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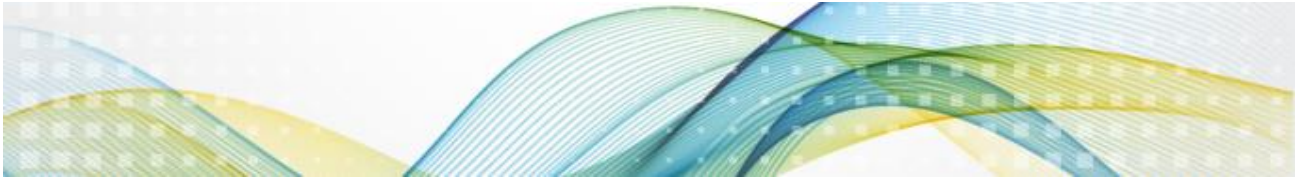
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# N°000041 - DESIGN OF A SIMULATOR ORIENTED PWR MODEL AND OPTIMIZATION OF LOAD-FOLLOW OPERATIONS

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The increase of the intermittent renewable energies contribution is a major challenge in the context of the French energy transition, with renewable energies forecasted to be around 30% of the total production by 2030, thus increasing the manageability required of nuclear power plants. This work aims at optimizing load-follow operations on French 1300MW pressurized water reactors, according to values of interests (volume of boron effluents and axial stability) by changing the operating parameters of the rods. A simulator oriented reactor model is designed, coupling a 0D secondary model and a core model with a model including 3D neutronics, multi1D thermal-hydraulics and fuel thermal effects. A simplified controller imitating the current "G mode" operator is presented. Finally, a study of the fitness landscape of the optimization problems shows the potential of this model and these parameters for the optimization process.

**KEYWORDS: OPTIMIZATION, PWR, LOAD FOLLOW, FITNESS LANDSCAPE**

## Introduction

Through the combined effect of the increase of renewables energies and the shutting down of highly carbonated power plants, France's energetic transition faces an issue of balance between consumption and production [1]. French agency RTE describes an electricity market without margins, and highly dependent on nuclear power plant (NPP) performances, because of the prominent place of nuclear power in the production mix. With a future mix made of 50% of nuclear energy and a high portion of renewable energy [1], nuclear power faces a manageability challenge.

NPP are designed so that they are self-regulating in the case of small power variations. However, in load-following transients, shifts in power can be important and therefore temperature can be quite far from its nominal value. Therefore, the management of control rods and soluble boron is crucial to mitigate temperature variations. Moreover, axial instabilities can develop because of the evolution of poisons such as xenon, and need to be mitigated by the operator. This work aims at optimizing the response of a NPP during an electrical power transient according to some values of interest by changing the control rod configuration.

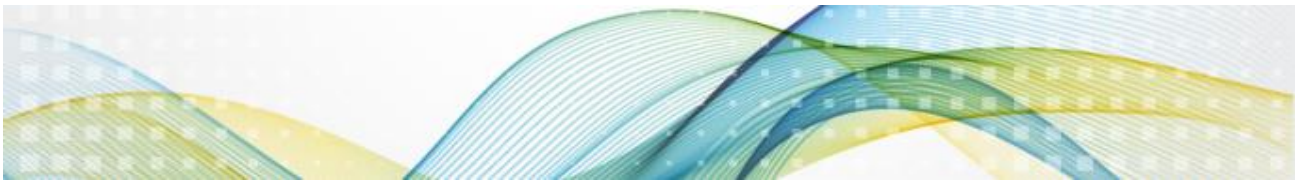
In this paper, a simulator oriented model of a French 1300MW PWR is presented, especially targeting load-following transients. The core calculation are performed thanks to the APOLLO3® [2] code, with a model including 3D neutronics, multi1D thermal hydraulics and fuel thermal effects, and a 0D kinetic model. This model is coupled to a 0D model of the secondary system. The NPP is controlled via a simulated operator based on the current G mode.

Finally, it is shown that this model can be used to optimize load-follow operations, via a study of the fitness landscapes [3] associated to the values of interest.

## I - Case Study

### I.A - Reactor Core

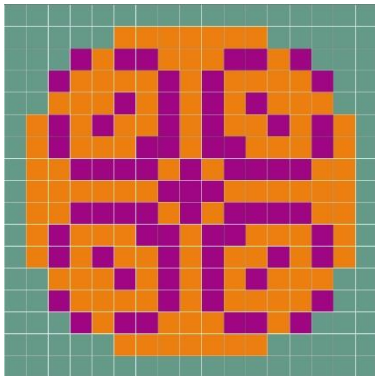
The reactor studied here is a French 1300MW PWR. Its maneuvering potential is important, and higher than that of the 900MW PWR. The core is 4m high, cylindrical and contain 193 assemblies, 120 made of Uranium oxyde (UO<sub>2</sub>) and 73 made of Uranium plus Gadolinium oxides. The reactor fuel is managed with the GEMMES mode, allowing an extended irradiation cycle, by the use of natural Uranium enriched to 4% in UO<sub>2</sub> assemblies and a fuel reloading by third. Fig 1 shows the reactor core.



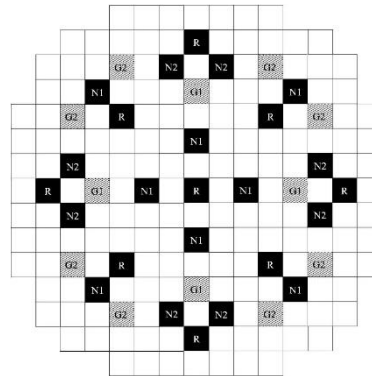
The reactor is conducted with the “G mode”. Two kinds of control rods are used in this mode, both made of pins of neutron absorber inserted from the top of core:

- Black rods, made of very absorbing pins ( $B_4C$  and  $Ag+In+Cd$ );
- Grey rods made of less absorbing pins (stainless steel and  $Ag+In+Cd$ ).

The position of the rods is given in Fig 2.



**Figure 1: Map of the different assemblies in the core ( $UO_2$  in orange,  $UGd$  in purple)**



**Figure 2: Position of the assemblies with control rods with their name and type**

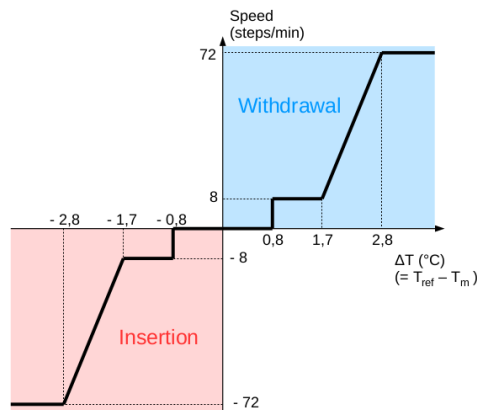
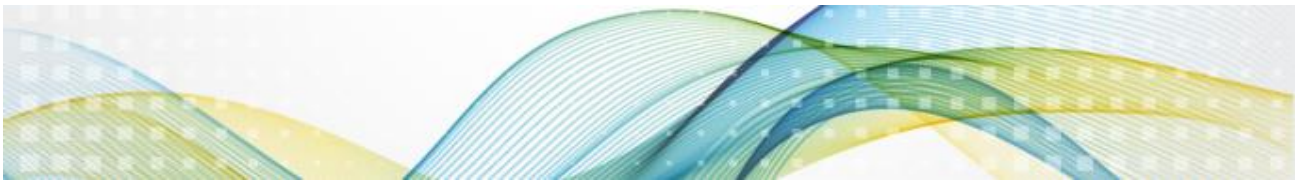
### I.B – Control strategy

Variations of electrical power lead to a series of reactions in the core. The goal of a control strategy is to maintain the reactor close to its set point. Here the focus is on the control of temperature and axial offset. More variables could be considered (primary pressure, water level in the pressurizer...), see [4,5] for more details.

In a 1300MW PWR, fluid temperature inside the core is not constant, in order to mitigate variations of pressure in the steam generator, but a function of the power. The temperature values at nominal power are a compromise between safety and efficiency. In order to avoid axial oscillations due to xenon evolution, the axial offset has to be constant.

In the G mode, two control means are available: rods and soluble boron. The rods are fully automatic and divided in two sets, while a human operator sets the boron concentration. The first set of rods consists of 4 groups: G1 (4 grey rods), G2 (8 grey rods), N1 and N2 (8 black rods each). Together they form the Power Shimming Rods (PSR). Their goal is to compensate the neutronic effects due to a change in electrical power. They work in an open loop, their position is directly linked to the electrical power via the so-called G3 calibration curve. The curve is recalibrated every 60 equivalent full power days in order to account for the fuel depletion effect. Each group moves as one, with constant overlaps between the different groups.

Theoretically, the PSR should be able to maintain the temperature to its set point. However, because of poisons evolution and calibration issues, the temperature needs to be regulated in a closed loop using the remaining 9 black rods, called the Temperature Regulation Rods (TRR). The TRR works via a speed program directly related to the difference between the actual temperature of the core and the temperature set point (see Fig 3). The TRR are limited to a maneuvering range in the higher part of the core, in order to maintain a satisfying reactivity margin. For a more detailed account of temperature regulations in French PWR, see [5].



**Figure 3: Temperature Regulation Rods speed program.**

Finally, the human operator sets the boron concentration. It serves multiple objectives:

- Taking over the TRR when temperature variations cannot be compensated within their maneuvering range;
- Avoiding large variations of the axial-offset (AO) (indirectly, see below);
- Offsetting the burn-up effects.

The boron is slower than the TRR because of flow rate limitations in the borication mechanism. Therefore it is used to control slow variations, such as poison evolution or fuel depletion effect.

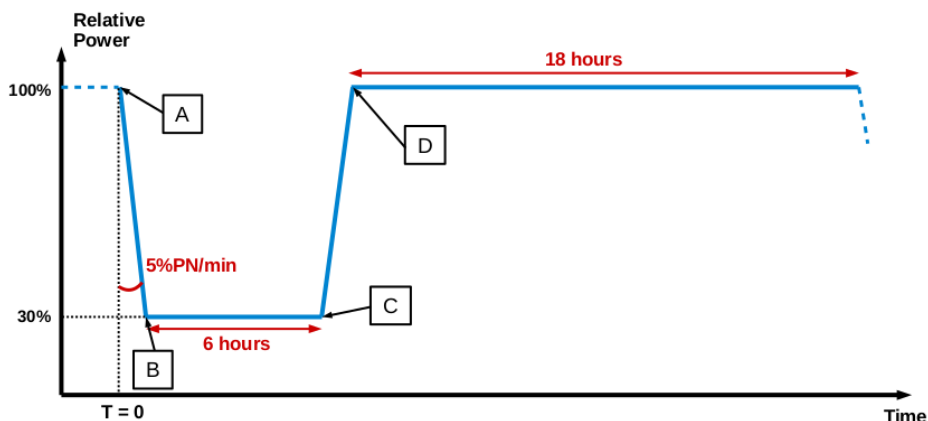
Because of their position in the higher part of the core, the TRR have a stronger effect on AO, they are an important tool to control xenon oscillations. The operator will voluntarily change the temperature with a borication or a dilution in order to trigger a reaction of the TRR that will have the desired effect on the axial offset. Though it is used in the 1300MW PWR, it is not managed automatically and the boron amount has to be computed by the human operator. The "T mode" of the European Pressurized Reactor has an automatic axial offset regulation based on this observation [6].

### I.C – Optimization problem

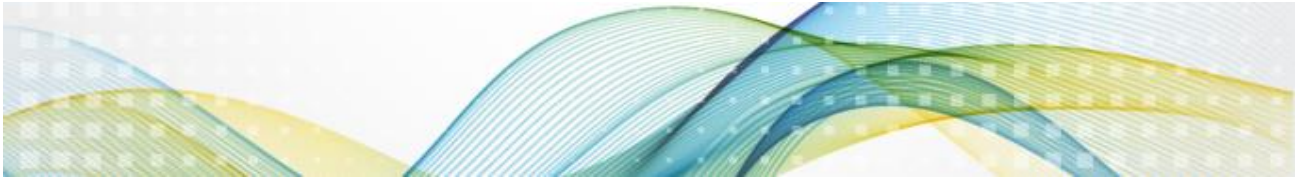
The purpose of this model is to compute the criteria of the multi-objective optimization study of load follow operations. The considered transient is a classic day/night load-following scenario (see Fig. 4). The power is set to 30%NP (Nominal Power) for 6 hours and then goes back to 100% NP. The slope is the maximum authorized slope of 5% NP/min. The optimization is bi-objective, with two opposite goals:

- Reducing the cost of the transient, by minimizing the volume of boron effluents;
- Assuring the axial stability of the transient, by minimizing an axial-offset integral.

Safety will also be considered via constraints related to the anti-reactivity margin.



**Figure 4: Load-follow transient considered.**



For this optimization problem, the free parameters are selected in the rod configuration:

- Speeds of the PSR rods (4 discrete parameters);
- Overlaps between the PSR rods (3 discrete parameters);
- Maneuvering band of the TRR (1 discrete parameter).

Their ranges are limited by technological and safety concerns. In this paper, the optimization problem will be addressed solely from the perspective of the fitness landscape – which is energy surface related to the parameters values, associated to both criteria. Further work will tackle the problem with evolutionary algorithms using the study of the fitness landscape.

## II – Nuclear Power Plant Model

### II.A – Core model

The core model presented here derives from the work of M. Muniglia [7]. Its key characteristics are presented in this section.

#### II.A.1 - Neutronics

The neutronics calculation are performed using a quasi-static model with uncorrelated time and space. The spatial effects are determined with a 3D diffusion calculation. The geometry is a quarter of core described with a mesh of 9826 nodes (cell dimensions are 10.7\*10.7\*14.2 cm<sup>3</sup>). The temporal effect are taken into account with a point kinetic model, using the Nordheim equation. Since load-follow transients are slow, low reactivity is assumed, and the equation is then linearized.

The calculations scheme is as follows. First, knowing the inlet temperature and enthalpy, and the rod positions and boron concentration, a first static 3D calculation is performed in order to compute the reactivity. The total power in the core is then updated using the point kinetics equation. Finally, a static 3D calculation is done to compute the shape of the power and temperature distributions.

The evolution of the poisons (Xenon, Iodine, Samarium...) and fissile isotopes is computed for each node of the 3D mesh, using simplified depletion chains. Their concentrations are updated at each time step.

#### II.A.2 - Primary Thermal-hydraulics

The thermal hydraulics model assumes that the fluid temperature is constant radially and that the variations of fluid properties are slow. Therefore there is simply an axial enthalpy balance in the core:

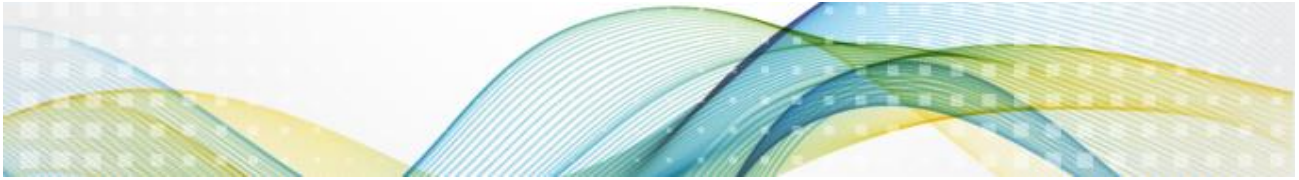
$$\frac{dH(z)}{dz} = \frac{\pi D_t \phi}{S_h \nu \rho(H)} \quad (1)$$

with:

- $H$  the enthalpy at axial position  $z$  (in  $J/g$ ),
- $D_t$  the sum of the diameters of the pins in the mesh,
- $\phi$  the heat flux between the pin and the fluid (in  $W/cm^2$ ),
- $S_h$  the hydraulic section (in  $cm^2$ ),
- $\nu$  the average fluid velocity (in  $cm/s$ ),
- $\rho$  the fluid density (in  $g/cm^3$ ).

#### II.A.3 – Fuel Thermics

The heat equation inside the pellets is written assuming that heat transfers are only radial, and assuming slow variations of power and temperature. The temperature is supposed to be constant over the height of the cell, and the power production uniform.



$$\frac{-1}{r} \frac{d}{dr} \left( r \lambda(T) \frac{dT}{dr} \right) = P_{vol} \quad (2)$$

with:

$\lambda$  the thermal conductivity (in  $W/cm/K$ ),  
 $T$  the temperature,  
 $P_{vol}$  the power density (in  $W/cm^3$ ).

## II.B – Model of the secondary system

The secondary system encompasses everything between the core of the reactor and the alternator. Its main components are: the turbines, the steam generators, the condenser and the pumps. These components are modeled in order to recreate the delays in power between the alternator and the core in a load-follow transient.

The following assumptions are done:

- Due to symmetry, only one loop is considered;
- The turbine and alternator are not modeled and are replaced by the electrical power required by the grid. Their efficiency is supposed to be a function of the electrical power, based on empirical observations [4];
- The pumps are supposed to provide a constant power  $P_p$  to the primary fluid;
- There is a constant mechanical loss of power  $P_l$  in the circuits.

The main equation of the model is a balance power of the primary system:

$$\Delta T = \frac{1}{mC_p} (P_{th} + P_p - P_l - P_{SG}) \Delta t \quad (3)$$

with:

$T$  the inlet temperature of the core (in  $K$ ),  
 $P_{th}$  the thermal power in the core (in  $W$ ),  
 $P_{SG}$  the power exchanged at the steam generator (in  $W$ ),  
 $mC_p$  the heat capacity of the primary system (in  $J/K$ ).

The power produced in the core is computed via the primary model. A steam generator model is needed to compute  $P_{SG}$ .

### II.B.1 – Model of the steam generator

A simple 0D-model of the steam generator is implemented, based on a balance between the extracted steam flow, the power given by the primary loop and the steam inside the generator. It is assumed that the heat extracted from the primary loop is entirely used to produce steam, and that the mass of water in the steam generator is constant.

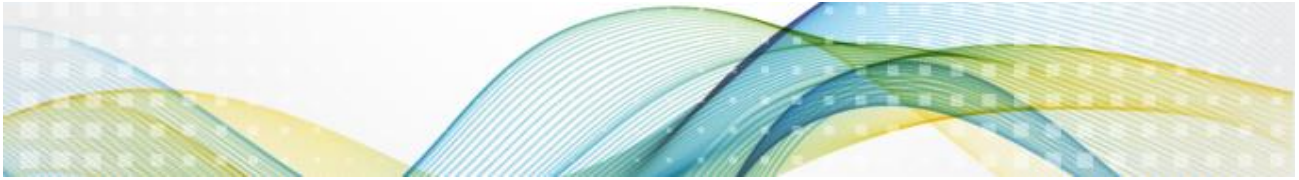
The extracted flow of steam is directly related to the electrical power of the plant:

$$Q_s = \frac{P_e}{\eta(h_s - h_i)} \quad (4)$$

with:

$Q_s$  the flow of outgoing steam (in  $kg/s$ ) and  $h_s$  its enthalpy (in  $J/kg$ ),  
 $\eta$  the efficiency of the turbine and alternator,  
 $P_e$  the electrical power (in  $W$ ),  
 $h_i$  the enthalpy of the ingoing water (in  $J/kg$ ).

The produced flow of steam in the steam generator  $\Pi_Q$  is given by the power exchanged between the primary loop and the steam generator water:



$$\Pi = \frac{P_{SG}}{h_s - h_i} \quad (5)$$

The difference between the results of Eq. (4) and (5) gives the variation of steam density in the steam generator and therefore the variation of the temperature of the saturated steam. Finally, the exchanged power between the primary and secondary fluids is computed using a simple heat exchange model [4]:

$$P_{SG} = H_s(P_{th})(T_m - T^{sat}) \quad (6)$$

where

$H_s$  is a coefficient related to the surface of the tubes over the thermal resistance (in  $W/K$ ), and is computed via empirical observations as a function of the thermal power produced in the core [4],

$T_m$  is the average temperature of the primary fluid (in  $K$ ),

$T^{sat}$  is the temperature of the saturated steam (in  $K$ ).

### II.B.2 – Condenser and steam generator water supply model

The goal of this model is to compute the enthalpy of the inlet water in the steam generator  $h_i$ . After the turbine, the fluid goes through a condenser at a constant temperature of  $33.6^\circ C$ , and is then reheated and stored in a tank. Finally after a second heating, the fluid is sent to the steam generator.

It is assumed that the mass in the steam generator is constant, so the flow of water going in is the same as the flow of vapor extracted. The reheating systems are modeled using empirical data from [4].

### II.C – Model of the operator

The hypothesis in the secondary model require a quasi-static transient, therefore the time step as to be larger than one minute. With this time-scheme, the TRR speed-program cannot be transposed directly since TRR speed cannot be updated often enough.

A new control mode, meant to imitate the G mode for a macroscopic time step is therefore implemented. This “MacroG” mode is based on the observation that the G mode’s role is to compensate non zero reactivity due to a difference between the temperature and the programmed temperature. Let  $\rho$  be this reactivity, the set point for the rod position is then computed knowing the TRR efficiency.

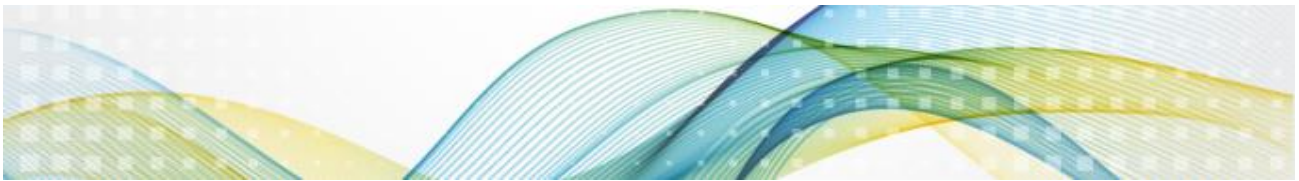
$$\Delta R = \rho / \varepsilon \quad (6)$$

where:

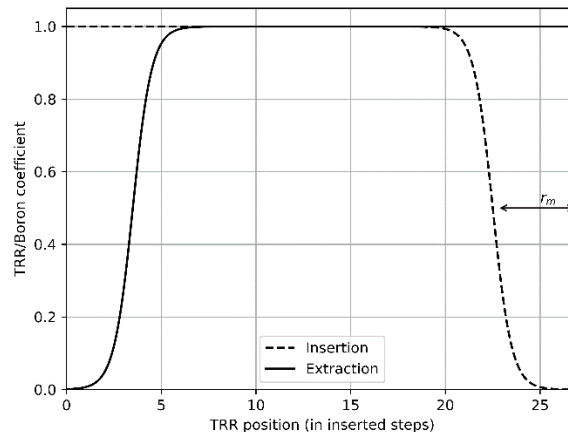
$\Delta R$  is the variation of position of the TRR (in steps),  
 $\varepsilon$  is the rods efficiency (in  $pcm/step$ ).

The reactivity could be computed simply as proportional to the temperature gap. However, such a system would not be as effective as the real mode G, because it would not take into account the evolution of the xenon level as quickly. In order to mitigate that problem, the Macro G mode computes the reactivity due to the evolution of the xenon for the next time step and add that to the temperature reactivity.

The G mode also requires a human operator who will use the soluble boron to further regulate the temperature if the regulation rods are out of their maneuvering band and to mitigate AO variations. In the first case, the human operator uses contrary actions with the soluble boron so that the change in temperature will lead the regulation rods to go back towards the center of their maneuvering band. Such contrary actions with a large time step would be counterproductive and cause important temperature oscillations in the core, which would not be representative of the original G mode. Therefore, the simulated operator must take the decision of using boron instead of regulation rods when near the limits of their maneuvering band beforehand. A coefficient is then introduced to distribute the reactivity between the regulation rods and the boron. Near the center of the maneuvering band, the coefficient value is 1, meaning that the whole reactivity will be compensated with regulation rods, and 0 near the maneuvering band’s limits. The shape of the transition is a hyperbolic tangent (see Fig. 5), with two parameters: the position of the transition  $r_m$  (counted as a step margins from the end of the maneuvering band) and the width of the transition,  $l$ .



Finally, a strategy for the control of the axial offset is implemented, with the idea that when the axial offset gap is above a certain threshold  $S_{AO}$ , the movements of the rods must try to reduce it.



**Figure 5: TRR/Boron usage coefficient for a standard 27 steps maneuvering range (0 corresponds to soluble boron use only, 1 to TRR only).**

The PSR G3 calibration curve has been computed before hands for a number of rod overlaps configurations, and an interpolator based on a sparse grid technique has been implemented so that the curve is be quickly computed for any overlaps. The calculation itself imitates the actual process used on nuclear power plants.

## II.D – Calculation scheme

The calculation scheme consists of two loops. The first loop is the physical calculation of a quasi-static state of the reactor by a coupling of the core calculation and secondary system calculations with an internal time step  $dt_c$  called coupling time.

Then the main loop follows the actual transient with a time step  $dt$ . For each step, the electrical power updates the PSR position. The isotopic depletion calculation for the time step is then computed. Based on the temperature and AO previously computed and the xenon evolution, a new set point for the TRR and soluble boron is computed by the Macro G operator. Finally the physical loop is called in order to compute the new state of the reactor.

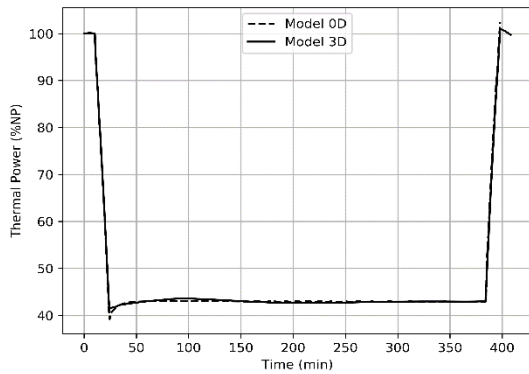
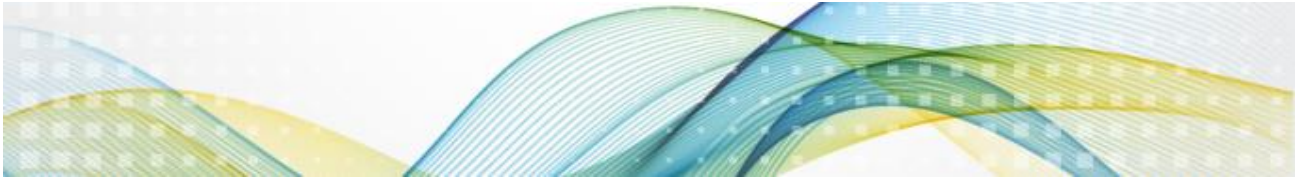
The choice of the two time steps is key. The number of iterations allowed for the physical loop is directly related to the transient time step, so that the evolution is consistent ( $numberofiterations = dt/dt_c$ ). Therefore the transient time step has to be large enough so that the core will actually converge. However, it needs to be small enough so that it will accurately represent the load-following scenario and the operator will be able to control the reactor.

## III – Results

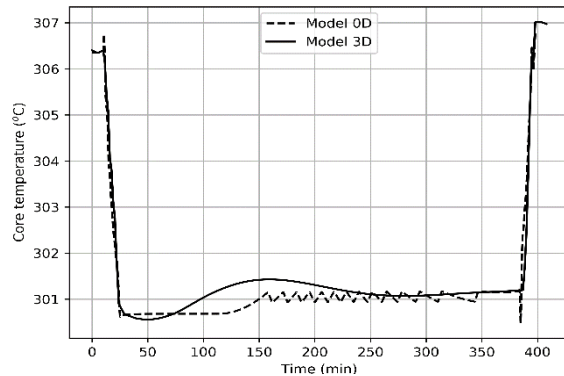
### III.A – Model validation

In this section, the transients obtained with this model, so called the 3D model are compared to a 0D model developed by H. Gard [4], and based on simulator feedback. The 0D model proposes a more refined description of the secondary systems. It reproduces the G mode operations for the PSR and TRR, and proposes a virtual human operator for the management of soluble boron. Even if it is not a best-estimate model, in the absence of available reactor feedback, it is a good point of comparison.





**Figure 5: Thermal power evolution during the transient for the 0D and 3D models.**



**Figure 6: Core temperature evolution during the transient for the 0D and 3D models.**

The comparison between the two models for a truncated transient is presented in Fig. 5 and 6 for the thermal power in the core and the primary fluid mean temperature. The behaviors are very similar, especially the thermal power, that quickly stabilizes to its equilibrium value. As for the temperature, the response is consistent. The 3D model gives a smoother evolution because of the “Macro G” model, which does not use a dead band for the TRR moves, as the G mode does (see Fig. 3).

The full transient (24 hours) with the 3D model has been computed in 17 minutes on a personal computer (Intel® Xeon® @2.1 GHz). The rather low computational cost will significantly ease the optimization process.

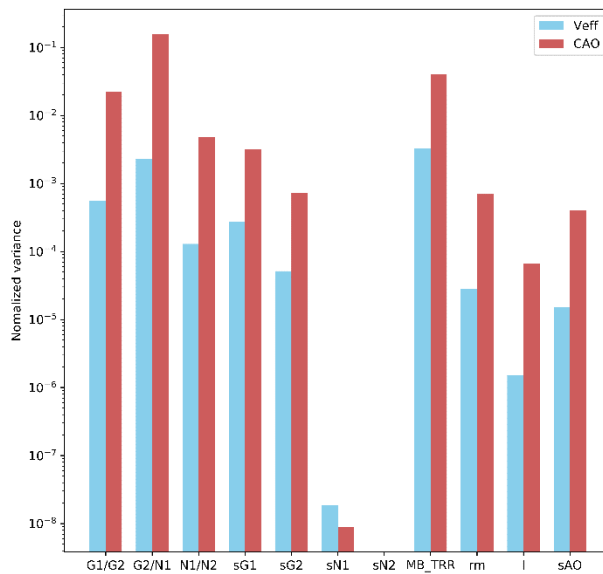
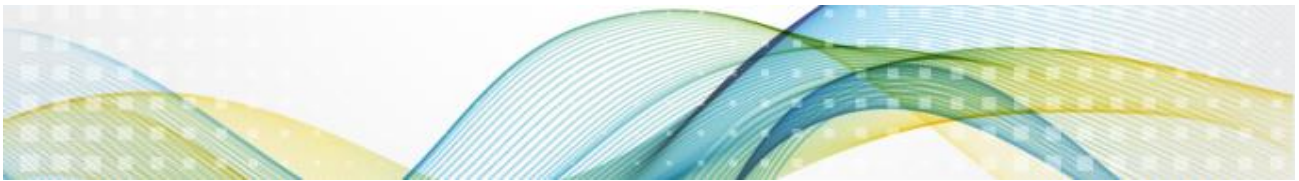
### III.B – Study of the fitness landscape

In this section, a first approach of the optimization problem is proposed, in order to confirm the interest of the problem and to choose a resolution method and tune its parameters.

The two values of interest for the optimization problem are the volume of boron effluents, called  $V_{eff}$ , and the integral of the DPAX error over time, called  $C_{AO}$ . Both must be minimized in order to ensure a good response of the NPP. The main set of parameters consists of the 8 discrete rod parameters described in section I.C. The 3 continuous operating parameters  $r_m$ ,  $l$  and  $s_{AO}$  of the macro G model are also considered as a second set of parameters.

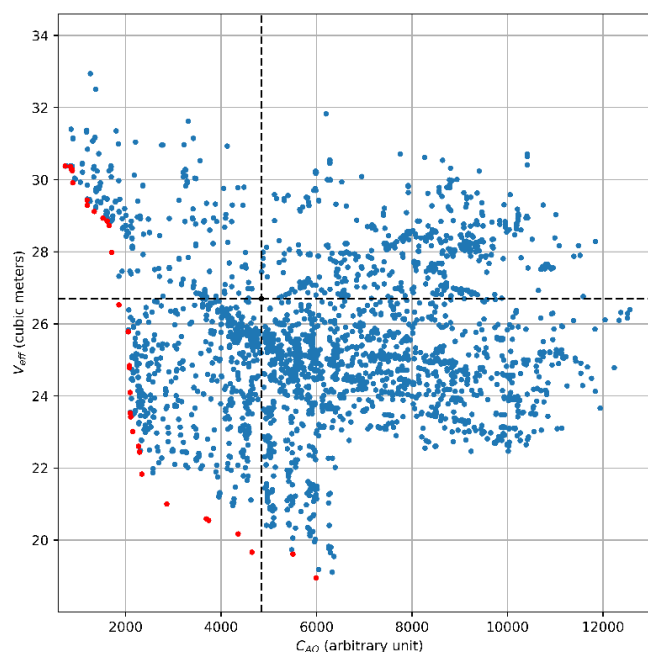
In order to gather information on the fitness landscape of the problem, a random walk is conducted over each set of parameters. At each step, only one parameter of the set is modified, with a uniform law for the rod parameters and a normal law for the operating parameters. A total of 104 starting points were considered, generated with Sobol sequences [8]. At each starting point and for both sets, three walks were carried with three different mutations (small, medium and big). The walks on the rod parameters were 16 step long and the walks on the operating parameters 6 step long. Overall, 6968 points were computed.

Some intuitive trends were proven with this analysis, further confirming the model. For instance, it can be shown that a wider maneuvering range for the TRR reduces the need for soluble boron, and therefore the volume of effluents. Important overlaps tend to reduce axial instability because the rods will not be inserted very low in the core.



**Figure 5: Variance of the normalized values of interests associated with the parameters (overlaps G1/G2, G2/N1, N1/N2, speeds of the PSR groups sG1, sG2, sN1 and sN2, maneuvering range of the TRR MB\_TRR, operating parameters  $r_m$ ,  $l$  and  $s_{AO}$ ).**

Fig. 5 shows the normalized variances of the values of interests over the parameters. As was expected, the maneuvering range of the TRR and the first two overlaps have the strongest influence. The overlap between G2 and N1 has a particularly strong influence because it separates a very efficient group of black rods and a group of less efficient grey rods. On the contrary, the speeds of the last two PSR groups N1 and N2 have quasi zero influence on the criteria. One can note that the variances associated with the operating parameters are at least one order of magnitude below these of the influential parameters. This does not mean that the operating strategy is not important, but that within this “Macro G” model, the parameters does not have an impact as much impact as those of the rod configuration. Different control strategies were studied, with strongly different values of the criteria. From the perspective of an optimization algorithm design, this analysis shows the more important parameters to modify during the optimization process in order to accelerate the convergence of the algorithm toward optimal solutions.



**Figure 6: Points of the random walk in the  $(C_{AO}, V_{eff})$  space. The approximated Pareto front is highlighted in red, and the nominal values in black dotted lines.**

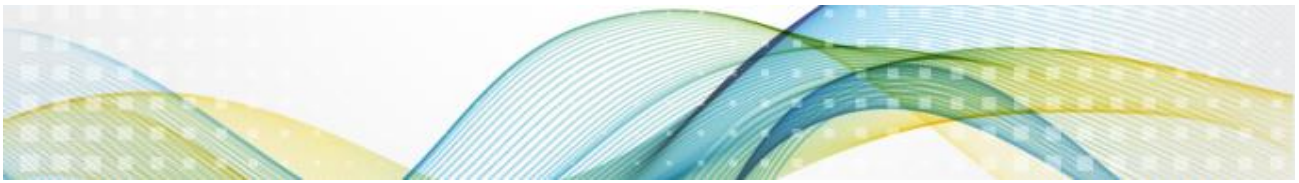


Fig. 6 shows the computed points in the plane  $(V_{eff}, C_{AO})$ , with a first approximation of the Pareto front. It can be noted that 88% of the computed points gives either a better  $C_{AO}$  or a better  $V_{eff}$  than the standard values, showing the potential of optimization of this load-follow transient. No linear correlation between the two values of interests seems to exist over the whole parameter space. However, for small values of  $C_{AO}$  (under 6000 arbitrary units), one can see that a negative correlation seems to appear, as shown by the shape of the Pareto front. This shows the importance of conducting a multi-objective optimization for these values of interest, in order to get closer to the real Pareto front.

## Conclusion

A model of a complete NPP has been presented interfacing a core model and a steam generator model. Comparing this model to another model based on simulator feedback has shown that this model is fully capable of describing the physical effects involved in an electrical power transient. It provides numerous indicators of performance and give physical information on the core and its safety, with a reduced computational cost. Some intuitions on the effects of the rod configuration on the values of interest were proven. Other potential values of interest will be considered in further developments.

It was also shown that this model can be used in a multi-objective optimization process with two values of interests: the volume of boron effluents and the axial stability, measured as an integral of axial-offset over the transient. Further developments are devoted to designing a multi-objective evolutionary algorithm in order to further study the optimization process.

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