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Traditional and Novel Measurement Methods for Validation of Multi-Physics Modelling and Simulation Tools

Report on Sub-Task 6 of EGMUP Task Force 1

A Working Paper by the Expert Group on Reactor Systems Multi-Physics (EGMUP)

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Foreword

The Nuclear Energy Agency (NEA) Nuclear Science Committee (NSC) mandated the Expert Group on Multi-Physics Experimental Data, Benchmarks and Validation (EGMPEBV) in 2014 to provide oversight of activities associated with the certification of experimental data and development of benchmark models for validation of multi-physics (MP) modelling and simulation (M&S) computational systems. In addition, this Expert Group was seeking to establish appropriate processes and procedures for the use of data and benchmark models for validation of M&S tools and data.

The EGMPEBV was organised into two task forces:

1. Evaluation of the status, expected needs, major challenges and priorities for the validation of MP M&S tools.
2. Providing best practices guidance for development of models for validation, identifying needs for specific experiments with the intended purpose of validating multi-physics M&S tools and data.

The EGMPEBV mandate expired in 2020 and its scope became part of the activities of the Expert Group on Reactor Systems Multi-Physics (EGMUP) supervised by the Working Party on Scientific Issues and Uncertainty Analysis of Reactor Systems (WPRS).

This working paper has been developed to support the Task Force 1 activities in providing an overview of the challenges with traditional and novel measurement methods for validation of multi-physics M&S tools.

Acknowledgements

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Special thanks are also due to the members of the Expert Group on Multi-physics Experimental Data, Benchmarks and Validation for their comments, review, and guidance.

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List of abbreviations and acronyms

ADC	Analogue to digital converter
BR1	Belgian Reactor 1 (Belgium)
BR2	Belgian Reactor 2 (Belgium)
CABRI	Research reactor (IRSN, France)
CALMAR	Spectrum adjustment code (CEA, France)
CALMOS	Calorimetric measurement system (OSIRIS, CEA, France)
CASL	Consortium for Advanced Simulation of Light Water Reactors (United States)
CEA	Atomic Energy and Alternative Energies Commission (France)
CROCUS	Zero-power research reactor (EPFL, Switzerland)
DNB	Departure from nucleate boiling
EGMPEBV	Expert Group on Multi-physics Experimental Data, Benchmarks and Validation (NEA)
EGMUP	Expert Group on Reactor Systems Multi-Physics (NEA)
EGRFP	Expert Group on Reactor Fuel Performance (NEA)
EPFL	Swiss Federal Institute of Technology (Switzerland)
FC	Fission chamber
FPGA	Field programmable gate array
FWHM	Full width at half maximum
HANARO	High-flux advanced neutron application reactor (Korea)
HPGe	High-purity germanium detectors
ICSBEP	International Criticality Safety Benchmark Evaluation Project (NEA)
IEA	International Energy Agency
IFE	Institute for Energy (Norway)
INL	Idaho National Laboratory (United States)
IRPhE	International Reactor Physics Experiments Project (NEA)
IRSN	Institute for Radiation Protection and Nuclear Safety (France)
JHR	Jules Horowitz Reactor (France)
LOCA	Loss-of-coolant accident
LVDT	Linear variable differential transformer
LTO	Long-term operation
LWR	Light water reactor
MADERE	Measurement applied to dosimetry for reactors experiment platform (CABRI, IRSN, France)

MALIBU	Radiochemical Analysis of MOX and UOX LWR fuels irradiated to high burn-up experimental programme (Belgonucléaire, Belgium)
MELODIE	Experiment for online cladding creep studies (OSIRIS, CEA, France)
MFC	Micro-fission chamber
MONACO	Multichannel acquisition system for neutron and gamma measurements (CEA, France)
MOX	Uranium-plutonium mixed oxide fuel
MP	Multi-physics
MPGD	Micro pattern gas detectors
M&S	Modelling and simulations
MTR	Materials test reactor
NEA	Nuclear Energy Agency
NEAMS	Nuclear energy advanced modelling and simulation programme (Department of Energy, United States)
NSC	Nuclear Science Committee (NEA)
NSRR	Nuclear safety research reactor (Japan)
NURESAFE	Nuclear reactor safety simulation platform project (European Commission)
OECD	Organisation for Economic Co-operation and Development
OSIRIS	Open pool research reactor (CEA, France)
OSLD	Optically stimulated luminescence detector
PARC	Phenomenon assessment and ranking chart
PCMI	Pellet-clad mechanical interaction
PIE	Post-irradiation experiment
PIRT	Phenomenon identification ranking table
PSI	Paul Scherrer Institute (Switzerland)
PWR	Pressurised water reactor
QOI	Quantity of interest
QPRT	Quantitative phenomena ranking table
RIA	Reactivity-initiated accident
SA	Sensitivity analysis
SPGD	Self-powered gamma detector
SPND	Self-powered neutron detector
ST	Sub task
TF	Task force
TLD	Thermoluminescent dosimeter
TREAT	Transient reactor test facility (INL, United States)

TRIPOLI	Monte Carlo radiation transport code (CEA, France)
TTL	Transistor-transistor logic
UOX	Uranium oxide
US	United States
WPRS	Working Party on Scientific Issues and Uncertainty Analysis of Reactor Systems (NEA)
ZPR	Zero power reactor

Executive summary

Novel modelling and simulations (M&S) capabilities in nuclear engineering offer comprehensive insights into physical phenomena with unpreceded spatial and temporal resolution and present new opportunities for the designer. The availability of dependable numerical predictions and complex sensitivity analyses form the foundation for swift, iterative design processes that lead to heightened safety margins and improved economics for new designs. Additionally, these advanced M&S capabilities yield more comprehensive, well-informed, and less conservative safety assessments of existing designs to support, e.g. nuclear long-term operation (LTO) by lifetime extension, power uprates of nuclear power plants, and higher fuel burn-up, which are key economic improvement factors for the operation of the current fleet of nuclear power plants (IEA/ NEA, 2020).

While the pronounced benefits of novel M&S tools, bringing much improved spatial and temporal resolutions, are evident, a validation challenge looms large. The heightened precision inherent to these tools necessitates the concurrent availability of high-resolution experiments for their validation process. However, there is a lack of both experimental data and reliable estimates of their associated uncertainties, both of which are crucial for validation purposes. Furthermore, it is often evident that a disconnect exists between the measured physical quantity and the computed values, necessitating a complex transformation process that can inadvertently introduce biases and additional uncertainties. This underscores the imperative for additional experimental data and innovative experiments.

The target audience of this working paper are experts in M&S of nuclear reactor systems, experimentalists, operators of research facilities and data curators. The working paper serves as input to the recommendation making process within the Expert Group on Reactor Systems Multi-Physics (EGMUP).

The working paper provides recommendations on the design of novel experiments suited to test multi-physics M&S tools for nuclear reactor systems. Thereby it does not aim to be exhaustive and focuses on a specific validation domain and a specific challenge problem to outline the design and decision-making process for providing optimum validation data.

The considered validation domains are pulsed reactors (CABRI/TREAT) as well as Gen-II/III reactors, preferably pressurised water reactor (PWR), assuming steady-state and transient events (normal operation and accident situations). The selected challenge problem is the pellet cladding mechanical interaction (PCMI) in transient reactors. Indeed, PCMI in a reactivity-initiated accident (RIA) covers most of the domains considered by the EGMPEBV, except chemistry, resonance/vibration or damages to the containment. The types of MP codes to be validated are considered to be similar to the novel approaches represented by the CASL, NEAMS and NURESAFE platforms (Turnsky and Kothe, 2016; Sofu and Thomas, 2017; Chanaron, 2019), i.e. tightly coupled tools with high resolution in space and in time.

The working paper outlines the conflict of increasing experimental needs and decreasing funding for the experimental facilities, and provides recommendations on how to reduce cost. The document proposes a methodology for defining validation requirements and for designing experiments based on Phenomenon Identification Ranking Table (PIRT) and Quantitative Phenomena Identification and Ranking Table (QPRT) approaches. It concludes that the cost of new experimental programmes can be reduced by supplementary simulations to focus the experimental efforts on the most relevant measurements and to gain better control of the relevant influence parameters. Better control leads to reduced experimental biases and uncertainties to match the improved accuracies and resolutions of the novel MP computational methods. It is stressed that the determination of the measurement techniques and their associated measured parameters should be specified based on an iterative process involving experimentalists and MP modellers.

The working paper illustrates the approach with an application to the modelling of PCMI in pulse type reactors. It is concluded that the available measurement capabilities are not yet fully suitable for MP code validation, and gaps have been identified mostly in the availability of online data and in the provision of improved spatial and temporal resolution. The working paper provides several references to new measurement types and also considers possible issues, e.g. related to radiation hardness. Single effects tests are still considered as a useful input for MP validation work as they typically exhibit reduced experimental uncertainties and fewer sources of potential measurement biases. Additionally, the cost for single effects tests are typically lower than for MP experiments. The working paper recommends a strategy in which electronic and data acquisition systems for MP experiments are designed to acquire and store as much raw data as possible from the sensors to enable offline data processing capabilities such as analysing time correlations between detectors, extending measurement ranges or correcting drifts in signals. A next generation scientific documentation tool such as literate programming is recommended to document the post-processing strategy within its source code.

1. Introduction

Novel modelling and simulations (M&S) capabilities in nuclear engineering offer comprehensive insights into physical phenomena and present new opportunities for the designer. The availability of dependable numerical predictions and complex sensitivity analyses form the foundation for swift, iterative design processes that lead to heightened safety margins and improved economics for new designs. Additionally, these advanced M&S capabilities yield more comprehensive, well-informed, and less conservative safety assessments of existing designs to support, e.g. nuclear long-term operation (LTO) by lifetime extension, power uprates of nuclear power plants, and higher fuel burn-up, which are key economic improvement factors for the operation of the current fleet of nuclear power plants (IEA and NEA, 2020).

On the nuclear reactor core level, the system behaviour is described by an interplay of different physical phenomena at various time and length scales, notably nuclear physics and neutron transport (neutronics), thermal hydraulics, and material behaviour. Novel M&S approaches for the reactor core simulations implement a fully coupled, so-called multi-physics (MP) approach, which yield unprecedented spatial and temporal resolution.

There is still a challenge to validate the novel multi-physics simulation tools. A code with high-resolution requires also high-resolution experiments to validate its predictions and ensure its stability. However, the availability of high-resolution datasets for the validation of the novel MP reactor core simulations is still limited. The deficiency lies in the absence of both experimental data and reliable estimates of their associated uncertainties, both of which are crucial for validation purposes. Moreover, one can frequently observe a disconnection between the measured physical quantity and the computed quantities[1], necessitating a complex process to connect them. This process can introduce unwanted biases and additional uncertainties. So there is a need for additional experimental input and innovative experiments.

This working paper aims to provide recommendations on how to mitigate the conflict of increasing experimental needs and decreasing funding for the experimental facilities. The question that will be addressed in this paper is*: "What would be the best experiment to validate a novel high-fidelity MP modelling tool?"*, and the main objective is to provide guidance on how to select and design the experiments.

Exhaustiveness is out of the scope of this paper. The validation domain considered for this paper are pulsed reactors (CABRI/TREAT) as well as Gen-II/III reactors, preferably pressurised water reactor (PWR), assuming steady-state and transient events (normal operation and accident situations). The types of MP codes to be validated are considered to be similar to the novel approaches represented by the CASL, NEAMS and NURESAFE platforms (Turnsky and Kothe, 2016; Sofu and Thomas, 2017; Chanaron, 2019), i.e. tightly coupled tools with high resolution in space and in time.

The main outcome of this working paper is a detailed methodology, which will be illustrated for a challenge problem. The challenge problem has been selected within the focus areas identified by the Expert Group on Multi-Physics Experimental Data, Benchmarking and Validation (EGMPEBV) in (NEA, 2016). It is the pellet cladding

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[1] An illustrative example is the k_{eff} parameter where voltage or current is measured and recorded, and a non-trivial process is required to determine the required physical quantity.

mechanical interaction (PCMI) in transient reactors. Indeed, PCMI in a reactivity-initiated accident (RIA) covers most of the domains considered by the EGMPEBV, except chemistry (link with crud deposition), resonance/vibration (grid-to-rod fretting) or damages to the containment. A similar approach should be carried out for each of the different challenge problems defined in (NEA, 2016) to design the experiments required for MP validation. Thereby, it will be required to make the difference between steady-state and transient operation situations, or between safety-oriented or industrial optimisation topics.

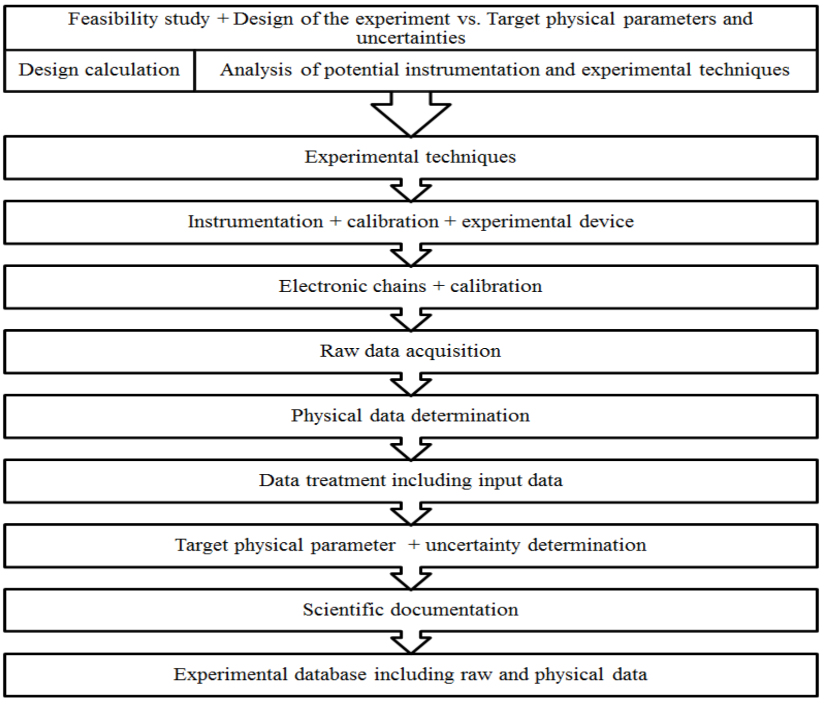
The paper is organised as follows. In the second chapter, the concept of a measurement is reviewed so as to clarify what is involved when an experiment is designed. In the third chapter, the methodology involved to design a new experiment is sketched. Reference to key bibliography is provided. Finally, the fourth chapter illustrates the methodology for the challenge problem of PCMI in transient reactors such as CABRI or TREAT. Specifically, to provide a picture of the state-of-the-art, the existing instrumentation of a pulsed reactor (CABRI as an example) is described first, listing all the quantities measured. Then the approach to determine what should be the novel instrumentation for measurements in support of MP validation is given.

2. Definition of a measurement

The measurement of a quantity is a very complex process that goes far beyond instrumentation. The objective of the present section is to review the major steps of a such process to identify the existence of potential weaknesses.

The overall process of performing an experiment is depicted in Figure 1 (Hudelot et al., 2018). It emphasises the fact that an experiment must not be resumed only to the choice of an instrumentation and to the measurement of raw data, e.g. signals delivered by the instrumentation, such as a current or a voltage. To transform the experimental raw data into the target measured physical parameter and its associated uncertainty, a number of steps are involved, which include 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).

Figure 1. Overall process to complete an experiment



Source: CEA, 2023.

One of the major issues with the generation of experimental data is the physical data determination. The physical data is the quantity that will be compared to a model prediction during the validation process. The link between the raw measured data and the physical information usually involves computation results based on models, which can potentially bias the "measured" physical data. So models are required to generate data for validating models, which is known as the Ouroboros paradox. In this setting, the degraded performance of one component of a system degrades the performance of the whole system, which, in turn, will further affect the degraded component behaviour.

The generation of experimental data has, e.g. been illustrated in (Rais et al., 2018), which deals with the measurement of control rod reactivity worth in the CROCUS zero power reactor (ZPR). The paper describes the process to go from raw experimental data (e.g. detector's count rate) to the physical quantity to be simulated (e.g. the control rod worth). The estimation of the control rod worth requires the use of parameters determined through calculation, which, in turn, alter the result of the measurement both in terms of accuracy and precision. In the paper, the effect of kinetic parameters and nuclear data libraries on the determination of the control rod worth was highlighted. The resulting experimental uncertainty increased from less than a percent for the inverse reactor period to around 3.5% for the control rod worth. Moreover, depending on the source of kinetic parameters, a bias of around 10% can be introduced in the experimental results. This work illustrates that even for experiments where the directly measured quantities (such as the inverse reactor period) are accurately and precisely determined, the physical quantity of interest (reactivity worth) can be biased using simulated parameters during the conversion from raw to physical data.

2.1. Reporting a measurement

The reporting of a measurement requires that the experimental setup as well as the facility itself are rigorously described. The description of an experiment includes the measurement methods used and the results obtained for the parameters of interest, as well as methods used to derive the physical parameters from the measurements. Experimental data include values of parameters that are needed to completely determine the boundary conditions of an experiment and that have been directly measured.

Care should be given to the reporting of the experimental information. The standard deviation and the mean value of the measured quantity are both essential when considering confidence intervals. Interested readers should refer to NEA (2019) for more information.

2.2. Determination of a reliable experimental uncertainty

It is generally agreed upon that estimates of physical data are useless if there is no knowledge of how reliable the estimates are. Therefore, reliable experimental uncertainties need to be determined.

A large body of work by the international community has been dedicated to the compilation of experimental database for the validation of neutron transport simulation through the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Working Group and of the International Reactor Physics Experiment Evaluation (IRPhE) Project released by the NEA. In the framework of those activities, best practices were developed for the evaluation of experimental uncertainties. The present text is a summary of those practices, which are themselves based on three main references, the respective US and European standards (ANSI, 1997; Bureau International des Poids et Mesures, 1999; ISO/IEC, 2008).

Even though the rigorous approach described in those references is used for neutron transport related experimental data, the guidelines for the evaluation of experimental uncertainty remain applicable to the other fields of nuclear engineering. It should be noted, however, that some of the steps (sensitivity analysis and combination of uncertainties) may be very difficult for the non-linear problems featuring important parameters with non-Gaussian distribution. Such problems are few in the field of neutron transport but are very likely to occur in the fields of thermal hydraulic or fuel performance.

Typically, uncertainties in measurements are of two types: there are aleatoric and epistemic uncertainties. The first type of uncertainties is the aleatoric (or random) type. An example of random uncertainties is the fluctuations of the number of counts recorded by a neutron detector.

The second type of uncertainty is the uncertainty of the epistemic uncertainty, also referred to as systematic error. A systematic error occurs when a series of measured values are incorrect by approximately the same amount. An example of systematic error is the power calibration of a research reactor. Unlike random uncertainty, repeated measurements of the parameter cannot reduce the systematic uncertainty. Those uncertainties are typically very difficult to estimate. One way to do so is to base the estimation of systematic uncertainty on the observed trends.

With respect to the inventory of the source of uncertainty, a rigorous approach needs to be undertaken to have an exhaustive reporting: each possible source of uncertainty in the experiment should be reviewed and considered. An example of such a rigorous approach is provided in Table 1 of the ICSBEP uncertainty guide (NEA, 2019). Uncertainties of the actual measurands and also for additional parameters of interest need to be provided. The parameters of interest are particular values of quantities that define the physical setup (dimensions, material compositions, masses, temperature, etc.) at the time of the experiment.

When an uncertainty estimation is missing, then an approximate uncertainty of the parameter can be estimated based on the typical uncertainty of the considered parameter at the experimental facility at the time of the experiments, information from the manufacturer of the measuring device, and personal experience. The basis of the uncertainty estimate should always be explained. A prime example of this approach was used in the "Radiochemical Analysis of mixed oxide fuel (MOX) and uranium oxide (UOX) light water reactor (LWR) Fuels Irradiated to High Burn-up" (MALIBU) programme (Boulanger, 2007) where a 10% uncertainty was assigned to certain isotope concentrations reflecting the spread of the measurements obtained at various institutions even if the precision of the measurements at a given facility was better.

Comparison of model results to experimental datasets with realistic uncertainties finally allows for revealing weaknesses in computational methods, reducing or eliminating them, and designing more accurate computational schemes for the future.

3. Process to develop an experiment dedicated to the validation of MP tools

The determination of the measurement techniques (both existing and novel) and their associated measured parameters for the "best experiment" should be specified based on an iterative process with multi-physics *(*MP) modellers as a clear expression of the needs for multi-physics validation is paramount to the proper use of experimental technique. In particular, modellers should express what exactly the quantity they want to measure is, and experimentalists should specify for each kind of measurement technique what the quantity measured is, and what the derived quantities are that should be obtained (Oberkampf and Roy, 2010).

The methodology for developing experiments should be composed of four steps as described in the following four dedicated subsections. It has for example been used to determine the kind of instrumentation to be included in the test vehicles of TREAT. The new instrumentation is developed to address the needs for validation of MP in a cheap and convenient way, and it will become obvious that simulations are envisioned as a driver for the experimental development.

3.1. Step 1: Determination of the validation requirements

A careful determination of the validation objectives is needed. Namely, what quantity needs to be predicted by the MP tool during the validation process? The regulatory body and industry are the usual end users of codes and simulation tools. As such, their needs will define the validation requirements.

A list of specific MP validation requirements including the Quantities of Interest (QOIs) and their target accuracies are expected as input.

3.2. Step 2: Expression of the modelling needs for code validation

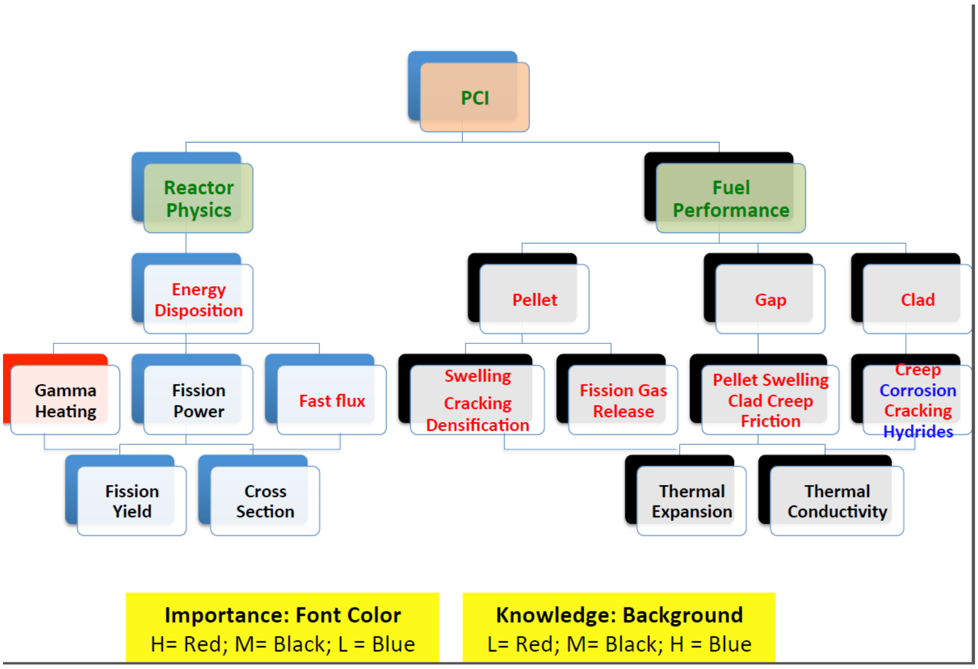
The modelling needs consist in a list of quantities to be measured with an associated resolution and target accuracy in order to fulfil the validation requirements. They include a list of global and local parameters usually predicted by MP codes. Global parameters are easy to instrument and measure but may not be relevant for MP validation purposes. However, because many of the local parameters are difficult to measure directly, calculations may be necessary to estimate local parameters based on global parameters. This is a challenge in validation, as the use of calculated local parameters does not validate a computational scheme.

Even though for controlled laboratory experiments, practically any parameter can be measured, the same measurement may not be possible in a MP validation experiment due to the measurement conditions (pressure, temperature, radiation field, etc.). Moreover, the precise knowledge of one parameter (e.g. clad temperature measured by thermocouple) may increase the uncertainties on other parameters (e.g. pressure and velocity). Non-intrusive measurements (e.g. by laser) may improve this.

An approach relying on "all possible quantities" is not reasonable: to reduce the cost of the next generation of experimental facilities, not all the predictable quantities should be measured and prioritisation is required. The required instrumentation should be developed to measure the quantities needed for validation purposes as well as to estimate their uncertainties.

The key to define the modelling needs is an exhaustive literature review on the phenomenon of interest, considering existing resolution and associated uncertainty. Such a review will produce Phenomenon Identification Ranking Table (PIRT) based diagrams. Figure 2 shows the PIRT example for PCMI. The PIRT diagrams aim at describing the physical parameters of importance from a modelling perspective. As far as measurements are concerned, together with the actually quantities of interest also all so-called “influence parameters” should be determined. These parameters, including, for example, the temperature field and pressure, then also need to be measured and reported. The PIRT shows also what measurement techniques could be applied to measure a quantity of interest for MP code validation for a given physical phenomenon (see row 4 of Figure 2, e.g. gamma heating, fission power).

Figure 2. Phenomena identification and ranking table (PIRT) decomposition of pellet-clad mechanical interaction (PCMI)



Source: CEA, 2023.

3.3. Step 3: Review of the existing measurements for the considered problem

After determining the validation requirements and the modelling needs to fulfil those requirements, the next step is to summarise the existing techniques for a given problem.

Based on the PIRT diagram, the existing instrumentation in the facility of interest is reviewed for each physical parameter of importance as well as for the influence parameters. The level of knowledge for each technique in application is assessed: spatial and time resolution, limitations. From this assessment and given the modelling needs, the limitations of the current experimental facility for MP code validation are determined.

Another method to determine which measurement requires improvement relies on the determination of a Phenomenon Assessment and Ranking Chart (PARC) through the input of expert and non-expert participants via online questionnaire. The PARC method was tested for pellet-clad interaction modelling problems, but its outcomes are not fully satisfactory as no real prioritisation of the various phenomena (and the associated QOI) was achieved as all physics were ranked with approximately the same weight.

3.4. Step 4: Selection of an existing solution or potential candidates to address the experimental needs

Once the limitations of the current measurement techniques for the requested QOI are determined, the novel measurement techniques can be designed using Quantitative Phenomena Identification and Ranking Table (QPRT) (Yurko and Buongiorno, 2012). If the MP simulation tools can predict a lot of detailed local information, it is not the case for the experimental data. To reduce the cost of the next generation of experiments targeting MP validation, the required instrumentation should be developed using a QPRT approach to prioritise which quantity should be measured and with which accuracy.

The idea is to perform a sensitivity analysis (SA) of a given QOI with respect to the input parameters using a simulation tool to gain a better understanding of the experimental parameters to control or to measure, which is key to reach the QOI target accuracy. Such an approach is used to determine the kind of instrumentation to be included in the test vehicles of TREAT (Jensen, 2016).

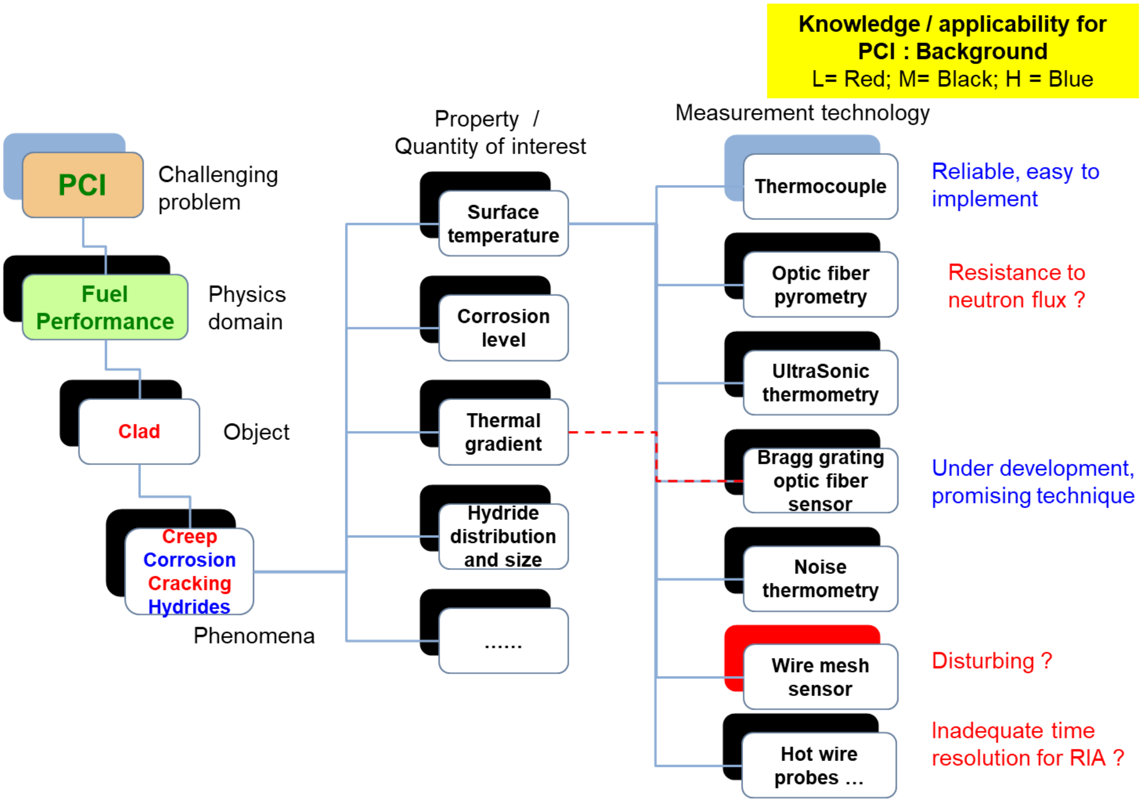
It should be noted here that the SA process depends on the quality of the applied calculation tools. When the tools exhibit a bias, which is not well understood (system codes for example), then the SA process might lead to completely wrong results and the subsequent experimental design might be flawed.

Figure 3 provides an example for the process of finding suitable measurement techniques for a given phenomenon. The example addresses the “creep/corrosion/cracking/hydrides” box of the PIRT diagram illustrated in Figure 2, and defines a list of quantities of interest to be measured to describe the phenomena (determined through the QPRT analysis for example). A few sensors and relevant measurement techniques are then proposed to improve the measurement of such quantities. A detailed application of this process is provided in Section 4.4.

Innovative techniques and instrumentation are not the only approach for better experimental data. Several methods/techniques, such as combining techniques to measure a single parameter allows for enhanced confidence levels and identified biases. The next generation of measurements looks at more detailed signal analysis which can, e.g. provide higher order moments of a given signal or correlations between signals.

Finally, even though the goal of the present working paper is to describe the design methodology for an MP experiment, the single physics experiments and specifically separate effect tests are also very useful. They are designed to isolate a phenomenon of interest: well-defined boundary conditions and/or improved instrumentation strategies can be designed to optimise the validation of a specific model in an MP tool. Guided by PIRT and QPRT studies, the implementation of simpler separate effect tests can lead to cost reduction. However, ultimately, a full MP experiment is still required to test the description of the coupling of the different phenomena.

Figure 3. Novel measurement approaches for the phenomena associated with the cladding during PCMI



Source: CEA, 2023.

4. Demonstration of the methodology for PCMI

This chapter provides a demonstration of the general methodology for designing new MP experiments as described in the previous chapters for validating PCMI in a pulsed reactor (e.g. CABRI and TREAT).

In this chapter, a technique is referred to as “state-of-the-art” when it is currently used in pulsed or material testing reactors. Some experimental techniques might already be readily implemented in other domains. However, if they are not yet applied in the considered reactors, such techniques are still categorised as “novel”.

To protect intellectual property, the description of measurement techniques will not include technical details, and references to open literature are provided, if available. It is noted that also the combination of “state-of-the-art” measurement techniques could lead to a better determination of the parameters of interest with reduced uncertainty, to a determination of quantities not yet measured, or to the identification of new phenomena. For example, initiating phenomena for PCMI could be analysed with the help of acoustic signals correlated with signals of pressure, temperature, flowrate and boiling detectors.

4.1. Steps 1 and 2: Validation requirements and expression of modelling needs

The PIRT diagram illustrated in Figure 2 including a phenomena identification and ranking table (PIRT) decomposition of the pellet-clad mechanical interaction (PCMI) is used as a starting point. The aim of this chapter is to illustrate the methodology and not to actually design the experiments that one would need for the validation of an MP code for PCMI analysis. So it is not a concern that Figure 2 is incomplete as, e.g. the thermal hydraulic related phenomena are missing, and not fully applicable to PCMI during a transient experiment.

Based on the PIRT in Figure 2, the following physical parameters are considered of importance for PCMI:

- gamma heating;
- nuclear fission power;
- fast flux;
- pellet swelling, cracking and densification;
- fission gas release;
- friction/bounding layer of gap;
- cladding properties.

The modelling needs[2] for the validation process requires online measurements with improved spatial and temporal resolution of the previously mentioned quantities; to match as closely as possible the resolution of novel MP codes.

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[2] Please note that a comprehensive overview on data requirements specific to fuel performance modelling, including PCMI, and on determining the types of experimental data, and their sources, which can be used to meet these requirements is currently prepared by the NEA Expert Group on Reactor Fuels Performance (EGRFP). More information on EGRFP activities is provided on the website: www.oecd-nea.org/jcms/c_12837.

The influence parameters to be controlled include:

- the material properties of the irradiated sample (e.g. history, composition);
- the reactor operating conditions (e.g. coupling factor, power profiles, reactivity determination, temperature coefficient);
- the test device conditions (e.g. local temperature fields, flowrates and energy depositions).

The following sections review the status of current instrumentations and experimental techniques to measure the above-mentioned physical parameters and the influence parameters related to the test device conditions.

4.2. Step 3: Review of the state-of-the-art of current instrumentation and experimental techniques

With the validation and modelling requirement set, the experimental techniques are reviewed to determine the limitations of the current experimental data for MP code validation. For each box of the PIRT diagram in Figure 2, the related experimental techniques at CABRI are listed in the following sections. A review paper (Kim et al., 2011) addresses most of the state-of-the-art techniques in use in irradiation testing of fuels and material and covers most of the experimental techniques listed below.

In the following, only sensors and experimental techniques are listed and discussed. As already discussed in Chapter 2, a measurement consists also in data processing of the experimental results including, e.g. time series or image processing steps. However, this second aspect will not be addressed in detail for the sake of conciseness.

It must also be kept in mind that some techniques have been developed specifically for a given facility, and may not easily be transferred to other experiments or be transposed from a small to a large facility.

Derived quantities are not directly mentioned but must be kept in mind. For example, the coupling factor (ratio of the driver core power to the tested rod or fuel assembly power) is not directly measured, but derived from power, temperature, gamma heating and some other influence parameters. Therefore, even the most usual measurement and data tables must be carefully checked and, if possible, enhanced.

4.2.1. Gamma heating

The gamma heating measurement aims at characterising the energy deposition in the surrounding of the fuel sample. Gamma thermometers (see Figure 4) and differential calorimeters (see Figure 5) have been developed to characterise the irradiation locations but only in unperturbed conditions (Van Nieuwenhove and Vermeeren, 2020) (e.g. without the sample to be irradiated and its container).

The thermometer principle is based on the measurement of the temperature difference between the tip of the inner body and the coolant measured by a differential thermocouple (type K). The inner body (made of stainless steel) is heated by gamma rays and is thermally insulated from the outer housing by a gas layer (0.7 mm).

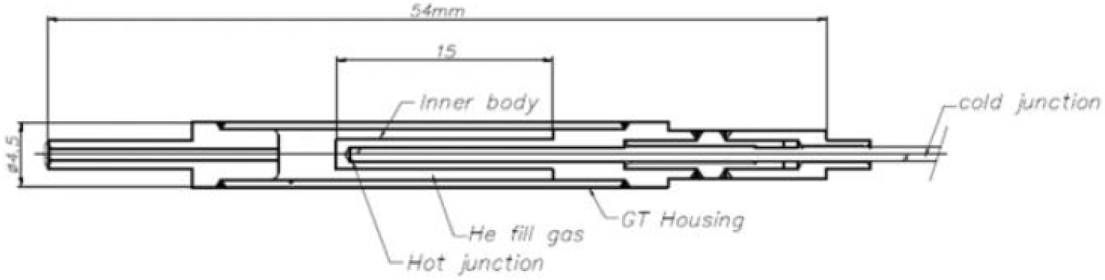
The differential CALMOS calorimeter device (Carcreff et al., 2018) developed for the open pool research reactor (OSIRIS) measures the differential temperature difference between the pedestal and the base of each cell and between the sample and the reference cells when they are exposed to the same irradiation field. The achievable performances of this kind of instrumentation with a measurement range from almost 11 W/g down to a tenth of mW/g with a 5% precision.

Due to their dimensions, this instrumentation cannot be inserted in the fuel element. Therefore, gamma heating in the fuel sample itself needs to be inferred from non-perturbed measurements noting that gamma heat deposit is roughly proportional to the Z of atomic element of the target medium.

The TRIPOLI 4 Monte Carlo code provides accurate simulations of the gamma heating as shown in (Carcreff et al., 2018). It can be noted that gamma heating is not a direct measurement of the gamma fluence (rate) because it depends on the energy effectively deposited in the medium by each photon.

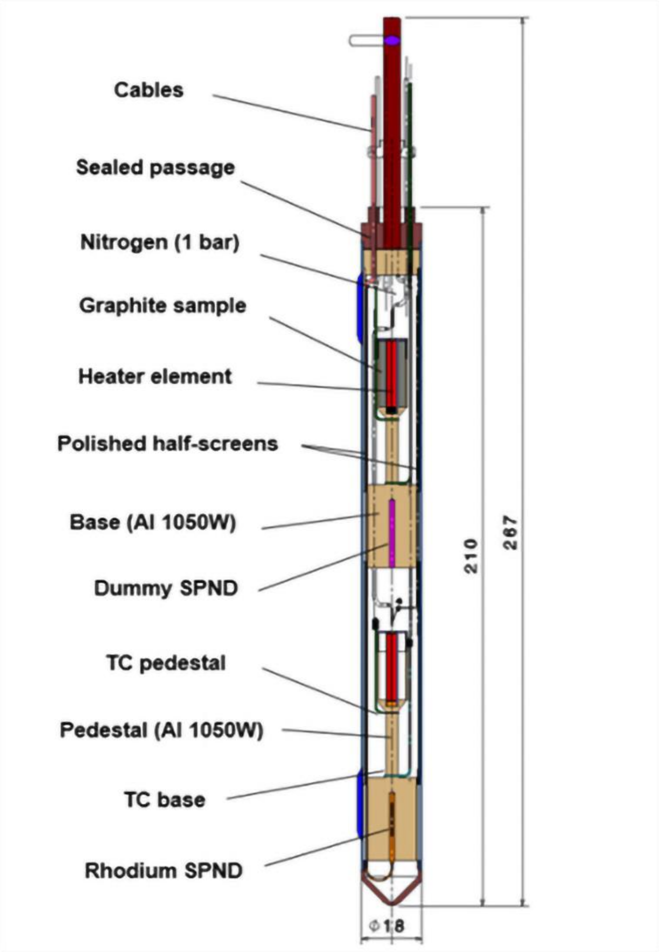
Gamma flux could also be measured by ionisation chambers as well as self-powered gamma detector (SPGD) as it was carried out at TREAT (Jensen, 2016; Bess et al., 2019). A SPGD differs from self-powered neutron detector (SPND) by the nature of the emitter (Bismuth) sensible specifically to gamma photons (see Figure 6) (Villard et al., 2016).

Figure 4. Schematic drawing of the SCK CEN gamma thermometer



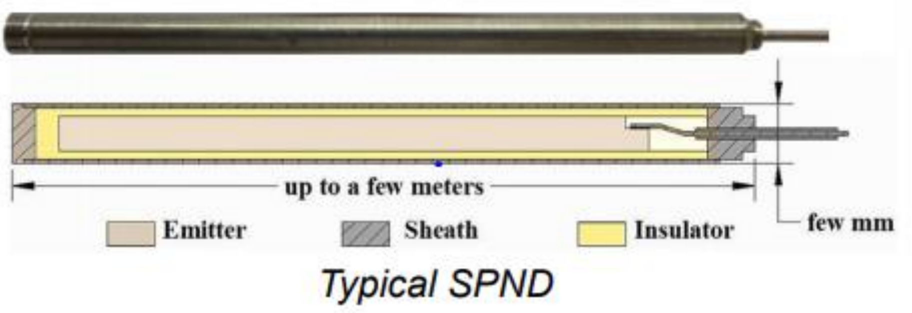
Source: SCK CEN, 2023.

Figure 5. Cross-section of the CALMOS-2 calorimetric probe (dimensions in mm)



Source: CEA, 2023.

Figure 6. Typical SPND/SPGD



Source: CEA, 2023.

4.2.2. Nuclear fission power

The determination of the energy produced at the location of the fuel sample is key to the determination of the energy deposited in the fuel. The next sections deal with the two types of fission powers needed to be determined accurately: reactor power and test vehicle power.

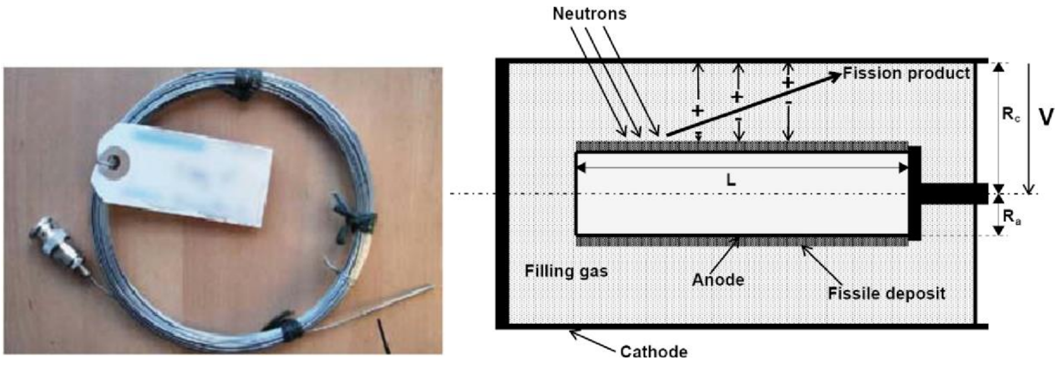
Reactor power

The power released by fission reactions in the reactor drives the energy deposited in the fuel sample. The thermal power is related to the number of fissions using the mean energy released by each fission. The macroscopic power of the reactor is classically monitored using ex-core boron-type ionisation chambers. Those online measurement techniques and sensors are detailed in (NEA, 2000; Harrer and Beckerley, 1974).

The determination of the thermal power of a nuclear reactor, which is directly linked to the number of fissions per second, relies on three different techniques depending on its effective power level and stability. For low reactor power, where no enthalpy measures are possible (e.g. due to an insignificant temperature difference in between input and output cooling fluid), the total number of fissions in the core is derived from online measurements performed by calibrated fission or ionisation chambers. They give access to the fission rate at the measurement location and, using neutronics simulations for mapping the fission distribution over the reactor core, the total fission number occurring can be deduced. Thermal reactor power is then derived from the fission rates considering the mean energy per fission as well as the energy loss due to gammas and neutrons leaking from the core at the periphery of the reactor.

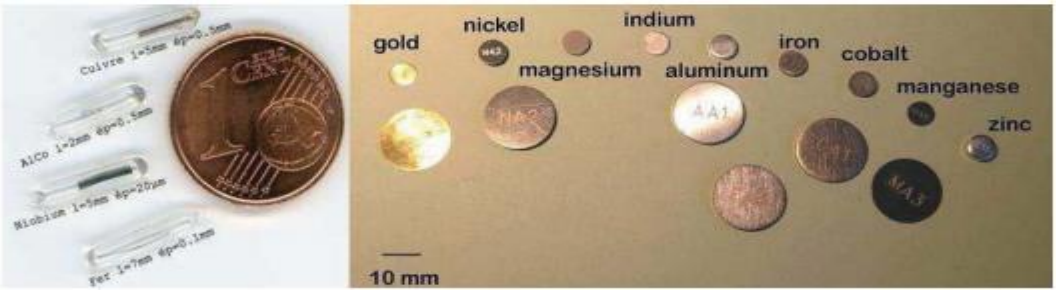
A fission chamber (FC) is an ionisation chamber filled with a neutral gas and is composed of a cathode and an anode on which a well-characterised fissile material is deposited. The fission reactions occurring in this material lead to the production of ions (fission products) and to the formation of an electrical signal (see Figure 7).

Figure 7. Example schematic and photo of fission chambers



Source: CEA, 2023.

Figure 8. Representative activation foils and wires



Source: CEA, 2023.

The absolute local flux level can be inferred from activation measurements, as it has been performed at the Measurement Applied to DosimEtry for Reactors (MADERE) platform for the CABRI reactor commissioning test (Lecerf et al., 2017) (see Figure 8) or from measurements using fission chamber calibrated for example in the BR1 neutron spectrum benchmark (Lamirand et al., 2014).

When the reactor power is sufficiently high (>100 kW), the coolant is heated during the circulation in the core and the absolute thermal power can be determined through enthalpy balance measurement (e.g. flow and temperature measurements) between input and output coolant flows. The relative change of the global power of the reactor is typically monitored by boron chambers calibrated at some specific steady state of the reactor. Few steady-state measurements are carried out over the full power range envisioned during the test. Determination of power and fluence rates at a specific location needs modelling and various corrections to be derived with a good accuracy (Pantera et al., 2014).

The power follow-up in transients (up to 25 GW) consists in energy balance measurements (integration of thermocouple responses). The linearity of the ratio of energy balance to count rates of boron chambers is established by showing repeatability over multiple pulses (Lecerf, et al., 2018).

Test vehicle power

The power deposited in the tested fuel sample is determined from the power produced in the core during the pulse and the knowledge of coupling factors relating the power deposition in the test vehicle to the core power. It is thus determined in a two-step approach:

1. An energy balance measurement is carried out in the test vehicle in steady state for the core power below 25 MW. The underlying assumption is that steady-state and transient neutronics conditions are the same.
2. The coupling factors are determined, which are measured as the ratio of energy deposition core/energy deposition in sample in steady state (both CABRI and TREAT). Energy deposition in the sample is determined by energy balance through online measurements. Dosimeter wires are used in TREAT for sample energy deposition but they require post-irradiation experiment (PIE) analysis to determine the coupling factors.

In some reactors (high-flux advanced neutron application reactor [HANARO] [Yang Noh et al., 2018], OSIRIS [Loubiere et al., 2012]), a spatially resolved power distribution in the core is determined through PIE by checking the activity of a few fuel rods by gamma activation measurements, but such measurements are not performed in CABRI.

In addition, miniature fission chambers can be inserted in the test vehicle in an empty location. They provide online fission power measurements, however, perturb the experimental conditions. So the measurements are not performed during the transient but only in steady state.

4.2.3. Fast flux

Fast flux measurement is relevant for steady-state irradiation and not so much for transient experiment in pulse reactor like CABRI. Nonetheless, spectral indices in CABRI are measured in steady state for a characterisation of fast flux.

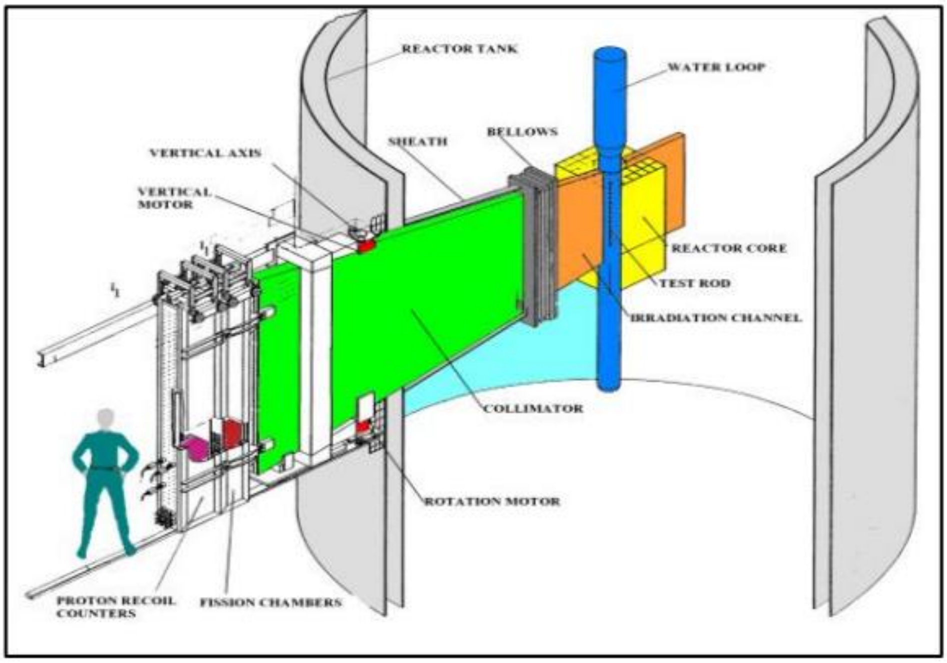
In the Institute for Energy (IFE) Halden reactor (Solstad and Van Nieuwenhove, 2011), SPNDs are used to determine the thermal flux. Modelling is used to infer the fast flux in the sample based on the thermal flux measurements.

4.2.4. Pellet swelling, cracking and densification

The axial motion of fuel pellet stack in the test vessel is monitored online during transients with the hodoscope, which is made of an array of fast-neutron detectors (proton recoil detectors and ^{237}Np fission chambers for CABRI). It allows measuring fuel distortion, elongation and relocation during transients. The spatial resolution of the hodoscope is not good as it has only few pixels but it provides temporal information about fuel geometry with a very good resolution of milliseconds. Depending on the measurement conditions, the hodoscope may detect a radial fuel motion as small as 0.2 mm, and an axial elongation as small as 2 mm. Complex post-processing is needed to handle background noise. Normalisation to fresh fuel is also needed.

In addition to the information provided by the hodoscope, experimental data is typically obtained before and after the test through ceramography. No experimental information on the size of the sample is available during the ramp. This means that only a partial validation of the MP simulation can be done.

Figure 9. Schematic of the CABRI Hodoscope

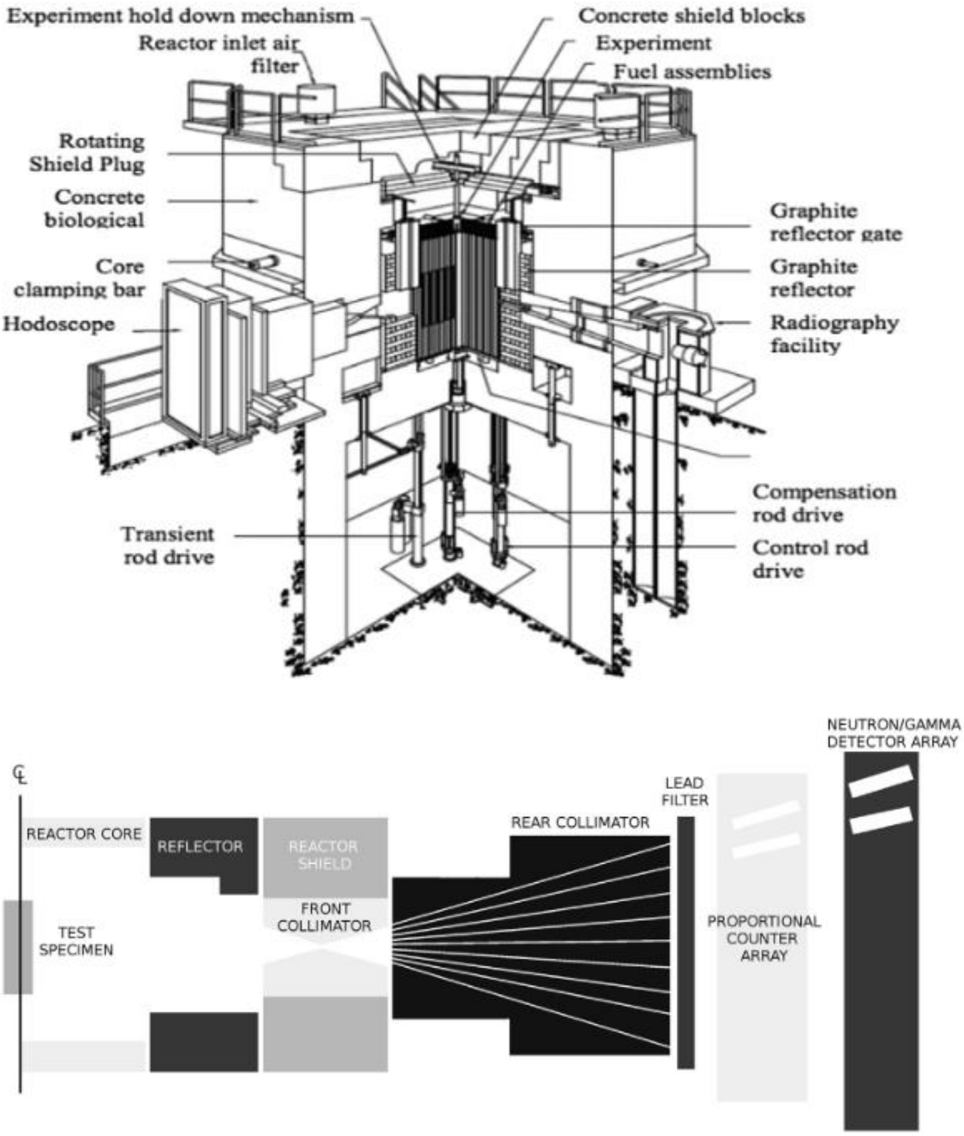


Source: IRSN, 2023.

The TREAT facility has also utilised in-pile high speed videography to directly image the behaviour of nuclear fuel under transient conditions. The high speed video has provided high value information on fuel motion and coolant voiding behaviours in dry and water environments.

Moreover, the fuel sample is examined with gamma-scanning, X-ray tomography and radiography before and after the pulse. In CABRI (also in TREAT), neutron radiography was performed in the past but is not available anymore. Progress has been made to improve the acquisition rates and digital imaging versus film development. Gamma spectrometry with high-purity germanium detectors (HPGe) focusing on ^{137}Cs is made before and after the test to create an exposure profile (Lemoine, et al., 2012). After the transient, changes in axial profiles allow the determination of changes in geometry. Depending on the collimation window, spatial resolution around 1 mm can be achieved.

Figure 10. Schematics of theTREAT Hodoscope



Source: INL, 2023.

Figure 11. Pre- and post-neutron and gamma scanning

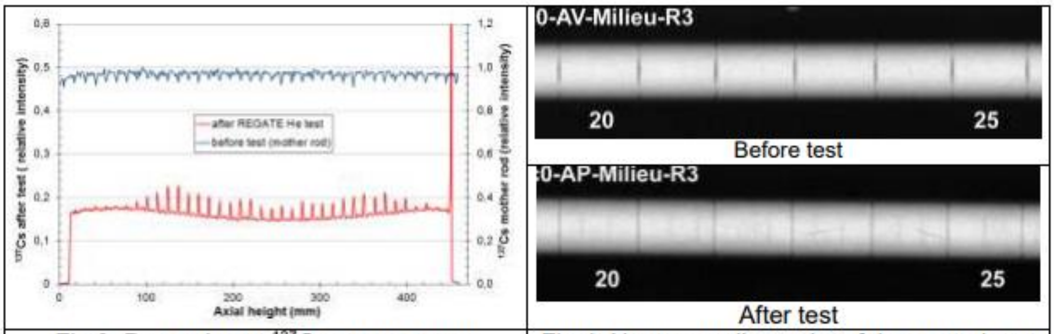


Fig 3. Pre and post ^{137}Cs gamma scan

Fig 4. Neutron radiography of the central part

Source: CEA, 2023.

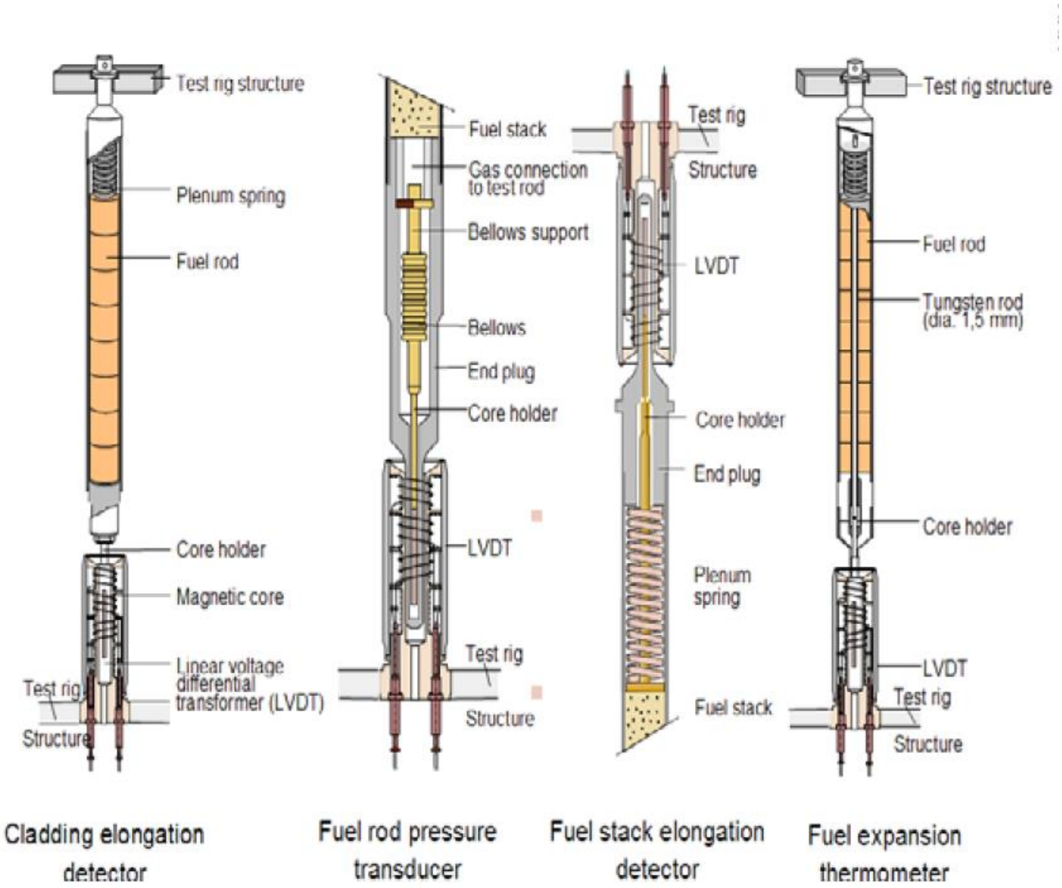
4.2.5. Fission gas release

Acoustic sensors have been used in the materials test reactor (MTR) OSIRIS to detect fission gas release (Lambert et al., 2011). The online determination of the gas composition is inferred from modifications in the speed of sound following changes in the gas composition. During the OSIRIS test, a 2% error was observed compared to other measurement techniques. The benefit of acoustic sensors is that they do not require specific fuel rods to be developed. Such sensors are sensitive to high temperatures and need to be optimised for operating in reactivity-initiated accident (RIA) conditions.

Another approach to determine the fission gas release is to monitor the pressure in the fuel sample outside of the core and the gas flow out of the fuel element where the activity composition is determined through gamma spectroscopy. The technique can be used for steady-state and loss-of-coolant accident (LOCA) type transients. However, it cannot be applied to RIA transient experiments because the transient is too fast and the gas transport out of the core does not represent the actual kinetics of the physical phenomena.

The absolute pressure inside the test fuel rod can be measured using linear variable differential transformer (LVDT) as shown in Figure 12 (Solstad and Van Nieuwenhove, 2011).

Figure 12. Different applications of the LVDT sensors



Source: Solstad and Van Nieuwenhove, 2011.

The fission gas release can also be assessed experimentally through post-irradiation drilling techniques if the fuel is intact. As it is a post-irradiation technique, such a measurement gives information about the equilibrium conditions, but not about the kinetic process. As a result, only a partial validation of the MP simulation can currently be done.

4.2.6. Friction/bounding layer of gap

Currently, no measurement is available in CABRI and TREAT.

4.2.7. Cladding properties

A few cladding properties can be measured online including the axial dimension of the test fuel sample using LVDT detectors. No measurements are available for the radial dimension besides a diameter gauge test by IFE (Solstad and Van Nieuwenhove, 2011).

Moreover, through acoustic measurements with two microphones upstream and downstream of the test pin, it is possible to detect cladding rupture (if any) during the pulse experiment (Traore et al., 2017).

Similarly to the pellet properties of the fuel sample, non-destructive examinations are carried out for the cladding before and after transients: a set of visual inspections as well as metrology type measurements (diameter) using a confocal microscopy system, Eddy current and ultrasonic testing for defaults checking and oxide thickness determination. X-ray tomography (IRIS facility) with a spatial resolution around 400 microns is carried out as well. It should be noted that radial displacement instrumentation has not yet been implemented, because it was proven to be too intrusive and disturbing for the representativeness of the fluid flow. An online cladding dimension measurement has once been carried out during the experiment for online cladding creep studies (MELODIE) using diameter gauges (Guimbal et al., 2013).

4.2.8. Influence parameters

“Influence parameters” are the physical parameters that affect the measurements of the processes of interest even though they are not strictly listed in the PIRT diagram in Figure 2 (e.g. the temperature field and pressure). Such influence parameters should be measured online as best as possible and should be reported.

Temperature

The temperature of the cladding in the test vessel is determined with thermocouples positioned on the surface of the cladding of the test fuel. To reduce the perturbation of the experimental conditions due to the measurement, no welding is done, only a mechanical contact is obtained through the use of a specific device called “cage”. Thermocouples are the state-of-the-art for temperature measurements. In the TREAT reactor, the temperature of the experimental vehicle is remotely measured through a window using an infrared pyrometer system (Jensen, 2016).

Flow condition in the test vehicle

The flow rate in the test vehicle is determined during the transient through flowmeters for transients, turbine flowmeters for steady-state measurements, and with Pitot tubes. Boiling can be detected through the use of piezoelectric ultrasonic sensors (one emitter and three receivers). Finally, the temperature of the flow can be measured with thermocouple at a given location facing the tested rod, but also upstream and downstream for the determination of the thermal balance in the test vehicle.

Pressure

Pressure measurements can be performed with LVDT. Counter-pressure sensors are used in the reactor of the Atomic Energy and Alternative Energies Commission (CEA) (Lambert et al., 2011), and piezoelectric sensors have been used for CABRI but have raised some reliability concerns. In the United States, in addition to the LVDT sensor, Fabry-Pérot detectors are tested (optic based deformation measurement) for pressure measurement in the gap (Jensen, 2016).

4.2.9. Electronic and data acquisition systems

Data acquisition systems are designed together with the detectors. Electronics should not be the weak link of an acquisition chain. The sampling rate, which is based on frequency bandwidth, data buffers size, and data transfer rate, and the acquisition input range must be adapted to the physical phenomena at hand as well as to the experiment at stake.

Taking the case of online detection of neutrons, for which detectors deliver current pulses, two types of acquisition systems are available depending on the flux range:

- At low flux, analogue or semi-digital acquisition systems can record and time stamp individual events to eventually deliver an event rate (also called counting rate). A standard (analogue) acquisition is based on a wide band current-to-voltage preamplifier, followed by a shaping amplifier and a voltage discriminator, which issue transistor-transistor logic (TTL) pulses fed to digital counting module. This process is reliable and robust, but limited by the dead time process to about six decades.

- For higher detection rates, detection events cannot be simply discriminated based on their amplitude. Acquisition systems then focus on sampling the overall current issued by the detector. This current is conveniently converted into voltage before sampling. Because the detection process is Poissonian, it is known that mean and variance (and more generally all the cumulants) of the current are estimators of the detection rate. This detection mode, standardly based on measuring the current mean over time using an electrometer, is limited to six or eight decades. Expanding the number of decades can be done at the expanse of temporal resolution.

In the past 10 years, a wide range of data acquisition systems have been developed for fission chambers. For example, systems by the CEA and Mirion rely on three measurement chains working in parallel on a single detector. A field programmable gate array (FPGA) module is in charge of online data processing (rescaling and data conversion) and producing a single flux estimator. These systems can cover up to 12 decades in neutron flux.

Nowadays, reactor physics is still using one measurement chain for each detector, whereas in particle physics, experimenters are used to integrated acquisition systems.

Neutron measurements, especially for pulse signals, deal with high frequency signals that have to be conveyed to the acquisition system on very long coaxial cables. The resulting signal to noise ratio is usually poor (around 10 or 20), sometimes impacting the quality or reliability of the measurement itself. Therefore, electromagnetic compatibility issues must be taken into account from the very beginning of the experiment design.

4.2.10. Scientific documentation

Measurement systems will be documented and operated following a quality assurance process. Raw data will be stored with the complete identification of each sensor.

The raw data are typically analysed, sometimes automatically, to produce a report. Results and reports will be archived in dedicated databases with meta data describing the experimental conditions. As the physical support (magnetic storage) and operating systems change periodically, databases need to be updated accordingly.

4.3. Step 4: Selection of an existing solution or potential candidates to address the experimental needs

4.3.1. Required improvements

Based on the outcomes of the previous steps of the analysis, the following improvements should be addressed by the measurements of the novel MP experiments in order to validate an MP tool:

- It appears that the amount of experimental data available for each transient test is rather limited. Specifically, the number and type of online measurements should be extended as to be able to validate the kinetics models. Indeed, a large amount of experimental data is determined through pre- and post-irradiation analysis.
- An improvement of the spatial and temporal resolution of the measurements is required as the MP codes typically lead to finer resolution; the computational results need to be compared to equivalent experimental data before to be trusted. Improvement in data

acquisition systems (e.g. sampling rates, signal to noise ratio) would allow a better temporal resolution with often the same sensor. Calibration and minimisation of the drift of sensor's response have also to be addressed to lower measurement uncertainties.

- The perturbation of the actual physical phenomenon by the sensor should be reduced by using distant sensors or by reducing its size, improving its compactness.
- Finally, the improvement of the data post-processing algorithms, in particular for acoustic signal, documentation and recording procedures would improve the experimental data treatment and could be helpful even for the re-analysis of past experiments.

4.3.2. Recommendations for the future instrumentation and experimental techniques

Once the limitations of the state-of-the-art measurement techniques have been determined, the experimental techniques in development or readily available in other domains are reviewed to find other solutions for meeting the MP code validation requirements. As pointed out already in Chapter 2, experiments consist of more than only instrumentation and require also, e.g. a collection of models, data, documentation, instrumentation and calibration as well as post-processing tools. Consequently, improvements can not only be obtained with improved instrumentation (e.g. with the help of an improved sensor) but also with improved measurement protocols (e.g. by better calibration, or by a combined use of measurement techniques).

The following paragraphs provide an overview of potential improvements by novel measurement techniques for each of the boxes of the PIRT diagram depicted in Figure 2. There is also complementary information available in (IAEA, 2013).

Noteworthy, many of the novel methods for inferring local parameters have been developed for controlled laboratory environments. Their potential in MP validation experiments with realistic power and irradiation conditions often still need to be demonstrated.

Gamma heating

Existing means to measure gamma heating rely on energy deposition and gamma flux measurements: differential calorimeters (CEA), gamma thermometers (Norway, Belgium). Such instruments may be relatively big and intrusive but are considered very reliable.

Miniaturisation has been identified as a progress priority, so measurement methods based on miniature gas ionisation chambers (CEA) and self-powered gamma detectors (CEA, Idaho National Laboratory [INL]) are now being investigated.

Delayed measurements of fine gamma flux profiles can be obtained using optically stimulated luminescence (OSL) and thermoluminescent dosimeter (TLD) detectors (CEA) even though such dosimeters are too sensitive for actual measurements during transients (Gruel et al., 2018; Le Guillou et al., 2017).

Miniaturisation of calorimeters with short response time has been investigated (CEA and Aix-Marseille University) (Reynard-Carette et al., 2018) with the possibility to insert them in the experiment vehicle. These types of sensors could be used for fuel ramp experiments, but not for RIA or LOCA type tests due to the very short time scale of the measurement.

Ongoing research is dedicated to estimate the impact of beta radiation on such measurements to evaluate its contribution to the overall radiation energy deposition.

Finally, online simultaneous gamma and neutron measurements are required to decouple the respective source of heat in the fuel sample. To this end, various sensors could be used simultaneously such as gamma thermometers, ultrasonic sensors, fission chambers w/o deposit (current mode), SPNDs and SPGDs. Temperatures measurements would ideally complete this set of measurements.

Fission power

For fission power measurements, there exist axial, radial, steady-state and time-dependent measurement techniques: fission power measurements are performed in real-time with fission chambers (FCs), and slightly delayed for SPND. The activation dosimetry technique gives a posteriori access to the precise evaluation of the integral number of fissions (e.g. total fission deposited energy).

The raw quantity measured are typically the reaction rates or the radioactivity of a sample at a given location. These raw data have to be corrected from gamma contributions such as photo-fission, photo-activation, gamma contribution to the delivered current to infer the true neutron induced reaction rates. Inferring local neutron power from such a measurement is not straight forward and includes normalisation of the local information to the thermal power produced by the reactor using modelling scheme. Therefore, neutron and gamma contributions should be measured simultaneously to enhance the precision of the local power estimation.

The global power produced by a given reactor is complicated to determine. The thermal balance method is the most appropriate and precise but it is not always possible for low reactor power. Neutron and gamma online measurements and activation techniques for post-irradiation calibration are used complementarily, and show-case the combined usage of several consistent experimental techniques to reduce the uncertainty on important experimental parameters.

The methods presented above are based on the default assumption of a constant neutron spectrum during the power pulse. This is not realistic because as the temperature increases, the effective cross-sections change (Doppler effect) and modify the spectrum especially in the epithermal energy range. Online measurements of the spectrum variation would therefore provide an improved characterisation of the power pulse. This measurement technique remains to be established, e.g. by using FCs or SPNDs sensitive to different spectral domains and by combining these measurements using a spectrum adjustment code such as the CALMAR code (Grégoire et al., 2016).

There are studies dedicated to test the similarity of steady-state and transient coupling factors, which is an important assumption to infer the fission power deposited in the fuel sample during transients.

Concerning modelling, the priority is given to the development of simulations of the existing detectors to understand the sensor behaviour (sensitive material loading, gas mixture and drift of the detector signal during the irradiation). The main challenge is to reduce modelling uncertainty, which is mostly driven by nuclear data and geometrical uncertainties.

In order to access to local flux, detectors could be inserted within the fuel pellet for online measurement. However, neutron flux measurements inside a fuel pellet, even with a 3 mm size micro-fission chamber (MFC), are considered to perturb the local conditions too much and to deteriorate the representativeness of the measurement.

Other techniques such as scintillators or optical fibres functionalised for dosimetry applications could be investigated but their current sensibility and linear type of response provide major drawbacks. However, recent studies on an optical fission chamber (Lamotte et al., 2020) and progress in SiC technology (Coutinho et al., 2021) have to be taken into account and could lead to significant progress in measurement techniques.

Fast flux

An accurate determination of the fast flux can be obtained by dosimetry techniques through the irradiation of a set of activation dosimeters with specific nuclear reaction thresholds. It is recommended to apply neutron spectrum unfolding methods to renormalise the absolute flux level and to evaluate the complete spectrum with realistic uncertainties.

For online fast neutron flux measurements during steady state and transients, FCs using specific fertile deposits (^{232}Th; ^{237}Np; ^{242}Pu) could be used. Those FCs have, however, a very low noise to signal ratio and a non-negligible gamma contribution, which can be reduced by running the FC in Campbelling mode. In addition, raw data should be corrected for thermal and gamma reaction contributions using thermal sensors or a dedicated neutron shield should be applied. Micropocket FCs developed by INL (Jensen, 2016) and optical FCs, which are promising sensors for this application should be investigated.

The hodoscope could also be used for time-dependent fast flux determination but the fast neutrons need to be discriminated from the thermal neutrons through signal post-processing. Several sensor technologies could be tested:

- The use of (micro pattern gas detectors [MPGD] – Micromegas sensors for CEA) could be envisioned as they were developed for giving an online neutron energy spectrum evaluation.
- Diamond detectors could be used for fast flux measurement. It was already used for instance in the Ulysse reactor in CEA Saclay, or in the CROCUS reactor of the Swiss Federal Institute of Technology (EPFL) (Hursin et al., 2018). Diamond detectors are good radiation detectors due to their wide gap width and high charge carrier mobility. These properties result in an excellent signal to noise ratio together with a very fast response time. Diamond detectors are very robust and can withstand large fluences without major degradation of their signal to noise ratio.
- SiC based sensors are interesting because of their improved irradiation resistance and of their increased energy sensitivity and larger dynamic ranges compared to diamond sensors.
- ZnS based scintillators could be used together with wavelength shifting fibres to achieve finer spatial resolution (Vitullo et al., 2020).

The feasibility of operating such measurement techniques in the demanding environments of pulse reactors remains to be demonstrated as they have been developed for relatively low flux levels.

Again, mixed sensor measurements can enhance the quality of the fast neutron flux determination to mitigate issues induced by the demanding measurement conditions with high thermal and gamma flux.

Pellet swelling, cracking and densification

Local porosity measurements are currently only accessible through post-irradiation analysis. However, there is also large interest in online measurement capabilities for detecting and differentiating cracking and porosity changes and to differentiate bulk and local phenomena.

Acoustic instrumentation allows for active and passive interrogation techniques to determine crack propagation. Those techniques are already used by the oil industry, are non-intrusive, and suited for high-pressure and high-temperature conditions.

Micro to millimetre resolution can be obtained through the use of linear variable differential transformer (LVDT) detectors. However, such detectors have large sizes and changes in temperature affect their measurements. Fabry-Pérot sensors have smaller size and only one wire (instead of 4 or 5 for LVDT). Diameter gauges have been designed by IFE since 1960s, but their application in pulse reactors is difficult because they cause a cold spot on the cladding, which might weaken the fuel and perturb the experimental conditions. Similarly, Bragg grating based sensors are used in buildings to monitor structure integrities (e.g. for pipelines). However, optical fibres are sensitive to large fluences and their transmissivity for visible light is degraded under irradiation since there is only a spectral window around 1µm with small attenuation. A pulse height based measurement design is not possible but interferometry is still applicable and has already been tested in the OSIRIS (Cheymol et al., 2007) and BR2 (Brichard et al., 2007) facilities.

Novel ultrafast X-ray tomographic technics with 5 kHz scans could be used, too. Deporting the X-ray source would allow using X-ray imaging under irradiation. Such technics could be investigated to measure clad-pellet gap evolution (Banowski et al., 2018).

Fission gas release

Fission gas release kinetics needs the measurement of two parameters to be characterised: pressure and composition.

Pressure measurement inside the gap and its evolution with time could be obtained by specific LVDT based sensors, as Japanese nuclear safety research reactor (NSRR) researchers have developed for measuring pressure inside test fuel pins during very fast transients (FWHM ~4 - 7 ms) (Fission Gas Dynamics programme) or through counter-pressure sensor (CEA). These sensors are bulky and require several gas lines or electric wires. Optical pressure sensors based on fibre optic properties or using a Fabry-Pérot sensors (as developed by CEA (Cheymol et al., 2020) in replacement of the LVDTs) could be advantageous. Classical direct pressure measurements based on the evolution of the amplitude of the ultrasonic signal cannot be applied because piezo-electric properties of the sensors are changing under irradiation.

Gas fission composition analysis could be performed in situ using a method of analysis of the acoustic wave propagation in the gap. The method determines the respective amount of He and fission products from the acoustic wave velocity in the gap, which is proportional to the molar mass of the gas. Post-irradiation measurements are also an option, and the slow nature of the fission gas release does not require a high sampling frequency or time resolution. The evolution of the elemental composition in Xe/Kr/He fission products could be measured online, giving access to the kinetic process of the gas release. Online measurement of molecular compositions during RIA may also be possible. Online in-core measurement by ultrasonic sensor was done in OSIRIS in 2011 (Lambert et al., 2011) for steady-state/ramp experiment. The temperature is a key influence parameter to be acquired during this measurement.

Friction/bounding layer of gap

Online measurements of gap profiles with acoustic interrogation (sonar like use) might be a candidate but two issues need to be resolved: development of a measurement device, which is moving during the experiment without perturbing the experiment, and optimising the acoustic coupling parameter (vibration, parallelism…) between cladding and the sensor all along the measurement area.

The differential movement of cladding with respect to the fuel pellet in the axial direction could be determined using LVDTs as performed by IFE (Solstad and Van Nieuwenhove, 2011). Even though, Eddy current based techniques could show the existence of a gap, its in-core implementation seems very difficult.

Cladding properties

The evolution of fuel dimensions (cladding length, densification) with exposure can be measured online using LVDTs as it is done in MTRs (HBWR, BR2, OSIRIS) and pulsed reactors (CABRI, NSRR). It is worth noting that transient measurements are possible but coils are sensitive to high radiation doses and electromagnetic compatibility effects. Replacement of the LVDT technology by an optical technology such as Fabry-Pérot sensors or dual Bragg grating measurements (one free fibre and one fibre is attached to the cladding being tested) have to be investigated as it allows miniaturisation of the sensors. Attention is required for the response time of these systems, which have to be coherent with the typical timescale of the observed physic phenomena.

The temperature of the cladding could be remotely measured using infrared thermometry technique as already performed at the TREAT reactor (Jensen, 2016). CEA (Bouvry et al., 2017) and IRSN are also developing infrared pyrometry systems using fiber optics to be applied respectively in Jules Horowitz Reactor (JHR) and CABRI. Infrared thermometry implies measuring a high surface temperature (above 800-900°C) in a significantly cooler surrounding media.

Acoustic methods for localisation and characterisation of clad cracking have to be further developed since acoustic signals are very rich in temporal and frequency information linked to different physics phenomena occurring in the fuel rod before and after the cracking (Traore et al., 2017). CEA is working on these techniques for future experiments as well as on improving the modelling the path of the acoustic waves.

Thickness and thermal diffusivity of cladding and of oxide layer could be measured during PIE with laser active pyrometry and phase sensitive modulation thermography (lock-in thermography). The measurement method might be suitable for irradiation conditions but further feasibility studies are required.

Influence parameters

The knowledge of the “influence parameters” listed below could be improved through dedicated online measurements with improved spatial and temporal resolution.

Temperature

Bragg grating (e.g. at CEA) and ultrasonic measurements (e.g. in the United States) provide fine and representative temperature profile measurements for the test pin. These measurements are more representative of the cladding temperature than thermocouples and far less intrusive.

Flow conditions in the test vessel

It may be possible to characterise the flow conditions in the test vessel through temperature variation measurements and, especially, the thermal noise technique, which comprises recording of temperature variations detected by different thermocouples at different locations along the fluid flow (Por et al., 2003).

Electrical impedance tomography can be used to accurately measure the mean void fraction. The spatial resolution of this method is low, but its temporal resolution can be very high with up to 1 kHz sampling rate.

Existing flow visualisation techniques used in thermal hydraulics in the PANDA facility could be adapted when possible (Paladino and Dreier, 2012). Particle image velocimetry could be used for the measurement of two-dimensional velocity fields (Kapulla et al., 2014). With respect to the determination of the two-phase flow in the test vessel following a departure from nucleate boiling (DNB) event, the following instrumentation could be adapted (it remains to be seen if those methods are suitable for the space and conditions constraints of the test vessel):

- Wire-mesh sensors based on measurement of electrical conductance are used for measuring two-phase flow parameters such as local void fraction, bubble velocity etc. They have also been used for measurements in single-phase flows where a small amount of tracer is added for studying fluid mixing. The typical data acquisition rate is about 20 Hz (Prasser et al., 1998; Ylönen et al., 2011).
- Cold neutron imaging: A non-intrusive imaging technique for non-transparent channels has been developed using cold neutrons. The technique was successfully applied for annular two-phase flow (Zboray and Prasser, 2013).
- Near infrared film thickness measurement: An optical method, where near-infrared light is used for the measurement of liquid film thickness using Beer-Lambart’s law (Mignot et al., 2018).

Finally, for high spatial-temporal resolution, distributed optical fibre sensors (Lomperski et al., 2015) could be used provided that those experimental techniques can be adapted to the pulse reactor type conditions.

Separate effect tests

In addition to the use of novel experimental techniques, another way to design MP experiment is through a separate effect test.

As mentioned in Chapter 3, performing separate effect tests before the actual MP experiment can help to reduce the overall cost of an MP experiment. Specifically, for the PCMI challenge problem, the manufacturing of fuel rods to match given fuel conditions (designed structure, porosity, pre-strained cladding mechanically and chemically, doping/artificial enrichment, hydrogen pickup, etc.) could be envisioned to produce tailored and controlled separate effect tests. Those tests are needed to improve the model performance according to pre-existing QPRT. Then more complex MP tests could be designed. Such an approach (several separate effect tests before the full MP test) could help to reduce the cost of generating relevant experimental data for MP validation, and typical biases of such experiments due to neutronics modelling (power history) of the considered fuel sample could be reduced. This approach is equivalent to using heated components in thermal-hydraulic experiments instead of nuclear heating.

Electronic and data acquisition systems

The MONACO system (Barbot et al., 2020), developed by CEA, is a suitable brick for MP acquisition system for neutron flux monitoring. It is a new wide range acquisition system for fission chambers dedicated to reactor physics experiments, which works in pulse, current and Campbelling mode (fluctuation mode) and accommodate four simultaneous and synchronised channels now commercialised as MONACO 3 system.

Instrumentation for MP experiments should be developed with the aim to acquire as much information as possible from the sensors, which is a strategy already successfully applied in high-energy particle physics. This strategy becomes even more important given the limited number of sensors in experimental vehicles. For example, for neutron flux measurements one should not only acquire the counting rates, but also energies and time of arrivals of experimental events. This strategy would enable new offline data processing capabilities such as analysing time correlations between detectors, extending measurement ranges or correcting drifts in signals.

For short experiments, like pulse reactor transients that last less than a second, the philosophy would be to limit as much as possible online data processing (like discriminating neutron pulses to produce TTLs) and, instead, acquire raw signals whenever possible similar to the analysis of acoustics sensors. It is already possible to digitise the whole signal of neutron detector (taken at the output of the preamplifier) with minimum loss of information. Of course, this type of “trigger-less” acquisition requires a large amount of storage and requires fast analogue to digital converters (ADCs).

Scientific documentation

The next generation of scientific documentation tool should be used (literate programming, a technique coming from computational engineering) to have documentation embedded in the post-processing code itself. The report could then be produced at the same time with the data itself. Choices have to be made, justified and documented; processed data are stored in a database with a coherent set of identification (meta) data.

The use of LaTeX or Markdown, a versioning system as well as the use of video recordings is beneficial. This approach is also very good for knowledge transfer.

5. Conclusions

This working paper summarises a methodology to design multi-physics (MP) experiments suitable for the validation of novel MP reactor core simulation codes. The method is illustrated for PCMI. The outcomes in terms of potential instrumentations are not meant to be exhaustive.

With respect to the status of the current state-of-the-art measurements in pulse type reactor, it appears that the measurements are not fully suitable for MP code validation. Gaps have been identified mostly related to the need for online data with an improved spatial and temporal resolution, but could partially be resolved with already existing techniques. However, the feasibility and usefulness of the proposed techniques under irradiation has to be demonstrated.

The determination of the measurement techniques (both existing and novel) and their associated measured parameters for the "best experiment" should be specified based on an iterative process with MP modellers: a clear expression of the needs for MP validation is paramount. In particular, modellers should express what exact quantity they want to measure; the experimentalists should specify for each kind of measurement technique what is the quantity measured, and what are the derived quantities that should be obtained, including uncertainties. For example, the cladding surface temperature or the thermal gradient within the cladding are not the same objects.

Finally, it should be stressed that although the goal is to validate MP simulation tools, measurements addressing only a single physical phenomenon at a time are still extremely useful as they allow reducing the experimental uncertainty and have better control on the potential measurement bias.

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