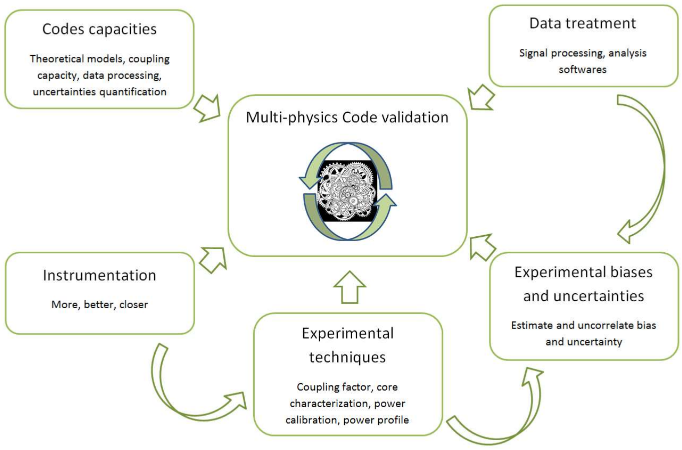

Figure 2 – Scheme of an iterative process between simulation and experimentation for reaching the multi-physics code validation.

The overall process for performing an complete, accurate and well documented experiment is described in Figure 3. It emphasizes the fact that an experiment must not be only resumed to the choice of an instrumentation that only delivers a raw signal (e.g. a current or a voltage). Further steps of analysis are necessary, first to transform raw signals into physical data (e.g. neutron flux or temperature) and finally to the target physical quantity (e.g. axial buckling or temperature profile).

Those further steps include a complex process that has to be well mastered in order to obtain optimized measured physical parameters and associated uncertainties that can be considered as the final experimental result. This specific process is described in Figure 4. It includes the need of input data (e.g. technological data, nuclear data…), sometimes of calculated data to transform raw data into physical data, of calibration data and of precise control of the boundary experimental conditions (e.g. environmental or human factor parameters). It is emphasized that the very good knowledge of boundary conditions of the experiments, of calculated or modeled input data and of calibration data is absolutely crucial to reach a controlled and realistic estimation of the experimental uncertainties.

In the end, any missing information in the steps and data (as described in Figure 3 and Figure 4) needed to provide an experimental dataset for the validation of calculational tools has to be considered as a lack to provide an ideal experimental benchmark. The gap between the ideal and the potential experimental dataset should lead to identify and lo lead the progress that has to be made in terms of instrumentation, experimental techniques and data treatment.

Below in this paper (see section 4), we will propose a critical analysis of the multi-physics available experimental data from the CABRI reactor, with the objective to provide a validation benchmark for Multiphysics codes.

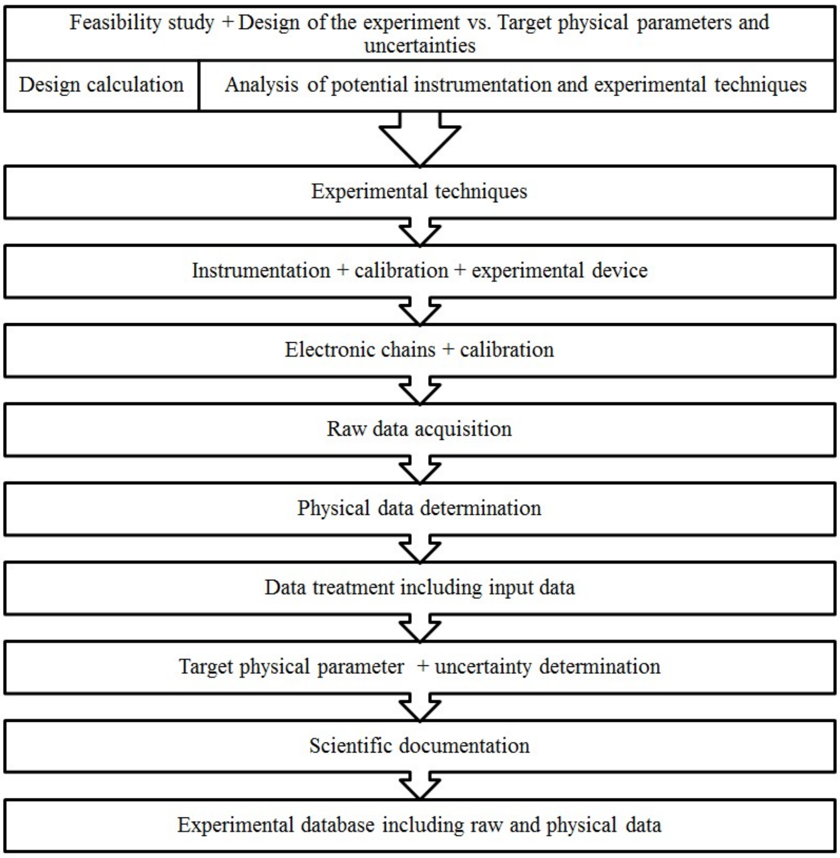

Figure 3 – Overall process to complete an experiment

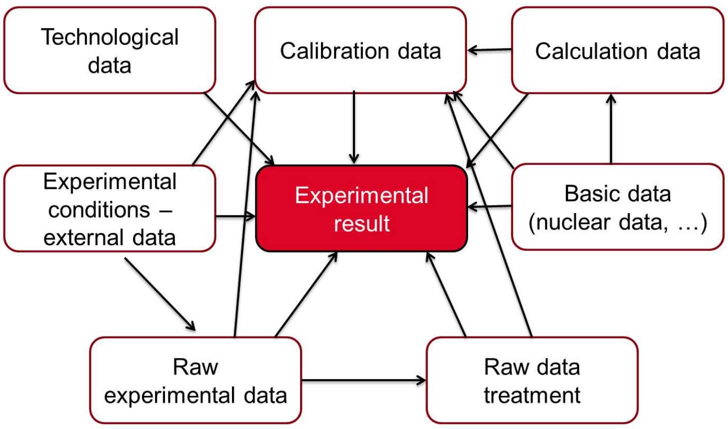

Figure 4 - Coupled and complex process to obtain experimental result with controlled uncertainties.

3. DESCRIPTION OF THE CABRI EXPERIMENTS

CABRI is an experimental pulsed reactor funded by the French Nuclear Safety and Radioprotection Institute (IRSN) and operated by CEA at the Cadarache research center. Since 1978 the experimental programs in CABRI have been aimed at studying the fuel behavior under Reactivity Initiated Accident (RIA) conditions. The purpose of the transient tests performed as part of these programs was to improve the safety of reactors in nominal and accidental operating situations, at validating the multi-physics calculation codes and at designing and testing innovating types of fuels (e.g. accidents tolerant fuels). For past Fast Breeder Reactor's fuel studies, a sodium experimental loop was designed and implemented at the center of the CABRI driver core, in order to accommodate the instrumented test device that contains the fuel rod to be tested, and to cool this fuel rod into the required thermal-hydraulic conditions.

In order to study the PWR high burn up fuel behavior, the facility was modified to have a water loop able to provide thermal-hydraulic conditions representative of the nominal operating PWR's ones (155 bar, 300°C). This project which began in 2003 was driven within a broader scope including an overall facility refurbishment and a safety review. The global modification is conducted by CEA. The experiments take place in the framework of the OECD-NEA Project CIP (CABRI Inter-national Program) [19] which is conducted by IRSN (Institut de Radioprotection et de Sûreté Nucléaire). IRSN finances the refurbishment and the operation of the CABRI reactor that is currently put at disposal of the IRSN for investigations into the safety of fuel.

3.1 GENERAL PRESENTATION OF CABRI

The CABRI facility (see Figure 5) is made of the CABRI core and of three main systems (pressurized water loop, transient rods and primary cooling system) allowing to perform transient tests (RIA, LOCA) with a high level of representativeness, accuracy and safety [3]. Those different components of the facility are described in the following sections.

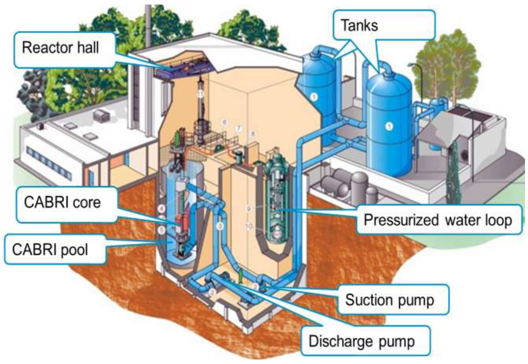

Figure 5 - Overall view of the CABRI facility.

3.1.1 CABRI Core

CABRI is a pool-type reactor, with a core made of 1487 stainless steel clad fuel rods with 6% ^{235}U enrichment. The reactor is able to reach a 23.7MW steady state power level. The reactivity is controlled via a system of 6 control and safety rods made of 23 hafnium pins each (see Figure 6).

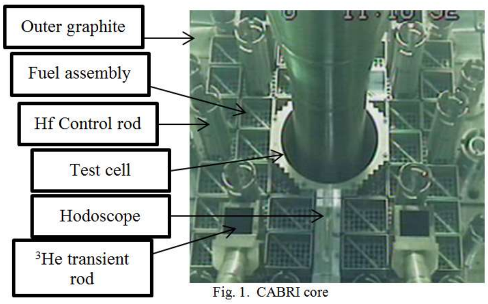

Figure 6 - CABRI core.

3.1.2 Pressurized Water Loop

The new test loop allows reproducing the thermal hydraulics conditions of a pressurized water reactor (300°C, 155bar, up to 6m3/h flowrate). It is composed (see Figure 5) of an in-pile part connected to the experimental device and of an outside tank containing the main components (pressurizer, pump, regulation valves…).

3.1.3 Transient Rods Circuit

The key feature of the CABRI reactor is its reactivity injection system [4]. This device (see Figure 3) allows the very fast depressurization into a discharge tank of the ^{3}He (strong neutron absorber) previously introduced inside 96 tubes (so called "transient rods") located among the fuel rods (see Figure 7). The rapid absorber depressurization translates into an equivalent reactivity injection possibly reaching 4$ within a few 10ms. The power consequently bursts from 100kW up to ~20GW (see Figure 7) in a few milliseconds and decreases just as fast due to the Doppler effect and other delayed reactivity feedbacks. The total energy deposit in the tested rod is adjusted by dropping the control and safety rods after the power transient.

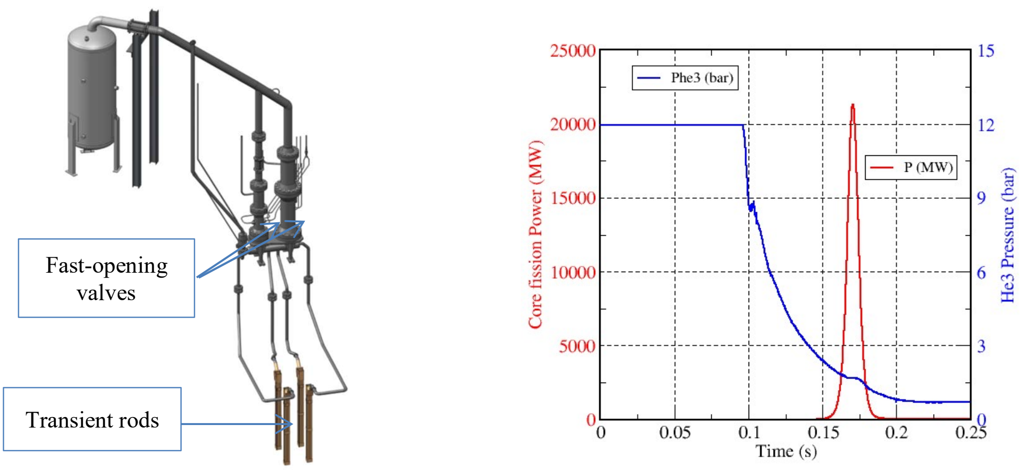

Figure 7 - Global view of the transient rods system (left) and of the typical CABRI 3He Pressure and core power shapes during a RIA transient (right).

3.1.4 Primary Cooling System

The primary cooling system [5] is illustrated in Figure 5. A steady water flowrate (up to 3215m3/h) is needed to cool the fuel pins of the reactor driver core so as to respect the safety margins about the temperature of the claddings and of the oxide fuel during the power steady states and transients. The two tanks (250m^3 each) feeding the cooling system are visible in the background. Water is sucked by two lines at the bottom of the tanks that join and merge into a single line of 600mm diameter. The suction and discharge pumps of the circuit are located at 11m below ground. Water thus passes initially by the suction pump, and then passes in the driver core of the reactor located in the pool and finally water is sent back to the top of the tanks through the discharge pump, which engages in order to regulate a stable level in the pool.

4. REVIEW AND CRITICAL ANALYSIS OF THE MULTI-PHYSICS AVAILABLE EXPERIMENTAL DATA FOR CABRI

The CABRI commissioning tests allowed to measure and collect a large quantity of relevant experimental data, concerning permanent and transient regimes of the reactor for both neutronics and thermal-hydraulics.

In this paper, we only consider the experimental data relative to the CABRI core. The experimental data relative to the test device and the test fuel are not addressed.

The experimental uncertainties are not given in this paper as they are still under treatment. However the typical target uncertainties and associated methods are described in references [3] [6] [7] [8].

4.1 Description of the available instrumentation

Figure 8 described the nature (see Table 1 and Table 2 for details) and the position of the different types of instrumentation that were used during the CABRI tests, both inside and outside the core. The detailed relation between those instrumentations and the measurement of the physical quantities of interest is given in section 4.2.

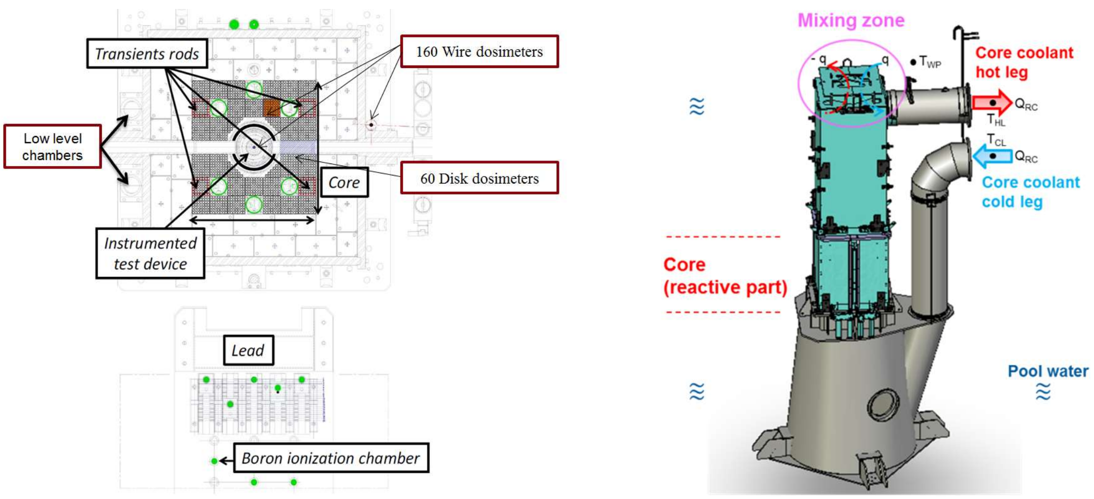

Figure 8: nature and the position of the different types of instrumentation inside and outside of the CABRI core

4.2 Physical quantities measurements during the commissioning tests of CABRI

4.2.1 Measurement of single neutronic quantities

Low power (<100kW) commissioning tests aimed at improving the neutronic characterization of the CABRI core as for safety criteria and as for control of the experiments. The main neutronic parameters that were measured were: critical states, reactivity effects (differential and integral reactivity worth of the control rods, reactivity worth of Helium-3, isothermal temperature coefficient, void effects in the test cell), axial and radial distributions of thermal and epithermal flux, kinetics parameters. Table 1 gives the detail of the measured neutronic parameters and makes the link with the associated instrumentation and experimental techniques [9] [10]. Additional neutronic parameters were measured at high steady-state power levels such as the power coefficient and the nuclear heating. The overall experimental dataset related to neutronics is thus a very complete one.

Measured physical quantity	Instrumentation	Experimental technique
Critical states in several configurations of operation	Low-level Fission Chambers High-level boron chambers	Critical state
Integral and differential reactivity worth of the control rods	Low-level Fission Chambers High-level boron chambers	Rod drop method + MSM Method [11] Doubling time method
Isothermal temperature coefficient	Low-level Fission Chambers High-level boron chambers Thermocouples	Critical state
Core stacking effect	Low-level Fission Chambers High-level boron chambers Flowmeters	Critical state
Kinetics parameters	CFUL01 fission chambers High-level boron chambers Au and Co wire dosimeters	Feynman-α and Rossi-α method [13] Dosimetry [12]
Axial and radial distributions of thermal and epithermal flux (core and test cell)	Au and Co wire and disk dosimeters	Dosimetry
Power coefficient (pcm/MW)	High-level boron chambers	Critical state
Void effects (in the test cell)	Low-level Fission Chambers High-level boron chambers	Critical state
Nuclear heating	High-level boron chambers Thermocouples	Heating of the structures
Reactivity worth of helium-3 inside the transient rods	Low-level Fission Chambers High-level boron chambers Thermocouples Piezo-resistive pressure captors	Critical state + Sum of differential reactivity worth of the control rods

Table 1: Measured physical quantity – associated instrumentation and experimental technique

4.2.2 Measurement of Multiphysics quantities

Dealing with Multiphysics measurements, the global tests of the CABRI facility that were performed at high power levels (> 100 kW) allowed to address two types of measurements:

1. Power transient measurements of various intensities and duration (Full Width at Half Maximum). The measured parameter is the online power of the core, measured by the mean of the experimental boron chambers located outside of the core.
2. Calorimetric balance measurements [8] between the inlet and the outlet of the primary cooling system, based on steady-states of power (from 8MW to 23MW) and on power transients of different characteristics (maximum power (from 3GW to 21GW), full width at half maximum (FWHM) (from 10ms to 30ms), energy deposit in the core (up to ~230MJ)). The measured physical quantities during transients are the coolant flowrate and the inlet and outlet temperatures (see Figure 8).

The thermal-hydraulics measured quantities are described in Table 2. It has to be noticed that no local thermal-hydraulics measured parameter (channel flowrate, moderator temperature, fuel temperature...) is so far available inside the CABRI core.

Measured physical quantity	Instrumentation	Experimental technique
Inlet and oulet core flowrates	Annubar and ultrasonic sensor	Preliminary calibration of the detectors
Inlet and outlet core temperatures	Thermocouples	Preliminary calibration of the detectors
Helium-3 pressure in the transient rods	Piezo-resistive pressure captor	Preliminary calibration of the detectors
Online Core power	Boron ionization chamber Annubar and ultrasonic sensor Thermocouples	Calorimetric balance [14]

Table 2: thermal-hydraulics measured quantities - associated instrumentations

4.2.3 Synthesis of the available measurements

The following table gives the synthesis of the available natures of measurements for the CABRI reactor, with the objective to validate single and multiphysics modeling and simulation tools.

Permanent regime	**Neutronics**	**Multiphysics** : Neutronics + Thermal-Hydraulics
Transient regime	**Multiphysics :** Neutronics + Thermal-Hydraulics	

Table 3: different available natures of measurements in transient and in permanent regimes

5. ADEQUACY AND COMPLETENESS OF THE CABRI EXPERIMENTAL DATASETS FOR THE VALIDATION OF COMPUTATIONAL TOOLS

5.1 Adequacy

It must first be emphasized that the experimental conditions such as the metrology and the material balance of the different components of the CABRI core and the calibration of all detectors are well known and controlled.
Among the measurements, most of are relevant for the validation of neutronic and of multiphysic simulation tools. Those measurements can be classified on the following way:

- Local and integral neutronic measurements for the validation of single neutronic simulation tools,
- Global core power measurements during steady states and during transients of power (see section 4.2.2) for the validation of multiphysics simulation tools,
- Measurement of the coolant temperature evolution vs. time at the inlet and at the outlet of the core (see section 4.2.2) for the validation of single thermal-hydraulics and of multiphysics simulation tools.

All those measured quantities can be directly calculated by modeling and simulation tools.

5.2 Completeness

Dealing with the main objectives of the CABRI RIA tests, a rather limited instrumentation of the core is available. This low number of instrumentations is also related to limitations in terms of core safety requirements, of size, of perturbation and of existing technology for sensors.

Among the physical quantities that are so far not measured in the CABRI core, the most important lacks are thus the following ones:

- the clad and fuel temperature and the clad strain during transient,
- the local flowrate and the potential boiling effects of the coolant during transient,
- the time-dependent gap between the fuel pellets and the cladding, the online energy-dependent neutron and gamma flux in the core.

5.3 Promising perspectives in terms of instrumentations

In the future, development of new types of instrumentation [15] could be used to fill these lacks of experimental knowledge (see section 5.2), such as for instance:

- Optical fibers (for Bragg gratings or pyrometry) for the measurement of local distributions of temperature and strain,
- SPND (Self Powered Neutron Detectors) and SPGD (Self Powered gamma detectors) detectors for the online measurement of energy-dependent gamma and neutron flux,
- Non intrusive acoustic measurements for a qualitative and quantitative boiling effect measurement in the CABRI core during transients of power.

The overall potential developments in terms of instrumentation are being addressed in the framework of the MPEBV expert group of OCDE.

In the future, such instrumentation could be implemented and tested in the CABRI core, first on dummy but prototypical pins, and then on real fuel pins.

Bragg gratings (see Figure 9) could inform about the online and local rise in temperature and strain of the claddings. For instance, first tests of Bragg gratings were successfully performed in the EOLE facility of CEA Cadarache [16], at low power and low temperature levels. The adaptation of such optical fibers to harsh environments (high temperature, high levels of neutron and gamma flux) is undergoing [15].

SPND and SPGD detectors [15] (see Figure 9) were developed at CEA Cadarache and were already successively tested in the OSIRIS reactor [17]. They could be easily implemented inside the CABRI core. For SPND, the choice of the fissile deposit of the chamber can allow to measure several ranges of neutron energies, for example thermal neutrons using a Uranium-235 deposit and fast neutrons using a Plutonium-242 deposit.

Dealing with acoustic measurements, recent works were performed on the acoustic emission signals from nuclear safety experiments [18]. The application of these works to the detection of boiling effect is planned by CEA within the next three years.

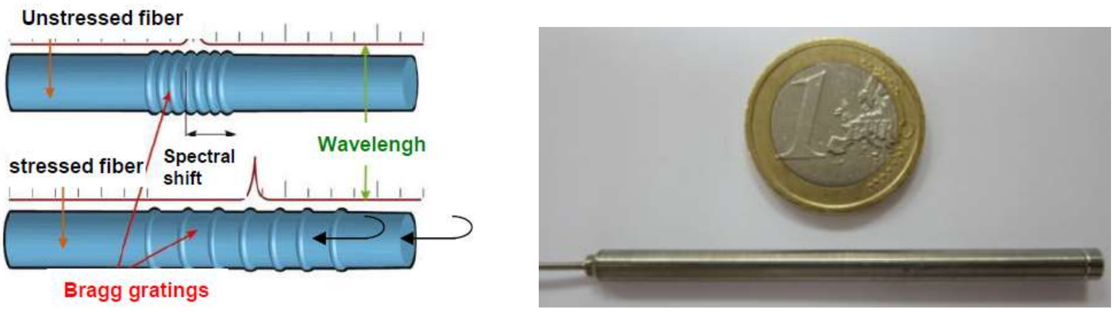

Figure 9: Bragg grating for the measurement of local fields of temperature and deformation of claddings (on the left side); SPND detector (on the right side)

6. CONCLUSION

This paper has presented a general approach and recommendations to be used to meet the requirements for experimental data and associated uncertainties in order to validate multi-physics modelling and simulation tools. An experiment must not be resumed to the measurement phase and to the choice of instrumentation. It also includes some crucial phases, as the design of the experiment vs. the target physical parameters and uncertainties, as the data treatment to convert measured data into measured physical quantity or as the scientific document of the experiment.

A review and a critical analysis of the available experimental data for CABRI have been performed. It concludes to the good completeness of the existing experimental datasets for the validation of neutronic calculational tools, but so far to the lack of some local and time-dependent thermal-hydraulics and online energy-dependent neutron and gamma flux measurement data inside the core to meet the overall requirements of validation for High-Fidelity multi-physics modelling and simulation tools. Promising perspectives of instrumentation such as optical fibers, innovative ion and fission chambers or non intrusive acoustic detectors could help to fill those gaps in the future.

7. ACKNOLEDGEMENT

The authors would like to acknowledge IRSN (Institut de Radioprotection et de Sûreté Nucléaire) for its financial, technical and scientific support and contribution to the CABRI experiments.

8. REFERENCES

[1] T. Valentine, M. Avramova, A. Petruzzi, J.P. Hudelot, U. Rohatgi, K. Velkov, OECD-NEA Expert Group on Multi-Physics Experimental Data Benchmarks and Validation, Proceedings of the 26th International Conference on Nuclear Engineering ICONE26, July 22-26, 2018, London, England

[2] P. Finck, T. Valentine, J. Dyrda, J. Gulliford, J.P. Hudelot, U. Rohatgi, “OECD-NEA Expert Group on Multi-Physics Experimental data, Benchmarks and Validation”, PHYSOR 2016 – Unifying Theory and Experiments in the 21st Century Sun Valley Resort, Sun Valley, Idaho, USA, May 1 – 5, 2016, on CD-ROM (2016)

[3] JP. Hudelot, E. Fontanay, C. Molin, A. Moreau, L. Pantera, J. Lecerf, Y. Garnier, B. Duc, “CABRI facility: upgrade, refurbishment, recommissioning and experimental capacities”, PHYSOR 2016 – Unifying Theory and Experiments in the 21st Century Sun Valley Resort, Sun Valley, Idaho, USA, May 1 – 5, 2016, on CD-ROM (2016)

[4] B. Duc, B. Biard, P. Debias, L. Pantera, JP. Hudelot, F. Rodiac, “Renovation, improvement and experimental validation of the Helium-3 transient rods system for the reactivity injection in the CABRI reactor,” IGORR2014 conference, 17-21 November 2014, Bariloche, Argentina

[5] JP. Hudelot, Y. Garnier, J. Lecerf, M. Fournier, S. Magnetto, E. Gohier, “CABRI reactor commissioning: results and analysis of the tests on the primary cooling system and on the control and safety rods,” IGORR2014 conference, 17-21 November 2014, Bariloche, Argentina

[6] JP. Hudelot, J. Lecerf, Y. Garnier, G. Ritter, O. Guéton, AC. Colombier, F. Rodiac, C. Domergue, “A complete dosimetry experimental program in support of the core characterization and of the power calibration of the CABRI reactor”, ANIMMA2015 Conference, Lisbon (Portugal), 2015

[7] J. Lecerf, Y. Garnier, JM. Girard, C. Domergue, L. Gaubert, Ch. Manenc, “Analysis of the dosimetry campaign performed during the CABRI commissioning tests,” Advancements in Nuclear Instrumentation Measurement, Methods and their Applications (ANIMMA), Liege, Belgium, June 19-23, 2017

[8] L. Pantera, Y. Garnier and F. Jeury, « Assessment of the Online Power Measured by a Boron Chamber in a Pool-Type Ressearch Reactor Using a Nonlinear Calibration Model,” Nuclear Science and Engineering, vol. 183, 247-260 June 2016

[9] G. Bignan, P. Fougeras, P. Blaise, JP. Hudelot, F. Mellier, "Handbook of Nuclear Engineering," ISBN 978-0-387-98130-7 – Volume 3 - Reactor Physics Experiments on Zero Power Reactors – pp. 2053-2184

[10] G. Perret, "amélioration et développement des méthodes de détermination de la réactivité – Maîtrise des incertitudes associées", PhD thesis, Orsay, 2003

[11] P. Blaise, F. Mellier P. Fougeras, "Application of the Modified Source Multiplication (MSM) Technique to Subcritical Reactivity Worth Measurements in Thermal and Fast Reactor Systems," ANIMMA International Conference, 7-10 June 2009, Marseille, France

[12] JM. Girard, H. Philibert, S. Testanière, Ch. Domergue and D. Beretz, "The MADERE Radioactivity Measurement Platform: Developments for a Better Addressing to the Experimental Needs", 978-1-4244-5208-8/09/ ©2009 IEEE

[13] I. Pazsit, C. Demazière, "Handbook of Nuclear Engineering," ISBN 978-0-387-98130-7 – Volume 3 – Noise Techniques in Nuclear Systems – pp. 1629-1737

[14] J. Lecerf, Y. Garnier, JM. Girard, L. Pantera, C. Domergue, "Study of the linearity of CABRI experimental chambers during RIA transients," Advancements in Nuclear Instrumentation Measurement, Methods and their Applications (ANIMMA), Liege, Belgium, June 19-23, 2017.

[15] B.G. Kim, J.L. Rempe, J.F. Villard, S. Solstad, "Review of instrumentation for irradiation testing in nuclear fuels and materials," Nuclear Technology, Vol. 176, Nov. 2011

[16] F. Mellier, G. Cheymol, G. Laffont, C. Destouches, J-F Ledoux, J. Di-Salvo, A. Morana, E. Marin, S. Girard, "Irradiation campaign in EOLE reactor facility of fibre Bragg grating sensors dedicated to the online temperature measurement in critical reactor facilities (SOMETIME project)", Advancements in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA 2015), Apr 2015, Lisbonne, Portugal

[17] Damien Fourmentel, "Mesures neutroniques et photoniques combinées pour la caractérisation précise des canaux expérimentaux du futur réacteur d'irradiation Jules Horowitz (RJH)", Thèse de doctorat : Instrumentation : Aix-Marseille : 2013

[18] O.I. Traore, L. Pantera, N. favretto-Cristini, P. Cristini, S. Viguier-Pla, P. Vieu, "Structure analysis and denoising using Singular Spectrum Analysis Application to Acoustic Emission Signals from Nuclear Safety Experiments", Measurement, Elsevier, 2017, 104, pp.78 - 88.

[19] https://www.oecd-nea.org/jointproj/cabri.html