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UNCERTAINTY ASSESSMENT ON THE PREDICTION OF THE CABRI POWER TRANSIENTS

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ABSTRACT

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. It is designed to study fuel behavior under RIA (Reactivity Initiated Accident) conditions. Reactivity is injected by depressurization of a neutron absorber (³He) situated in the so-called “transient rods” inside the reactor core. A multiphysics code, called SPARTE (Simulation, Prediction and Analysis for RIA Transients and Excursions), was developed and designed to predict the CABRI power transients. This paper presents a method for uncertainty assessment on the the CABRI power transients prediction with the SPARTE code. It is based on a BEPU (Best Estimates Plus Uncertainties) approach.

The SPARTE code includes surrogate models based on Best Estimates simulations and experimental analysis. The surrogate models were developed through the ROOT-based URANIE uncertainty platform. Specific models were developed for ³He depressurization, ³He reactivity function of the pressure, Doppler coefficient variation, prompt neutron generation time, axial profile of neutron flux determination and rod dropping reactivity insertion. Those models are now included in the SPARTE code and are being experimentally validated. Coupled with the platform URANIE, SPARTE is optimized for uncertainty analysis thanks to an adapted dataset and a short simulation time (below 1 min).

The uncertainty propagation method consists, first, in building a design of experiments (DOE) based on the Sobol sequence with normal distributions of the parameters around their nominal values. From every simulation, we extract the characteristics of the power transients (maximum power, peak time, energy, Full Width at Half Maximum (FWHM)). Mean values and standard deviations for each output are extracted from the results of hundreds of simulations. This method allows the uncertainties evaluation linked to the prediction of a specific CABRI power transient. The paper gives an overview of driving parameters as a function of the CABRI transient type.

KEYWORDS: CABRI, URANIE, Power transients, Point Kinetics, Uncertainty

1. INTRODUCTION

CABRI is an experimental pulse reactor funded by the French Nuclear Safety and Radioprotection Institute (IRSN) and operated by CEA (Commissariat à l'Énergie Atomique et aux Énergies Alternatives) at the Cadarache research center. Since 1978, the experimental programs have been aiming at studying the fuel behavior under Reactivity Initiated Accident (RIA) conditions. In order to study PWR high burn up fuel and new cladding materials behavior under such transients, the facility was modified to accept a pressurized water loop in its central part able to reproduce thermal-hydraulics characteristics representative of PWR nominal operating conditions (155 bar, 300 °C). This project, which began in 2003 and supported first commissioning power tests from October 2015 to March 2017, was driven within a broader scope including both an overall facility refurbishment and a complete safety review. The global modifications have been conducted by the CEA project team and funded by IRSN, which is operating and managing the CIP experimental program (CABRI International Program), in the framework of an OECD/NEA agreement. The CIP program will investigate several fresh and burnt UOx and MOX LWR fuel samples with new cladding materials under RIA conditions, with a foreseen completion by the end of 2023. Power transients are generated by a dedicated so-called transient rods system [1] allowing the very fast depressurization of ^3He tubes positioned inside the CABRI core.

This study uses a Best Estimates Plus Uncertainty (BEPU) approach in order to analyse prediction of the CABRI power transients. The first goal is to improve the CABRI power transients prediction. And the second one, is to estimate the uncertainties associated with those predictions. In this paper, we describe our method of uncertainty propagation with our SPARTE [2,3] (Simulation, Prediction and Analysis for RIA Transients and Excursions) multiphysics code, based on the URANIE [4] uncertainty platform.

2. MATERIAL AND METHODS

2.1. The SPARTE code

SPARTE is a multi-physics code developed to improve the prediction of the CABRI power transients. The power transients are calculated by a point kinetics algorithm, the same as DULCINEE [5]. Point kinetics is adapted to our problem as CABRI is a small reactor, the reactivity is injected in an homogeneous way as the transient rods are disposed at the 4 corners of the core and the RIA phenomenon is very fast. The injected reactivity is defined at the beginning of the simulation, whereas feedback reactivities are computed at each time step. Heat transfers are computed by Fourier equations and thermal hydraulics by continuum equations. A dataset describes the geometry, kinetic parameters, meshing, of the CABRI core. This dataset was updated in the SPARTE code, in order to take into account the last studies (neutronics, core material balance). Moreover models were added [3], in order to take into account a variable Doppler coefficient during transients (due to neutron spectrum and high fuel temperatures variations), ^3He density variation into the transient rods, updated law for ^3He reactivity and other models. During power transients, an effect of supplementary reactivity can happen, due to the heating of ^3He , it is named "TOP" effect [2]. A surrogate model was created, in order to take into account this effect. It allows us to better predict some transients with high initial ^3He pressure. The SPARTE calculations are automatized and analyzed with the URANIE platform. Depending of the transient characteristics, a

SPARTE calculation lasts between 10 and 60 s on a Linux 3.40GHz processor. This relatively fast calculation time allows the realization of uncertainties studies for different transients.

2.2. The URANIE uncertainty platform

URANIE is an uncertainty platform based on ROOT [6]. It is used to make DOEs, to create surrogate models, to launch codes in series or parallel and get the outputs, for sensitivity analysis and uncertainty evaluation (SU). A lot of methods are implemented in the platform like Sobol indexes, Morris screening for sensitivity analysis and artificial neuronal networks for surrogate models creation.

2.3. CABRI reactivity injection system

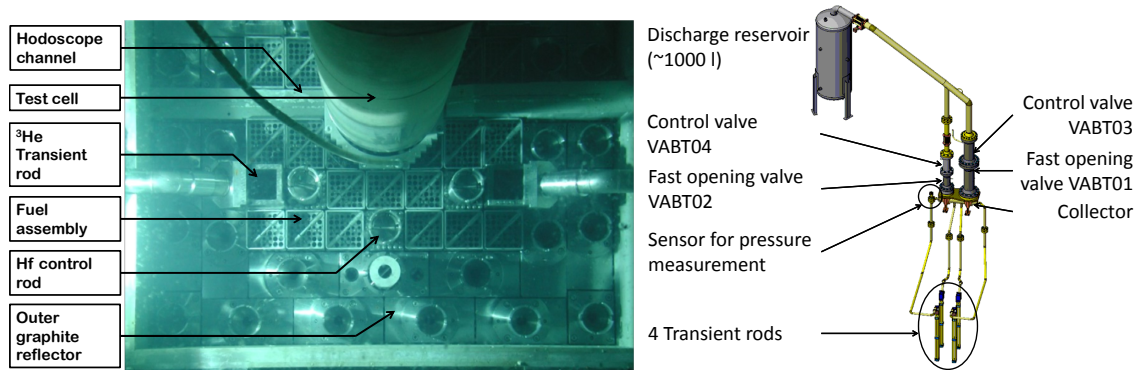


Figure 1: CABRI transient rods system

The key feature of the CABRI reactor is its unique reactivity injection system [1]. This device allows the very fast depressurization of the ³He (strong neutron absorber) into a discharge tank. The CABRI transient rods system is made of the following main components (see figure 1):

- 4 fuel assemblies (7x7 pins) equipped on their periphery with 24 tubes instead of 24 fuel rods. These tubes are connected together in the upper part of each assembly in order to join a collecting line leading to a main collector.
- From the top of this collector, two flow channels (low and high flow rates) lead to a 1000 l discharge tank set under vacuum before operation. Both channels are equipped with a fast-opening valve (respectively with small and large diameters) followed by a controlled valve.
- A specific control device that triggers the different orders of the experimental sequence as for the opening time of the two fast-opening valves and the shutdown of the reactor control rods.

The transient rods depressurization causes the absorber ejection that induces a reactivity injection reaching up to 3.9 \$ in few milliseconds. The characteristics of the transient (maximum power, Full Width at Half Maximum (FWHM) and energy deposit) depend on the experimental sequence applied to the fast valves and on the adjustment of the associated controlled valves. Short FWHM power transients, so called “natural transients”, will be generated by the fast opening of the unique

high flow rate channel. In order to be representative of other LWR accidental conditions, an increase of the transient pulse FWHM is necessary. This can be done by successively opening the fast opening valves of the low-flow and then the high-flow rate channels. In this paper, a “natural” and a “structured” transient [2] (see figure 2) will be studied.

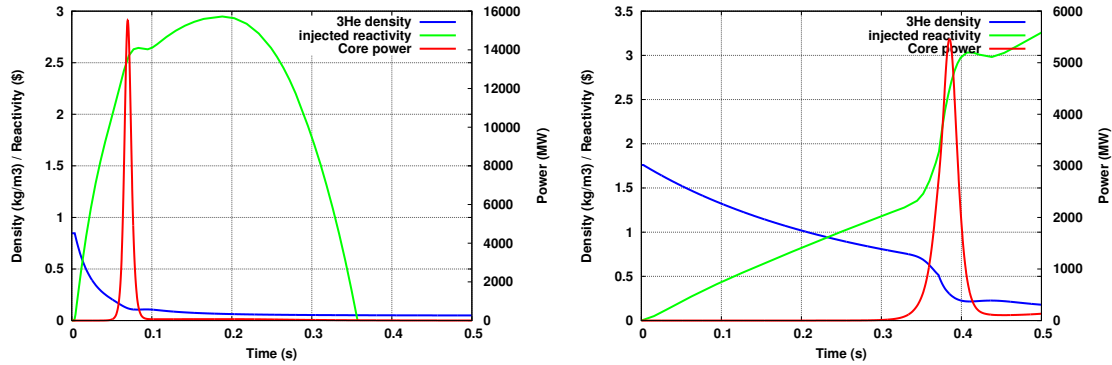


Figure 2: Calculated “natural” transient (left) and “structured” transient (right) with SPARTE

3. EVALUATION OF THE OUTPUTS UNCERTAINTIES

In this part, we will evaluate the uncertainties associated to the prediction of each power transient by uncertainty propagation through the SPARTE code.

The first part of this work is to evaluate the uncertainty associated to each experimental parameter (linked to the instrumentation sensitivity) and surrogate models. Then, with the URANIE platform, a DOE on the uncertain parameters following the Sobol sequence (space filling DOE) is created. It is composed of hundreds of datasets, in order to have a good estimation of the output’s standard deviation. Every parameter is defined with a central value and a standard deviation with a normal distribution. Then, SPARTE is launched according to the DOE. Finally, the results are analyzed by watching the mean values and standard deviations for maximum power, deposited energy, FWHM and peak instant.

There are two types of uncertainties to study: uncertainties linked to the measure of input parameters and uncertainties linked to the surrogate models or calculated parameters. There are measured input that have uncertainties coming from the transducers precision:

- H03 (mm), $\sigma = 0.12 \text{ mm}$, the aperture of the high flow-rate channel control valve;
- H04 (mm), $\sigma = 0.06 \text{ mm}$, the aperture of the low flow-rate channel control valve (“structured” transients);
- P0 (bar), $\sigma = 1 \%$, the initial ^3He pressure;
- T0 (K), $\sigma = 0.5 \text{ K}$, the initial system temperature.

The ^3He purity is controlled every year by a pollution test: $\text{pur} (\%)$, the ^3He purity is about 99 % with a standard deviation $\sigma = 0.25 \%$.

The stabilized power before the transient is measured by fission chambers and boron ionization chambers. The thermal assessment [7] shows a good linearity of the chambers: power (W), $\sigma = 1.5 \%$.

For “structured” transients the time between the 2 openings of the fast valves is mastered with a maximal precision. Electronics, detection precision and time steps lead to: $t_{open} \text{ (ms)}$, $\sigma = 1 \text{ ms}$.

The kinetics parameters are calculated by the IFP [8] method with the Monte-Carlo TRIPOLI4 [9] code and the JEFF-3.1.1 [10] library. An expert [11] recommendation leads to:

- $\beta_{eff} \text{ (pcm)}$ (beta), $\sigma = 3 \%$, the effective delayed neutron fraction;
- $\Lambda_{eff} \text{ (}\mu\text{s)}$ (dlamb), $\sigma = 5 \%$, the prompt neutron generation time, dlamb is the uncertainty on the calculated Λ_{eff} .

The comparison between neutronics calculations and measures and the propagation on measure uncertainties on the determination of reactivity effects lead to:

- $\rho_{^3He} \text{ (pcm)}$ (drho), $\sigma = 4 \%$, the injected ^3He reactivity, drho is the uncertainty on the calculated $\rho_{^3He}$;
- $\rho_{Dop} \text{ (pcm)}$ (ddop), $\sigma = 5 \%$, the Doppler feedback reactivity, ddop is the uncertainty on the calculated ρ_{Dop} .

The last uncertainties are linked to the depressurization model. The model is based on a physical law and was validated by CFD assessment [2] of the ^3He depressurization. The uncertainties come from comparisons to the experiments and are increased to take into account the low amount of informations on some phenomenon (TOP effect particularly):

- $\Delta t_c \text{ dt}_{depr}$, $\sigma = 5 \%$, the uncertainty on the calculated depressurization speed;
- $\Delta TOP \text{ dtop}$, $\sigma = 10 \%$, the uncertainty on the TOP effect amplitude;
- d_{final} , $\sigma = 5 \%$, the uncertainty on the final ^3He density.

The Sobol sequence has a good coverage of the input space, it is used to make the DOE for the uncertainties propagation. An example of sampling is represented on figure 3, we can observe a good space filling sample with a normal distribution of the inputs. It needs less assessments of the code than a classical random sampling to determinate a estimation of the mean values and standard deviations of the outputs. 960 simulations are launched for the “natural” and 1120 for the “structured” power transient. It is equal to 80 simulations per input parameter. They are resumed in the table 1 (“natural” transient) and the table 2 (“structured” transient).

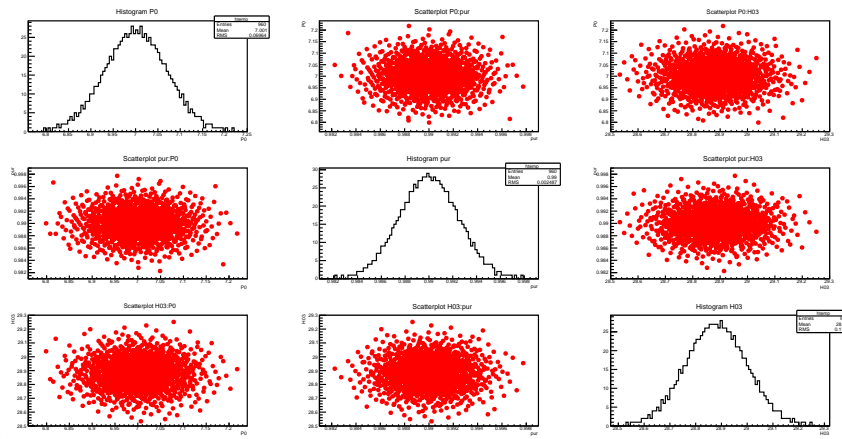


Figure 3: 960 points Sobol sampling of the first 3 driving parameters

Table 1: “Natural” transient with a 7 bar initial pressure

	Min	Max	Mean	σ
P_{max} (MW)	10100	23200	15900	2100
$FWHM$ (ms)	8.00	12.48	9.92	0.62
$Energy$ (MJ)	152	254	195	18
t_{peak} (ms)	57.5	79.2	67.9	3.1

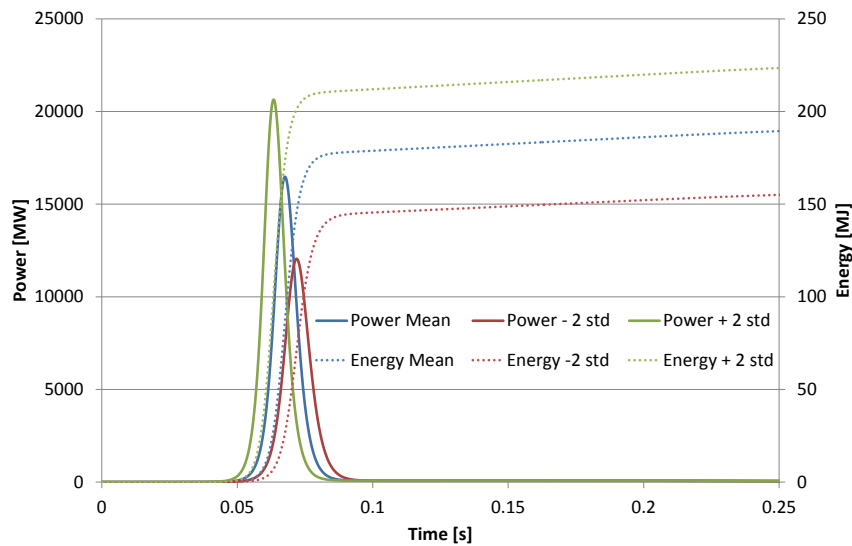


Figure 4: Time dependence of core power and energy deposit by a CABRI “natural” power transient calculated with SPARTE with uncertainties

From table 1 and simulation data, figure 4 was built. It represents the mean power transient with the associated plus and minus 2σ uncertainty power curves. Uncertainties on maximum power and peak time are reproduced on the figure.

Table 2: “structured” transient with a 14.5 bar initial pressure

	Min	Max	Mean	σ
P_{max} (MW)	3310	9500	5300	860
$FWHM$ (ms)	14.2	34.4	24.4	2.7
$Energy$ (MJ)	155	292	219	22
t_{peak} (ms)	313	473	381	23

This method allows us to predict the CABRI power transient characteristics and give the associated uncertainties. From those tables, we can observe that the uncertainties on prediction depend on the type of power transient (natural or structured). A sensitivity study will help us to understand which parameters are the most sensible on the outputs values.

4. THE SENSITIVITY ANALYSIS

The goal of the sensitivity analysis is to inform experimenters and programmers on the influence of each parameter and to advise them on improvement tracks. The sensitivity analysis is divided in two parts. The first one consists in a qualitative analysis, allowing the classification of the parameters importances and separate the less influent ones. The second one is a quantitative analysis allowing the evaluation of the variances associated to each parameter.

4.1. Description of the sensitivity analysis methods

The Morris screening method [12] is an effective screening procedure. It consists in ordering the input variables according to their influence on the output variables. This method consists in varying every input parameters 5 to 10 times with randomly chosen starting points in the input parameters space. It leads to $r(n + 1)$ code assessments where n is the number of input parameters and r is an entire number between 5 and 10. Then, elementary effects are computed. It is possible to compute basic statistics on the elementary effects computed for every input parameter.

$$\mu_i = \frac{1}{r} \sum_{t=1}^r EE_i^t, \mu_i^* = \frac{1}{r} \sum_{t=1}^r |EE_i^t|, \sigma_i^2 = \frac{1}{r-1} \sum_{t=1}^r (EE_i^t - \mu_i)^2 \quad (1)$$

μ_i and σ_i represent respectively the mean and standard deviation of the parameter elementary effect. μ_i^* is the mean of the absolute values of the EE_i^t and is called the screening importance. The results are visualized in the (μ^*, σ) plane, allowing to sort the inputs in 3 different categories. Some factors have negligible effect on the output with both μ^* and σ small. Other factors have linear effects, without interactions with other inputs with large μ^* and small σ . The last ones have non linear effects and/or interaction with other inputs: both μ^* and σ are large.

This method requires a low computational cost, but the obtained information is insufficient to estimate each input of model uncertainty contribution to the output uncertainty. A more precise method is needed for that.

The Sobol indexes method produces numerical values for the Sobol indexes. The first order sensitivity index (2) describes the contribution to the output variance (Y) of the main effect of the input X_i . It measured the effect of X_i varying alone.

$$S_i = \frac{Var[E[Y|X_i]]}{Var[Y]} \quad (2)$$

The total-order index (3) measures the contribution to the output variance of X_i , including all variances caused by its interactions, of any order, with any other input variables.

$$S_{Ti} = \frac{E(Var[Y|X_i])}{Var[Y]} \quad (3)$$

It requires a higher numerical cost as numerous code assessments are needed (100 to 1000 times the number of input parameters). The method is optimized in URANIE with the Saltelli resolution scheme [13]. SPARTE is fast enough for this method (~ 1 -2 days calculation).

4.2. Sensitivity analysis for the “natural” transient

The first step of this sensitivity analysis is to sort the uncertain parameters with the Morris screening method. 116 simulations were launched for a total of 1 hour of computing time. The figure 5 represents 2 (μ^* , σ) planes corresponding to the maximal power and the FWHM outputs. We can assume from the Morris screening method that the uncertainties on the ^3He purity, the initial temperature, the initial power and the aperture of the high flowrate channel control valve have negligible impacts on the total uncertainties. The other factors have non linear effects and/or interactions more particularly the uncertainty on the ^3He reactivity. The uncertainty on the Doppler coefficient has a big influence on the maximum power uncertainty. The uncertainty on the prompt neutron generation time has a big influence on the FWHM uncertainty.

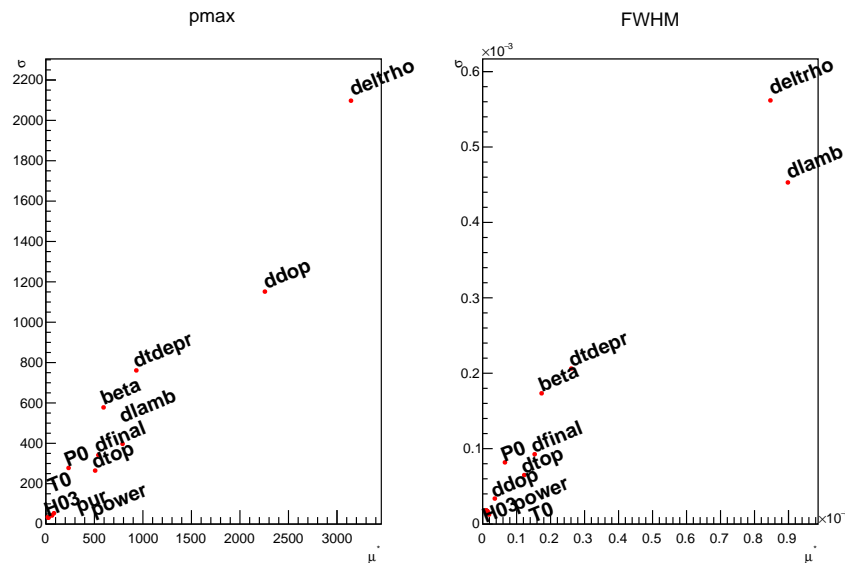


Figure 5: Input sensitivity ranking with Morris method for the “natural” transient

The second step consists in computing the Sobol indexes. From the Morris screening method, the 4 uncertainties parameters with negligible impacts are eliminated in order to improve the performances of the Sobol indexes method. 8 uncertainties parameters are studied, 3000 simulations were launched to estimate the Sobol indexes. The Sobol indexes are represented as histograms on figure 6 for the maximum power P_{max} and the FWHM.

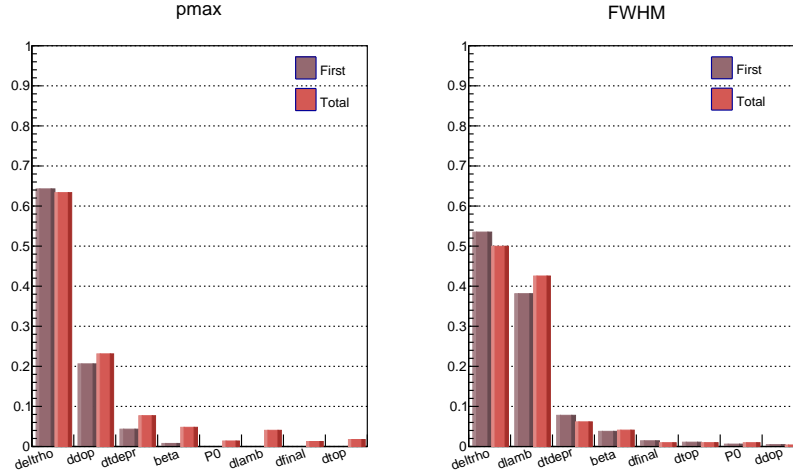


Figure 6: Sobol indexes associated to the maximum power and on the FWHM

Let's rank the uncertainties parameters according to figure 6:

1. $\Delta\rho_{3He}$ (deltrho): $S_{\Delta\rho_{3He}}(P_{max}) = 71\%$, $S_{T\Delta\rho_{3He}}(P_{max}) = 59\%$, $S_{\Delta\rho_{3He}}(FWHM) = 50\%$, $S_{T\Delta\rho_{3He}}(FWHM) = 47\%$;
2. $\Delta\Lambda$ (dlamb): $S_{\Delta\Lambda}(FWHM) = 36\%$, $S_{T\Delta\Lambda}(FWHM) = 40\%$;
3. ΔD_{op} (ddop): $S_{\Delta D_{op}}(P_{max}) = 23\%$, $S_{T\Delta D_{op}}(P_{max}) = 21\%$;
4. Δt_c (dtdepr): $S_{\Delta t_c}(P_{max}) = 5\%$, $S_{T\Delta t_c}(P_{max}) = 7\%$, $S_{\Delta t_c}(FWHM) = 7\%$, $S_{T\Delta t_c}(FWHM) = 6\%$;
5. β_{eff} (beta): $S_{\beta_{eff}}(P_{max}) = 1\%$, $S_{T\beta_{eff}}(P_{max}) = 5\%$, $S_{\beta_{eff}}(FWHM) = 3\%$, $S_{T\beta_{eff}}(FWHM) = 4\%$;

The other parameters have negligible effects. The uncertainties on models represent most of the total uncertainties on the transients characteristics for “natural” transients.

4.3. Sensitivity analysis for the “structured” transient

The same approach is applicable to the “structured” transients. Here is one example trying to reproduce a 30 ms FWHM transient. The figure 7 represents 2 (μ^*, σ) planes corresponding to the maximal power and the FWHM outputs. The Morris process took 80 minutes of computing time to simulate 134 transients. We can assume from the Morris screening method that the uncertainty on

the aperture of the high flowrate channel control valve and on the stabilized power are negligible. The other factors have non linear effects and/or interactions, more particularly the uncertainty on the opening instant of the second fast valve.

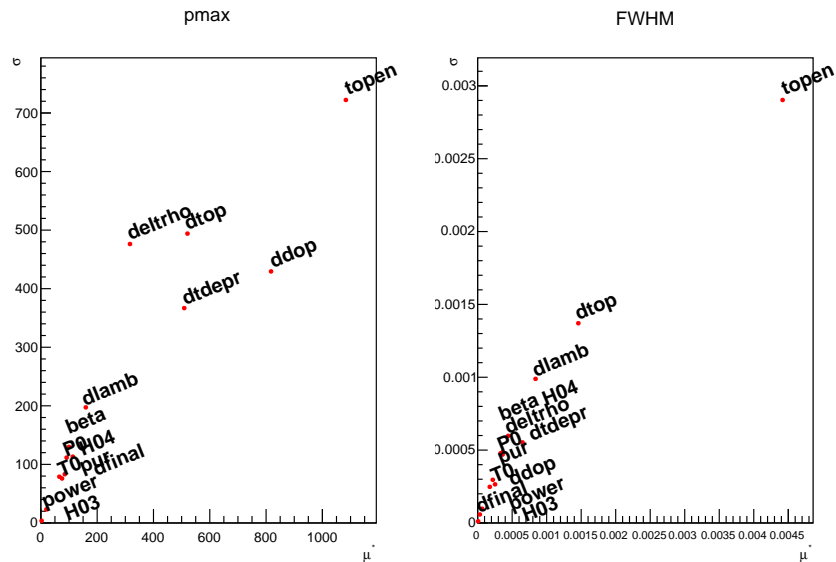


Figure 7: Input sensitivity ranking with Morris method for the “structured” transient

From the Morris screening method, the 2 uncertainties parameters with negligible impacts are eliminated in order to improve the performances of the Sobol indexes method. 12 uncertainties parameters are studied, 4200 simulations were launched to estimate the Sobol indexes. The Sobol indexes are represented as histograms on figure 8 for the maximum power P_{max} and the FWHM.

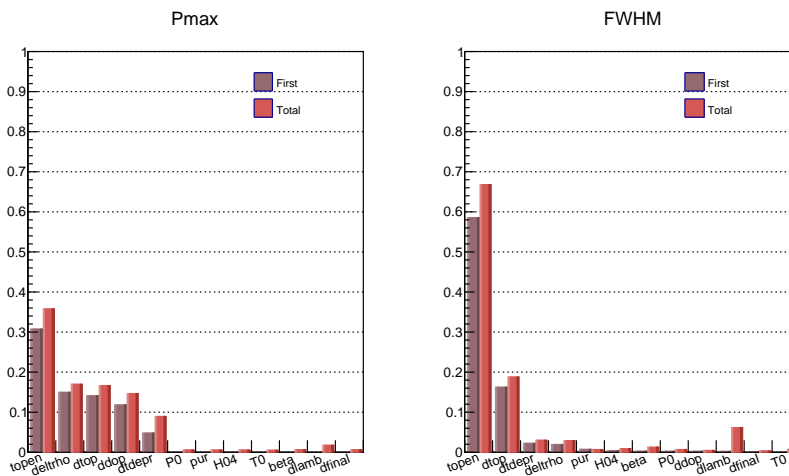


Figure 8: Sobol indexes associated to the maximum power and the FWHM of the transient

According to figure 8, the Sobol indexes ranking changes compared to the “natural” transient:

1. Δt_{open} (topen): $S_{\Delta t_{open}}(P_{max}) = 40\%$, $S_{T\Delta t_{open}}(P_{max}) = 36\%$, $S_{\Delta t_{open}}(FWHM) = 72\%$, $S_{T\Delta t_{open}}(FWHM) = 65\%$;
2. ΔTOP (dtop): $S_{\Delta top}(P_{max}) = 18\%$, $S_{T\Delta TOP}(P_{max}) = 17\%$, $S_{\Delta TOP}(FWHM) = 20\%$, $S_{T\Delta TOP}(FWHM) = 18\%$;
3. $\Delta \rho_{3He}$ (deltrho): $S_{\Delta \rho_{3He}}(P_{max}) = 20\%$, $S_{T\Delta \rho_{3He}}(P_{max}) = 17\%$, $S_{\Delta \rho_{3He}}(FWHM) = 2\%$, $S_{T\Delta \rho_{3He}}(FWHM) = 3\%$;
4. ΔDop (ddop): $S_{\Delta Dop}(P_{max}) = 16\%$, $S_{T\Delta Dop}(P_{max}) = 17\%$;
5. Δt_c (dtdepr): $S_{\Delta t_c}(P_{max}) = 6\%$, $S_{T\Delta t_c}(P_{max}) = 9\%$, $S_{\Delta t_c}(FWHM) = 3\%$, $S_{T\Delta t_c}(FWHM) = 3\%$;

Contrary to the “natural” transient case, the uncertainties on “structured” transients prediction is mainly due to an experimental parameter (topen). It impacts the test reproducibility. The uncertainty on FWHM for “structured” transients is also observed in real reactor conditions [3]. The TOP effect uncertainty has also a big influence on the “structured” transient uncertainty contrary to the “natural” transient case.

The sensitivity analysis shows that different parameters can have an impact on the power transient shape. We should continue efforts for knowledge on poison reactivities (3He , control rods) especially the interactions between them. The Doppler feedback uncertainties can be improved by analyzing nuclear data impact on Doppler coefficient and materials thermal properties impact on fuel temperature during the transients. We can reduce the uncertainties on the depressurization models and on the TOP effect model by measuring a lot of “natural” transients in different configurations. It includes a more precise estimation of the kinetic parameters ($\beta_{eff}, \Lambda_{eff}$) and their uncertainties. We should also improve the precision of the fast opening valves timing for the “structured” transients in order to reduce the uncertainty on FWHM.

5. CONCLUSIONS

The newly developed SPARTE code, based on physics, Best Estimates simulations and experimental analysis allows the prediction of the CABRI power transients calculation. In this paper we broached the subject of uncertainties associated to the prediction of the power transients by calculations. Uncertain simulation parameters and models were chosen and their uncertainties estimated in order to propagate through the SPARTE code. We dealt with 2 examples, corresponding to the CABRI typical power transients (“natural” and “structured” transients). The sensitivity study shows that the uncertainties on prediction are mostly due to model uncertainties in the case of a “natural” transient. Those uncertainties don’t affect the reproducibility of those power transients. The sensitivity study confirms measurements showing that the uncertainty on “structured” transients is mostly due to one parameter: the second fast valve opening time. We can conclude that the SPARTE code associated to the propagation method is ready to predict the CABRI power transients and estimate the uncertainties of this prediction. Those overall uncertainties could be reduced by the reduction of inputs and models uncertainties. The present approach opens the way to optimization study of the CABRI power transients characteristics.

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