Analysis of the rod-drop experiments performed during the CABRI commissioning tests

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ANALYSIS OF THE ROD-DROP EXPERIMENTS PERFORMED DURING THE CABRI COMMISSIONING TESTS

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ABSTRACT

CABRI is an experimental pulse reactor operated by the CEA at the Cadarache research center. After its refurbishment, it is now able to provide experiments in prototypical PWR conditions (155 bar, 300°C). Before operating, commissioning tests were performed, including control rod worth measurements. These experiments are done thanks to the rod-drop technique, which gathers static and dynamic effects. This paper reminds the theoretical background of the rod drop analysis. Then it gives a rigorous definition for the MSM factors (i.e. spatial correction factors to take into account the modification of the detector efficiency). An uncertainty analysis is performed and results prove the validity of the proposed model. Finally, the conclusion focuses on some possible improvements, like a rigorous importance calculation using the stochastic code TRIPOLI-4® and the use of different nuclear data libraries.

1. Introduction

CABRI is an experimental pulse 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 have aimed at studying the fuel behavior under Reactivity Initiated Accident (RIA) conditions. From 2003 to 2010, it was refurbished in order to study the PWR high burn up fuel behavior. The facility was modified to have a water loop able to provide RIA and LOCA (Loss Of Coolant Accident) experiments in prototypical PWR conditions (155 bar, 300 °C). This project is part of a broader scope including an overall facility refurbishment and a safety review. The global modification has been conducted by the CEA project team and funded by the French Nuclear Safety and Radioprotection Institute (IRSN), which is operating and managing the CIP experimental program (CABRI International Program), in the framework of the OECD/NEA project.

During the restart, commissioning tests were performed for all equipment, systems and circuits of the reactor. Before beginning the experimental measurements, it is indeed necessary to prove that it is possible to accurately predict the safety parameters for the reactor operation and to effectively control the reactor. In particular, neutronics commissioning tests have been performed in 2016. This paper focuses on the analysis of the rod-drop experiments performed in CABRI, and analyzed with inverse point-kinetics. Some interesting spatial and dynamic effects were observed, and required more sophisticated analysis.

In the second part, the CABRI reactor and commissioning tests are briefly described. In the third part, a significant work is done on the theoretical background of the rod-drop methods. No deterministic geometrical model is currently available to calculate the CABRI core. The fourth part deals with this particularity, since rod-drop experiments are usually interpreted with deterministic solvers. The fifth part gives the main results and uncertainties of this study. A substantial effort was done to provide rigorous conclusions with respect to the main assumptions of the model. Finally, some perspectives are suggested to improve the analysis of rod-drop experiments.

2. CABRI Reactor and Commissioning Tests

CABRI is a pool-type reactor, with a core made of 1487 stainless steel clad fuel rods with 6% ^{235}U enrichment. The reactivity is controlled with a system of 6 control and safety rods (CR) made of 23 hafnium pins of each. The reactor is able to reach a 25 MW steady state power level. The core is cooled by a forced water flow of 3215 $m^3.h^{-1}$ when the core power is upper than 100 kW and by natural convection with the pool water otherwise.

The key feature of CABRI reactor is its reactivity injection system. This device allows the very fast depressurization of the ^3He (strong neutron absorber) previously introduced inside 96 tubes (so called “transient rods”) located among the CABRI fuel rods. The rapid absorber depressurization translates into an equivalent reactivity injection possibly reaching 4$ within a few 10 ms. The power consequently bursts from 100 kW up to ~20 GW in a few ms, and decreases just as fast due to the Doppler effect. The total energy deposit in the tested rod is adjusted by dropping the control and safety rods after the power transient **[1]**.

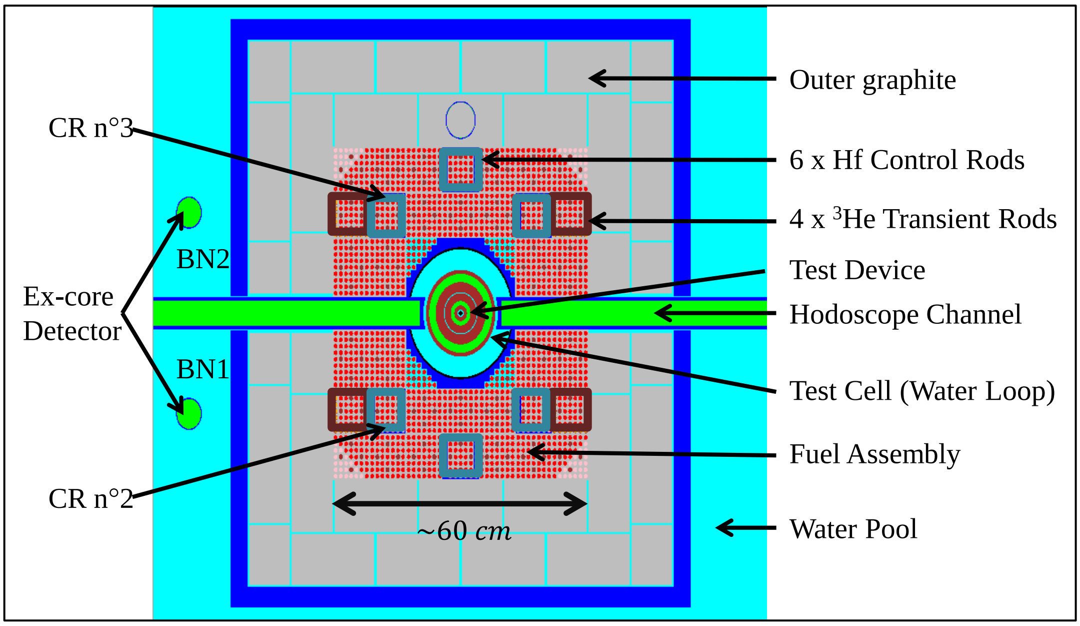

Fig 1. 3D Model representing the CABRI core calculated with the stochastic code TRIPOLI-4®

Figure 1 shows the CABRI geometrical model used for the TRIPOLI-4® computations (see §4). In the center, the test device can be withdrawn. In such case, the internal structure of the test cell may be filled with water or empty (only air). During the commissioning test, a factice rod (usually lead compound) can be positioned inside the test device.

The neutronics commission test aimed at precisely characterizing the neutronics parameters of the core of CABRI: reactivity effects, power distributions and kinetic parameters. They were carried out at low power (< 100 kW). These tests are designed to demonstrate the ability of CABRI core to provide appropriate testing conditions and safety margins. The associated uncertainties are to be controlled in the best possible way (see **Table 1**). Another goal is to validate the preliminary neutronics calculations performed for the design of the safety and the performances of the core of CABRI **[2]**.

The rod drop experiments include several core configurations, with a variable ^3He pressure (in order to change the initial position of the hafnium control rods). The experimental cell is either empty (air filled) or it contains the test device with the factice lead rod. Generally the six control rods are dropped simultaneously, except for two configurations were only one rod (respectively number 2 and 3) moves from the top to the bottom, the five other being at critical height. The ex-core detectors are the two fission chamber BN1 and BN2.

Neutronics parameters	Measurement technique	Target uncertainty (1σ)
Critical height Reactivity Effects inside the water loop Isothermal temperature coefficient Core stacking reactivity worth	Critical State	± 1 mm ± 5 % ± 1 pcm/°C ± 5 %
Core Power Distribution Axial Flux Profile Axial distribution and integral of fission rates	Dosimetry	± 2 % ± 2 % ± 2 %
Effective fraction of delayed neutrons Effective prompt neutron lifetime	Rossi and Feynman-α methods	± 3 % ± 3 %
Reactivity Worth of the ^{3}He transient rods **Integral Reactivity worth of CR** Differential reactivity worth of CR	Critical State **MSM & Rod-Drop** Doubling time	± 5 % **± 4 %** ± 1 %

Tab 1. Neutronics parameters, measurement techniques and target uncertainties for neutronics commissioning tests **[2]**.

3. Theoretical Background of the Rod-Drop Methods

The Rod-Drop method is a commonly used technique to measure the reactivity value of control and safety rods of a reactor. In principle, the reactivity value is deduced from the time behavior of the neutron population after a rapid insertion of a negative reactivity into the critical system. It may be applied to all type of reactors. In-core (if available) neutron detection equipment can be used. It gives the possibility of measuring large reactivity values without any safety problems (up to several $).

First, the following question must be answered: what kind of reactivity are rod-drop methods able to provide? Then the main assumptions of this study are described.

3.1. Dynamic versus Static Reactivities [3]

The definition of the static reactivity, ρ_λ, is based on the λ-mode eigenvalue problem (equation **(1)**). In this equation, the migration and loss of neutrons, described by $\boldsymbol{M\Phi}$, is made equal to a modified source of fission neutrons, $\lambda\boldsymbol{F\Phi}$, by introducing the eigenvalue λ in front of the fission neutron source $\boldsymbol{F\Phi}$. Such equation can be easily solved by numeric codes thanks to the power iteration method.

$$\boldsymbol{M\Phi} = \lambda\boldsymbol{F\Phi} \quad \Rightarrow \quad \rho_\lambda = 1 - \lambda \tag{1}$$

This traditional convention yields a uniquely defined value of ρ_λ for each individual state, described by the operators $\boldsymbol{M}$ and $\boldsymbol{F}$. Specific physical changes in the reactor system lead to corresponding changes in the static reactivity. This method allows determining the « S » worth curve of the control rods (individually or all rods) from their fully inserted position to their critical position. However, **such reactivity cannot be directly measured**, as explained in **[3]**. Consider only one point: the λ mode eigenvalue problem **(1)** is no longer representing physical phenomena, since the fission source is altered by the eigenvalue λ.

The definition of the dynamic reactivity, ρ_d, is also based on a convention described below. First step is the time-dependent transport equation for neutrons (with external source). Then, the conceptual starting point is the factorization of the neutron flux $\psi(\boldsymbol{r},E,t)$ into a purely time-dependent function $n(t)$ and a shape function $\varphi(\boldsymbol{r},E,t)$. This factorization is made unique by means of the conventional constraint conditions indicated below ($w(\boldsymbol{r},E)$ is an arbitrary weighting function).

$$\psi(\boldsymbol{r},E,t) = n(t) \times \varphi(\boldsymbol{r},E,t) \quad ; \quad \int_V \int_0^{+\infty} \frac{w(\boldsymbol{r},E)\varphi(\boldsymbol{r},E,t)}{v(E)} dEdV = \text{Constant} \tag{2}$$

Factorizing the neutron flux, applying an arbitrary weighting function, introducing an arbitrary denominator and constraining the variation of the flux shape by **(2) do not introduce an approximation**. **The exact point kinetics equations are derived**: hereafter is presented the differential equation for the amplitude function $n(t)$ where $S_d(t)$ is the delayed neutron source and $S_{ext}(t)$ the external source.

$$\frac{dn}{dt}(t) = \frac{\left(\rho_d(t) - \beta(t)\right)}{\Lambda(t)} n(t) + S_d(t) + S_{ext}(t) \quad \textbf{(3)}$$

With the initial adjoint flux as a weighting function $(w = \Phi_0^+)$, and the traditional choice for the denominator $\dot{\mathrm{F}}(t) = \langle \Phi_0^+, \boldsymbol{F}\varphi \rangle$, the dynamic reactivity, $\rho_d(t)$, and the effective delayed neutron fraction, $\beta(t)$, are defined by equations **(4)** (similar definition exists for the fission generation time $\Lambda(t)$).

$$\rho_d(t) = \frac{\langle \Phi_0^+, (\boldsymbol{F} - \boldsymbol{M})\varphi \rangle}{\langle \Phi_0^+, \boldsymbol{F}\varphi \rangle} \quad \text{and} \quad \beta(t) = \frac{\langle \Phi_0^+, \boldsymbol{F}_d\varphi \rangle}{\langle \Phi_0^+, \boldsymbol{F}\varphi \rangle} \quad \textbf{(4)}$$

The proper analysis of the flux transients could yield the dynamic reactivity $\rho_d(t)$. However, the arbitrarily introduced denominator $\dot{\mathrm{F}}(t)$ cannot be obtained from transient analysis, since $\dot{\mathrm{F}}(t)$ has no effects on the results. Consequently, only ratios of integral kinetics parameters such as ρ_d/β may be inferred from the analysis of transients, as shown in next section.

3.2. Reactivity assessment by a rod-drop experiment

Rod drop experiments are usually analyzed using inverse kinetic equations in the point model **[4]**. However, given a few assumptions, the subcritical level after the rod-drop may be estimated based on the count rates only before and after the drop (see also **Figure 2** for the definition of the states named "0" and "0+"):

- Prompt Jump (PJ): it is similar to the quasi-static approach, based on the prompt flux adjustment that occurs directly after the perturbation. $\frac{dn}{dt}(t)$ can be neglected in equation **(3)**.

- Constant Delayed Source (CDS): the delayed neutron source is constant from the initial state, due to the "instantaneous" change in the core configuration. **Table 2** gives the effectives delayed neutron data for a thermal fission of ^{235}U (the effective delayed neutron fraction in CABRI is close to this value). The shortest decay constants (in red) and the rod-drop duration are similar, but CDS is verified for most of the delayed neutrons.

β_i (pcm) (¢)	24 (3.5)	123 (18.1)	117 (17.2)	262 (38.6)	**108 (15.9)**	**45 (6.6)**	679 (100)
T_i (s)	54.5	21.8	5.98	2.23	**0.495**	**0.179**	7.84

Tab 2. Delayed neutron fraction (pcm) and half-life times **for a thermal fission of ^{235}U**.

- Start from a critical state: rod drop may be done from a subcritical state to another one. Nevertheless, such approach requires the determination of inherent source and an accurate reference value of reactivity **[5]**. In this study, the initial state is critical. The neutron flux is high enough to neglect the external source (independent sources or spontaneous fissions) compared to the fission source or the delayed neutron source. Moreover, just after the rod-drop, background or noise effects are weak compared to the neutron population intruding into the detector (compared for instance to measures done on longer periods **[6]**)

- No reactivity feedback: the initial power level is such that feedback effects are neglected.

- Point model: the shape factor $\varphi(\boldsymbol{r}, E, t)$ does not depend on the time, so the core behavior during a transient is only a variation of its power amplitude. Therefore, the reactivity, effective delayed neutron fraction and the fission generation time are constant during the transient. Moreover, the constant delayed source is simply estimated by $\beta n(0)$ and the detector count rates (noted T_d) are directly proportional to the amplitude function. The point-model assumption will be discussed later.

Using these assumptions, it comes the following estimation of the reactivity variation from equation **(3)**. Basically, it is the **measured value** ρ_m provided by the core operators, and the value usually saved during past commissioning tests (the count rate profiles are not necessarily archived).

$$0 = (\rho - \beta) n(0^+) + \beta n(0) \quad \Rightarrow \quad \frac{\rho_m}{\beta} = 1 - \frac{n(0)}{n(0^+)} = 1 - \frac{T_d(0)}{T_d(0^+)} < 0 \tag{5}$$

This measured reactivity has to be compared to a dynamic reactivity (equation **(4)**). To estimate this latter, the concept of micro-kinetics is worthwhile. This concept describes the fission rate in terms of prompt fission chains instead of single fission events. It was applied to fast reactors with short generation time, such as MASURCA **[7]**, but its use in the thermal core of CABRI is consistent with the CDS assumption. Finally, the neutron flux just after the rod-drop may be estimated by the following equation (the index p is for *prompt*, the index d for *delayed*).

$$\left(\boldsymbol{M} - \boldsymbol{F_p}\right)\psi(0^+) = S_d(0) = \boldsymbol{F_d}\psi(0) \quad \Leftrightarrow \quad (\boldsymbol{F} - \boldsymbol{M})\psi(0^+) = \boldsymbol{F_d}\psi(0^+) - \boldsymbol{F_d}\psi(0) \tag{6}$$

Finally, with a constant effective delayed neutron fraction between states 0 and 0^+, it comes the calculated estimation of the dynamic reactivity for the rod-drop experiment.

$$\rho_d = \frac{\langle \Phi_0^+, (\boldsymbol{F} - \boldsymbol{M})\psi(0^+)\rangle}{\langle \Phi_0^+, \boldsymbol{F}\psi(0^+)\rangle} = \frac{\langle \Phi_0^+, \boldsymbol{F}_d\psi(0^+)\rangle}{\langle \Phi_0^+, \boldsymbol{F}\psi(0^+)\rangle} - \frac{\langle \Phi_0^+, \boldsymbol{F}_d\psi(0)\rangle}{\langle \Phi_0^+, \boldsymbol{F}\psi(0)\rangle} \times \frac{\langle \Phi_0^+, \boldsymbol{F}\psi(0)\rangle}{\langle \Phi_0^+, \boldsymbol{F}\psi(0^+)\rangle}$$
$$= \beta - \beta \times \frac{\langle \Phi_0^+, \boldsymbol{F}\psi(0)\rangle}{\langle \Phi_0^+, \boldsymbol{F}\psi(0^+)\rangle}$$

$$\frac{\rho_d}{\beta} = 1 - \frac{\langle \Phi_0^+, \boldsymbol{F}\psi(0)\rangle}{\langle \Phi_0^+, \boldsymbol{F}\psi(0^+)\rangle} < 0 \tag{7}$$

3.3. Spatial Correction Factor

In the exact point kinetics equations, $n(t)$ must be the core averaged neutron density. But ex-core detectors (or even in-core detectors) does not represent the core averaged behavior (it gives probably only an information on core peripheral assemblies). E. K. Lee formalized this difficulty by the following question **[6]**: *How to relate the core averaged neutron density to detector signals?*

It is the starting point of the ***Modified neutron Source Method*** *(MSM)*. Hereafter, T_d is a **measured** count rate in a detector, while $\langle \Sigma_d \psi\rangle$ is a **simulated** reaction rate. The f_{MSM} factors are **calculated values**, and do no depend on the amplitude function before or after the rod-drop.

$$\frac{\langle \Phi_0^+, \boldsymbol{F}\psi(0)\rangle}{\langle \Phi_0^+, \boldsymbol{F}\psi(0^+)\rangle} = \frac{\langle \Phi_0^+, \boldsymbol{F}\psi(0)\rangle}{\langle \Phi_0^+, \boldsymbol{F}\psi(0^+)\rangle} \times \left[\frac{\langle \Sigma_d \psi(0^+)\rangle}{T_d(0^+)} \times \frac{T_d(0)}{\langle \Sigma_d \psi(0)\rangle}\right] = \frac{\langle \Sigma_d \psi(0^+)\rangle}{\langle \Phi_0^+, \boldsymbol{F}\psi(0^+)\rangle} \Big/ \frac{\langle \Sigma_d \psi(0)\rangle}{\langle \Phi_0^+, \boldsymbol{F}\psi(0)\rangle} \times \frac{T_d(0)}{T_d(0^+)}$$
$$\Rightarrow \quad f_{MSM} = \frac{\langle \Sigma_d \varphi(0^+)\rangle}{\langle \Phi_0^+, \boldsymbol{F}\varphi(0^+)\rangle} \Big/ \frac{\langle \Sigma_d \varphi(0)\rangle}{\langle \Phi_0^+, \boldsymbol{F}\varphi(0)\rangle} \tag{8}$$

The f_{MSM} factors give the change of the detector efficiencies (the ratio between the detector signals to the fission source in the whole core) between just before and just after the rod-drop. The MSM factors also take into account the modification of the source. Such factors are well known in the literature **[2][8]**. **The particularity of the method described in this study is that it links a critical state to a subcritical one where only prompt neutrons are propagated, instead of the usual link between two subcritical states**.

Finally, the measured reactivity is corrected using **(8)**, before its comparison with the calculated dynamic reactivity ρ_d defined by **(7)**. In this equation, f_{MSM} is **calculated** while ρ_m is **measured**.

$$\frac{\rho_{m,Corrected}}{\beta} = 1 - f_{MSM} \times \left(1 - \frac{\rho_m}{\beta}\right) < 0 \quad \textbf{(9)}$$

3.4. Discussion on rod-drop experiments

The analysis of transient implying a control rod movement requires distinguishing at least two kinds of spatial effects. Y. A. Chao described them in **[9]**. *First, the static spatial effect is caused by the core environment change due to the bank insertion. This results in an immediate redistribution of the prompt neutrons. Second, the dynamic spatial effect is caused by the delayed neutron spatial distribution trailing behind that of the prompt neutrons.*

The parameters that control (or quantify) these both effects may be called static spatial factor (SSF) or dynamic spatial factor (DSF) in Chao. In **[6]**, the names are *Neutron-to-Response conversion factor* (NRCF) and *Dynamic-to-static conversion factor* (DSCF). More importantly, they are computed trough a complex combination of static and dynamic simulations. In others words, 3D kinetics scenarios must be computed.

A major difference of this study compared to the works **[6]** or **[9]** is the duration of the transient. In one case, the rods are dropped, whereas in the other case, the rod banks are inserted into the bottom of the core at maximum stepping rate. The validity of the CDS assumption is questionable in the latter. Finally, with only a few hypotheses, only two simulations are needed to properly interpret any rod-drop experiment, as explained below at CABRI.

4. Using the French Stochastic TRIPOLI-4® Code in a subcritical Mode

The rod-drop experiments were simulated using the French stochastic TRIPOLI-4® code **[10]** in both a critical and a subcritical mode. Data library was JEFF-3.1.1. The scope of the computation is described on **Figure 2**. The counting rate is schematic.

The MSM factor requires the adjoint flux computation, which is a rough task with a stochastic code. That is why the adjoint flux was assumed to be equal to 1 everywhere in the core, waiting for further investigation with a new version of the TRIPOLI-4® code.

The ex-core detectors are far from the fissile region, outside the graphite reflector, and above more than 40 centimeters of water. It is the main drawback of the MSM factor technique, because it reaches the limits of the computational resources. To improve the statistics (and reduce the variance of the score estimators), homogeneous fission chambers were modelled. The spatial self-shielding inside the detector is neglected. In any cases, since the MSM imply a ratio of two reaction rates, a systematic error should not change the MSM factor.

For this study, 7 cases are analyzed. Name “6R_P4” (in **tables 3 and 4**) means a 6-rods drop with an initial ^{3}He-pressure of about 4 bars. Changing the initial pressure of ^{3}He allows exploring several initial positions for the controls rods. When this pressure increases, the control rods are withdrawn to ensure criticality. The four first experiments are done with various ^{3}He pressures and the experimental water loop inside the core (with a lead factice rod), while the 3 lasts are done with air in the experimental cell and without ^{3}He. Name “1R_N2’ means that only control rod number 2 is dropped almost from the top to the bottom, the five others being at the critical height.

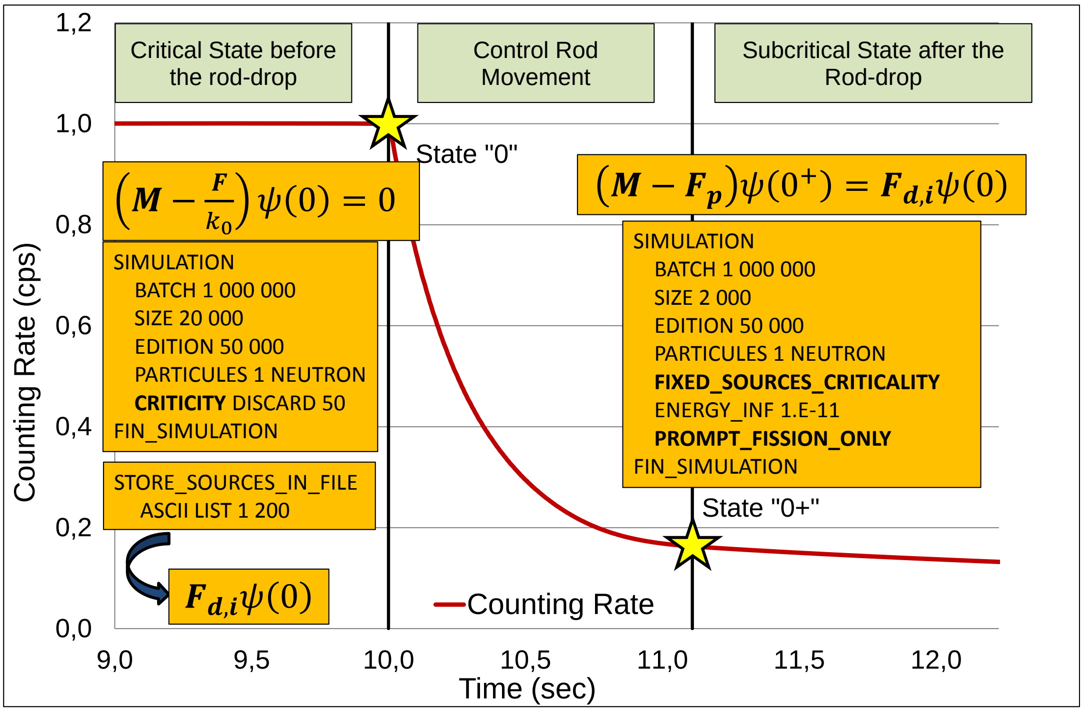

Fig 2. Theoretical outlet of the detector and representation of the two calculations required to interpret rod-drop experiments with a stochastic code like TRIPOLI-4®.

5. Main Results and Uncertainty propagation

5.1. Results of the simulation

Table 3 gives the main results of the simulation. Static and dynamic reactivity (with a constant adjoint flux) are compared. For the 6-rods-drops, a relative error up to 6% is observed. This error is greater than the target uncertainty (see **Table 1**). Based on the discussion of section 3.1, **the dynamic reactivity $\delta\rho_d$ must be considered for the comparison with the measured reactivities.** For the one-rod drop, the inferred reactivity is smaller ("only" 3 $), and the difference between $\delta\rho_\lambda$ and $\delta\rho_d$ is reduced. This tends to show that the shape of the fundamental mode Φ_λ and the subcritical exact flux $\psi(0^+)$ are close. In other words, the conditions of the fundamental mode are verified.

Table 3 gives also the results of the measured reactivities (equation **(5)**). Without spatial correction factors, there are strong discrepancies up to 20% between the simulation and the experience. This proves that the spatial/energetic corrections to be applied to experiments (MSM factors, see Section 3.3) are important and need to be made.

Configuration	**6R_P0**	**6R_P4**	**6R_P7**	**6R_P14**	**6R_Air**	**1R_N2**	**1R_N3**
$\delta\rho_\lambda$ ($)	-12.8	-15.2	-15.8	-16.6	-12.6	-3.0	-2.9
$\delta\rho_d$ ($) → C	-12.2	-14.3	-14.8	-15.5	-12.1	-3.0	-2.9
$\delta\rho_d/\delta\rho_\lambda$	**0.96**	**0.94**	**0.94**	**0.94**	**0.96**	**1.00**	**1.00**
ρ_m($) (BN1) → E	-9.9	-12.0	-12.7	-13.6	-9.9	-4.4	-3.7
C/E	1.23	1.19	1.17	1.14	1.22	0.68	0.78
ρ_m($) (BN2) → E	-10.0	-12.2	-13.0	-13.6	-10.1	-4.2	-4.0
C/E	1.22	1.17	1.14	1.14	1.20	0.71	0.73

Tab 3. Calculated Reactivity Worth ($) of Control Rods and comparison with the measurements without spatial correction factor.

Table 4 summarizes the analysis of the rod-drop experiments during the CABRI commissioning tests. The C/E are generally lower than 1: it means that the calculated reactivity worth is smaller than the corrected measured one. In other words, the controls rods seem more efficient during the experiment than expected by the computations.

Configuration	ρ_m($) (BN1)	f_{MSM}	$\rho_{m,Corrected}$ (→ E) ($)	C/E for ρ_d	ρ_m($) (BN2)	f_{MSM}	$\rho_{m,Corrected}$ (→ E) ($)	C/E for ρ_d
6R_P0	-9.9	1.266	-12.8	0.96	-10.0	1.247	-12.7	0.96
6R_P4	-12.0	**1.270**	**-15.6**	0.92	-12.2	**1.339**	**-16.7**	0.86
6R_P7	-12.7	**1.141**	**-14.6**	1.01	-13.0	**1.207**	**-15.9**	0.93
6R_P14	-13.6	1.249	-17.3	0.90	-13.6	1.300	-17.9	0.87
6R_Air	-9.9	1.311	-13.3	0.91	-10.1	1.387	-14.4	0.84
Mean 6R				**0.94**				**0.89**
1R_N2	-4.4	0.687	-2.7	1.10	-4.2	0.895	-3.7	0.81
1R_N3	-3.7	0.911	-3.3	0.88	-4.0	0.735	-2.7	1.08
Mean 1R				**0.99**				**0.94**

Tab 4. Reactivity Worth ($) inferred from the measurements and corrected by spatial MSM factors. Comparison with the calculated values.

Results for "**6R_P4" and "6R_P7"** are questionable (red values in **Table 4**), because the corrected measured reactivities seem inconsistent. In fact, when the ^{3}He increases the control rod are withdrawn, which leads to a higher neutron flux in the top of the core (near the ex-core detector) for the critical state. But in the same time, the flux is smaller radially due to the strong absorption in the transient rods, especially near the BN chambers. This absorption is present both during the critical state and the subcritical state. Finally, there is a competition between these two effects (radially and axially) which deserves further investigation. It seems that assuming a uniform adjoint flux could explain this inconsistency.

Nevertheless, discrepancies between computed and measured reactivities are strongly reduced, which confirms the interest and the validity of the MSM theory.

5.2. Sensitivity analysis

Previous tables were given without uncertainties. In this section, a method is proposed to analyze the uncertainties during rod-drop experiments. Firstly, the experimental uncertainty is assumed being 3,5% (a 1σ). It includes uncertainty of the counting rate and of the position of the state "0^+" after the rod-drop see **Figure 2**). Concerning this last point, the reference **[5]** presents at least two methods that can be employed to give inferred reactivities from the detector signals: the area method and the prompt drop method. Secondly, the statistical uncertainty on the MSM factors is 4% (at 1σ).

These two uncertainties have different origins, and equation **(9)** gathers multiplication and subtraction, which makes the uncertainty propagation very complex. For instance, it is irrelevant to propose an usual quadratic summation of the uncertainties: this choice would lead to a 5%-uncertainty at 1σ for $\rho_{m,Corrected}$. Finally, the C/E values are consistent in respect of the target uncertainty presented in **table 1**.

Another method is described in **figure 3**: the abscissa deals with the MSM factor, whereas the ordinates give the C/E values. Dashed lines are for the extrema (at +1σ or -1σ) of f_{MSM} or ρ_m. Point C is the best-estimate C/E value, and points A, B, D and E provide a confidence interval of the C/E values. Figure 4 outlines all results in respect of these definitions. Green dashed lines represent the target uncertainty of $\pm$4%. Based on this figure, it can be noticed that the analysis of the rod-drop experiments during the CABRI commissioning tests are satisfactory. BN1 chamber provides better results, but it is known that the two chambers are not consistent together. Finally, there is still room for further improvement, as suggested in the conclusions and perspectives.

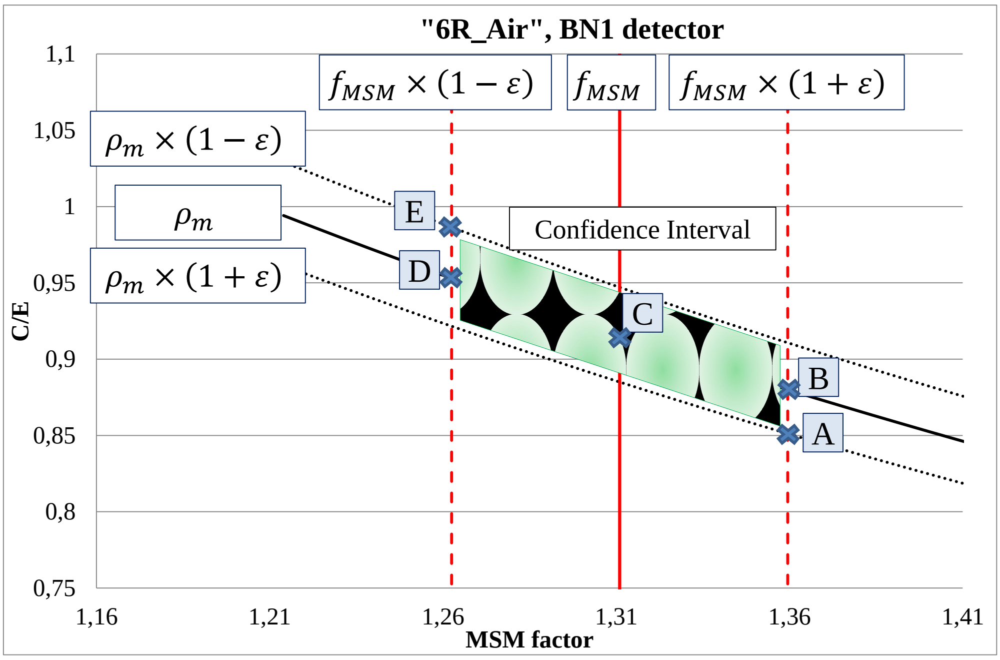

Fig 3. Description of a model to provide a confidence interval of the TRIPOLI-4® computations, considering experimental and stochastic uncertainties.

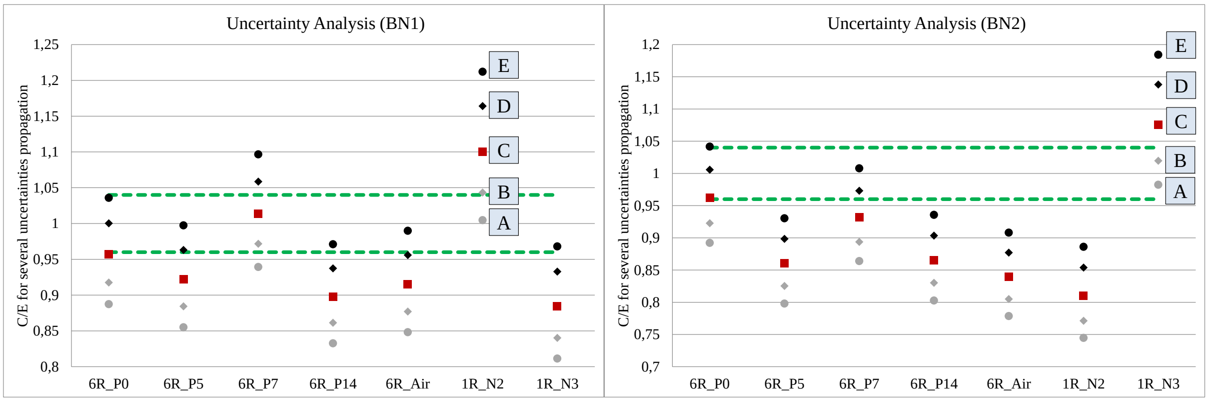

Fig 4. Uncertainty propagation on the C/E values computed for the experiments analyzed in this study. Comparison with the target uncertainty of the tests.

6. Conclusions and Perspectives

This paper described the experimental results of the rod-drop experiments performed during the commissioning tests of the CABRI facility. Such experiments are challenging the core calculation scheme, because it includes both spatial and dynamic effects. This paper reminds the theoretical background needed to analyze rod-drop experiment. In particular, it distinguishes static and dynamic reactivities. Moreover, it shows that if a few conditions are satisfied, only 2 states are to be computed, one critical and another one subcritical just after the rod-drop.

Results obtained during this campaign prove that spatial correction factors are mandatory to take into account the modification of the source and of the efficiency of the fission chamber during the rod drop measurements. It is the Modified Source Method. Finally, the C/E are 0.94 and 0.99 (respectively 0.89 and 0.94) for the BN1 ex-core detector (resp. BN2). If the uncertainties are considered (both statistical and experimental), it was shown that the target uncertainty of 4% for the control rod worth is reached.

However, several options can be explored in order to fully understand the rod-drop experiments. Hereafter, these options are briefly discussed:

- This paper deals with the CABRI experiments, where the ex-core detectors are very far from the inner core. However, rod drop are regulatory testing before operating any reactor. So there is an enormous database of experiments which may be analyzed thanks to this theory. Moreover, in-core detectors could be used because the power does not need to be very high for such experiments.

- The data library used in this work was JEFF-3.1.1. Discrepancies between data libraries have been noted in the past, for the cross-sections of hafnium (in control rod) and for the delayed neutron fractions. Even if the reactivity worth are given in $, a change in the delayed neutron fraction would have consequences on the C/E. Indeed, it would change the initial weight of the constant delayed source and it would change all prompt fission chains (equation **(6)**).

- The adjoint flux can be computed in a rigorous way using the TRIPOLI-4® code. This work will be performed in the future, and it is expected that the results for increased ^{3}He pressure should be improved.

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