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Feasibility Study Of Design Of Control Rods With Reactivity Worths In Successive Powers Of Two For Precise Reactor Power Regulation

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ABSTRACT

An innovative design of low-absorption control rods has been proposed for power regulation of a nuclear reactor operating in a load-following mode. Control rods for power regulation contain materials with lower absorption cross sections and lower reactivity worth than regular, shutdown 'black' control rods and are intended to be inserted over the entire height. These control rod clusters have been designed to study their feasibility. A 2D model representing a typical PWR reactor core has been created using Monte Carlo Serpent code. The temperature defect has been calculated as a different between HZP and HFP conditions to define the reactivity worth requirements that need to be fulfilled by the control rods assemblies. Different designs have been developed as well as their geometrical configuration in the core, analysing important reactor physics parameters. In this regard, attempts have been made to minimize the interference effect between the control rod clusters.

1 INTRODUCTION

The great majority of nuclear power plants are operated in base-load operation mode, maintaining a steady and continuous full rated power. One exception is the necessity to reduce the power or shut down the reactor for maintenance and refuelling or for other reasons related to operation and safety. In addition, there is an increasing need of some countries to operate nuclear reactors in a flexible way due to grid requirements, the so-called load-following mode [1]. Under this operation mode, significant power variations are carried out every day to satisfy the market needs. The necessity of the load-following mode also arises from the fluctuating electricity generation, influenced by the important growth of some energy generation forms that are not easily controllable. These include wind turbines and solar photovoltaic panels, which are extremely dependant on the weather conditions.

The significant power variation of nuclear reactors operating in the load-following mode produces different effects in the neutron transport properties of the reactor that need to be addressed. Among these effects, there is the fuel and moderator temperature change, the variation of the concentration and distribution of the neutron absorber ^{135}Xe and modification of the axial power profile [2].

In this regard, the present work aims to study the possible use of low absorption control rods as an alternative solution for reactor operation under load-following mode. The so-called 'grey' control rods allow to maneuver the power without introducing large perturbations. They receive their name from the 'grey' neutron absorber that they use, which absorbs less neutrons than a 'black' neutron absorber. In this regard, 'grey' control rods produce smaller reduction of the neutron flux and the power around the rod. These clusters are placed symmetrically in the core to avoid the appearance of a tilted flux that could affect the performance of the reactor.

2 PWR 2D MODEL

A model [1] representing a PWR reactor core has been considered for the elaboration of this work. In particular, a NuScale reactor core has been reproduced using Serpent code [3, 4, 5]. In this work, a 2D model has been developed in order to focus the analysis of the geometrical aspects of the design in the radial direction. In this respect, the possible axial effects that could arise from the control rods assemblies (CRA) design have not been considered. The reasons for choosing PWR as the reference reactor design for this work are that fuel burnup in PWR is axially more homogeneous compared to some other types of reactors. In addition, PWR reactors represent the most widely used design in the world. The justification to use a 2D model includes the fact that the core height is normally larger than its diameter and that the axial geometry is often homogeneous whereas in the radial direction, the scale of heterogeneity is mm to cm. Therefore, higher gradients can be found in the radial direction.

2.1 Core design

The NuScale reactor core consists of 37 fuel assemblies (FA) surrounded by a radial stainless steel neutron reflector to improve the fuel utilization by reducing the escape of neutrons from the core. Each FA design is a 17×17 square design, as shown in Figure 1. The assembly is equipped with 24 guide tubes and a central instrumentation tube. Hence, each fuel assembly contains 264 fuel rods.

2.2 Fuel elements design

The considered fuel is uranium dioxide (UO_2) with gadolinium oxide (Gd_2O_3) as a burnable absorber homogeneously mixed to establish a favorable radial power distribution and control the reactivity.

From the previously mentioned fuel materials, two different geometries of FA are constructed: the first one only contains uranium dioxide rods and the second one contains both uranium dioxide pins and a mix of uranium and gadolinium oxide pins (see comparison in Figure 2).

In addition, three different ^{235}U enrichment values have been considered for the pin-level composition. On the basis of these, three different types of fuel assemblies were constructed for the reactor use:

1. 2.6 wt.% ^{235}U
2. 4.55 wt.% ^{235}U +10 wt.% Gd_2O_3 [2]

[1] Elaborated from a previous model created and kindly shared by Blaž Levpušček.
[2] The gadolinium oxide mass fraction is expressed as the mass of Gd_2O_3 in the total fuel mass.

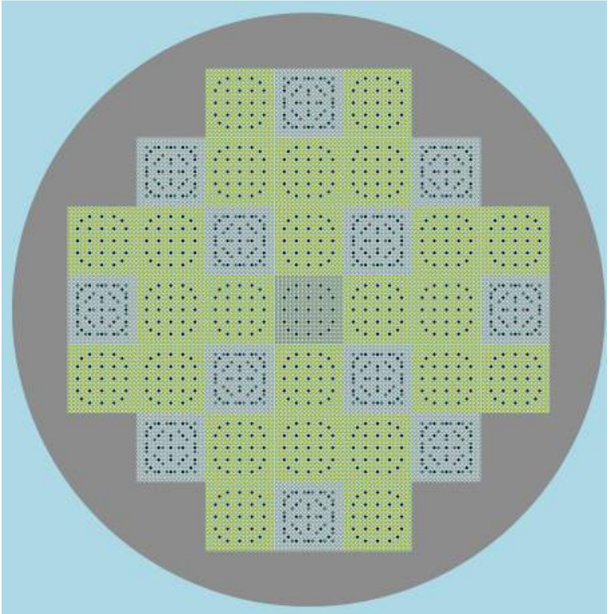
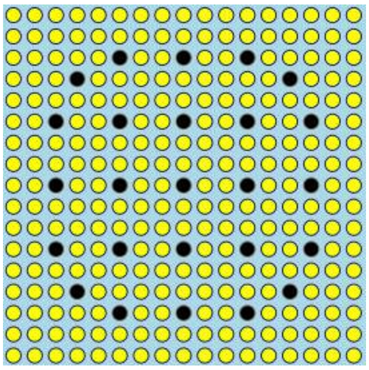
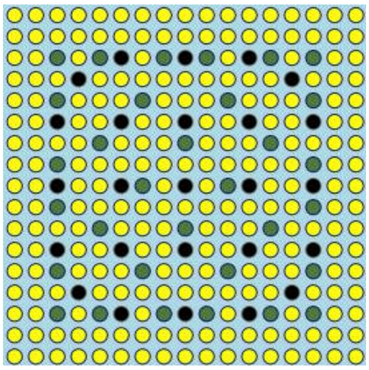


Figure 1: Scheme of the NuScale PWR 2D model core.



(a) FA with pure UO_2 pins (yellow coloured).



(b) FA with pure UO_2 and UO_2 + Gd_2O_3 pins (green coloured).

Figure 2: Types of fuel assemblies considered in the computational model.

3. 4.05 wt.% ^{235}U

The first type is the one with the lowest enrichment and it is located in the central position of the reactor. The second one has the highest enrichment and contains gadolinium (blue color in Figure 1. Finally, the third type is the one with medium enrichment (yellow color in Figure 1).

2.3 Temperature defect calculation

At Hot Zero Power (HZP) conditions all fuel elements, cladding, moderator and other structural elements are assumed to be at the same temperature of 600 K. At Hot Full Power (HFP) conditions, the temperature of the fuel was increased to 900 K, keeping the temperature of other components at 600 K. The reactivity difference between both reactor operating states is known as the temperature defect. In this case it can be noted that only the effect of the fuel temperature increase is evaluated. Even if an axial temperature gradient is present in the core, an average temperature of 600 K is considered for the coolant. Hence, the temperature defect could be calculated as

$$\Delta\rho = \rho_{\text{HFP}} - \rho_{\text{HZP}} = 834 - 29 = 805\,\text{pcm}\,. \tag{1}$$

The obtained value is in accordance with typical PWR values [6].

3 CONTROL RODS DESIGN

The choice of the absorber material represents an important aspect of the control rods since it will determine the capability to modify the fission chain reaction. In this regard, boron and cadmium present high absorption cross section values, representing good materials for thermal neutron absorption. For these reasons, boron and cadmium are the most used materials for PWR control rods in the form of boron carbide (B_4C) and in an alloy with silver and indium (AIC) respectively. Other absorber materials include e.g. hafnium, gadolinium or europium [7, 8].

3.1 Position variation

The first part of this analysis aims to show the effect that the position of the CRA in the core has on the inserted reactivity and the fission rate distribution. In this case, one inner and one outer position of the core are analyzed. These are positions 54 and 24 respectively [3]. The composition and the density of the CRA as well as the multiplication factor and the reactivity obtained at the inner and the outer positions are shown below in Table 1. In addition, the uncertainty included in brackets corresponds to the Monte Carlo statistical uncertainty, without considering any other uncertainty contribution.

Table 1: Influence of the CR position on reactor reactivity.

Materials	**Zr**	**Ag**	**In**	**Cd**
Mass fraction [%]	96	0.4	0.6	3
Density [g/cm^3]	6.59112			
	Position 54			**Position 24**
k_{eff}	0.99200 (2)			0.99929 (2)
Reactivity [pcm]	-807 (2)			-71 (2)

As it can be noted, there is significant influence of the position on the value of the inserted reactivity. The reason is the increased neutron flux towards the center of the core. The radial distribution of the neutron flux is approximately given by a Bessel function of first kind $J_0(\mathrm{r})$ [4], which has a maximum at the center of the core. Therefore, the effect of the CRA insertion will be higher at position 54, where a higher neutron flux is present. The same effect can be observed by comparing of the fission rate when all rods are withdrawn and when a CRA assembly is inserted at position 54 (see Figure 3).

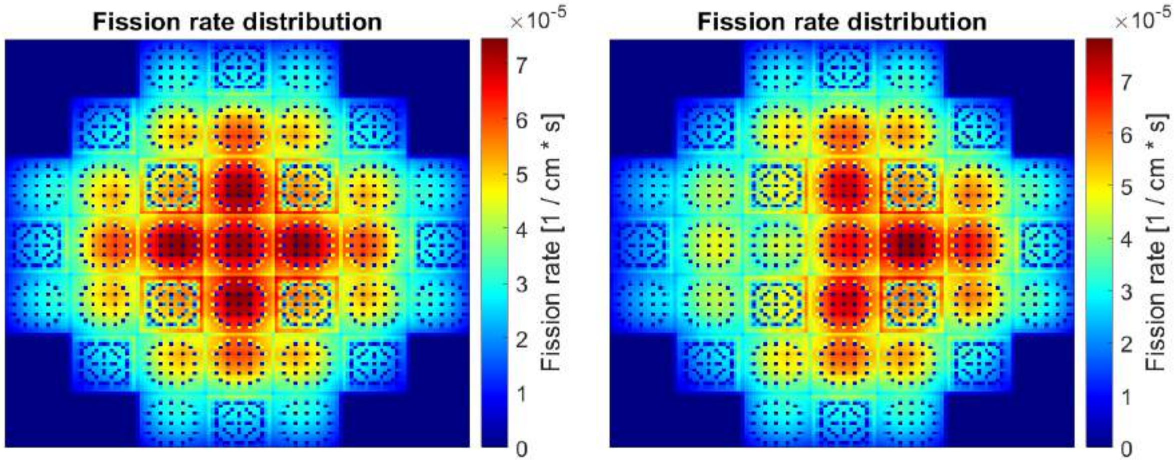
Comparing both figures, it can be noticed that the insertion of the CRA at position 54 produced a displacement of the neutron flux towards the right side of the reactor. This represents a dangerous situation since a tilted flux would cause an unbalanced burnup and an overheating of some fuel assemblies that could affect the safe operation of the reactor.

3.2 Reactivity worth variation

In this simulation, the influence of the neutron absorber materials composition was studied. In order to do that, one control rod cluster containing AIC and zirconium was inserted at

[3] Each position is defined by a two-digit number where the first and the second number respectively correspond to the row and the column of a 9 $\times$ 9 mesh representing the different positions of the core where the assemblies are located.

[4] Diffusion approximation valid for a homogeneous cylindrical reactor without reflector.



(a) Core with all control rods out.

(b) CRA inserted at position 54.

Figure 3: Comparison of fission rate distributions.

the inner position 54. Then, the cadmium concentration was reduced to one tenth of its original concentration and the zirconium concentration was increased to compensate for that. The obtained results as well as the composition of the control rods are shown in Table 2.

Table 2: Influence of the CR material composition on reactor reactivity.

CRA inserted positions	Mass fraction				Reactivity [pcm]
	Ag	In	Cd	Zr	
54	0.004	0.006	0.02	0.97	-761 (2)
54	0.004	0.006	0.002	0.988	-346 (2)

Attending to the results above, it can be noted the big impact of the control rods composition on the inserted reactivity in the core. In this case, the reactivity worth was reduced by a 45 % of its original value when the cadmium concentration was reduced to one tenth. Therefore, even if the neutron absorber concentration is slightly changed, it will have a great influence on the reactivity value.

3.3 Concentration variation

The third part of this analysis focused on the impact of neutron absorber material concentration on reactor reactivity. Neutron absorber concentration was reduced by 5 % in twelve steps, while maintaining a constant total material density by increasing zirconium content. Six control rod assemblies (CRA) were placed at positions 35, 43, 47, 63, 67, and 75.

Reactivity dependence on absorber concentration is depicted in Figure 4. Reactivity uncertainties, though small, are represented by horizontal bars. The figure illustrates reactivity decrease as neutron absorbers are replaced with zirconium. Diminishing absorber concentration boosts reactivity due to reduced neutron capture by CRA.

The figure also highlights a linear relation between reactivity evolution and absorber concentration, supported by the linear trend line and coefficient of determination (R^2). This coefficient, ranging from 0 to 1, signifies how well the model fits the data. Here, a high R^2 suggests a precise fit of the linear trend to the data.

3.4 Configuration 1

After these analyses, different CRA configurations were designed. The first considered design consists of a cluster of six CRA intended to insert the reactivity worth of the entire tem-

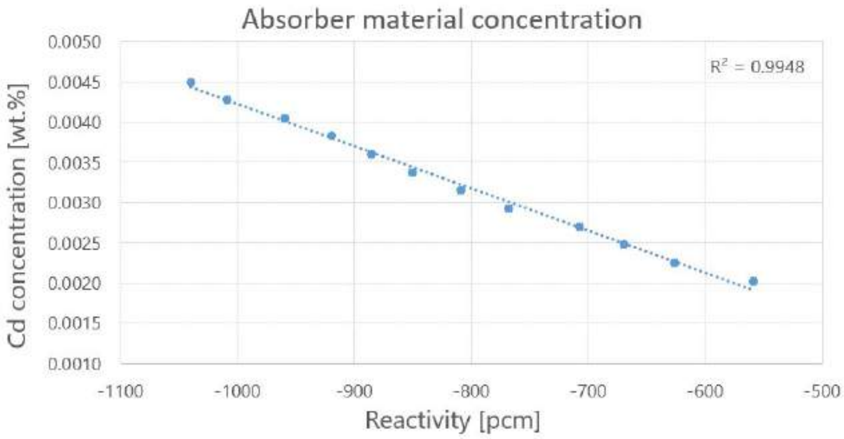


Figure 4: Dependence of the reactor reactivity on absorber material concentration.

perature defect. This design considers two different CR materials concentrations: one for two CRA located in inner positions of the core (53 and 57) and one for the other four CRA located in outer positions of the core (33, 37, 73 and 77). Each CRA was first inserted individually to evaluate its impact on the reactivity. Later, all six CRA were inserted together. The specific CRA composition as well as the numerical results obtained are shown below in Table 3.

Table 3: Composition and results of Configuration 1.

CRA inserted positions	Composition				Reactivity [pcm]
	Ag	In	Cd	Zr	
33-37-73-77	0.05	0.05	0.4	0.5	-84 (2)
53	0.002	0.003	0.004	0.991	-249 (2)
57	0.002	0.003	0.004	0.991	-245 (2)
SUM					-830 (5)
6 CRA inserted					
33-37-73-77	0.05	0.05	0.4	0.5	
53-57	0.002	0.003	0.004	0.991	-1050 (2)

After analysis, the CRA's influence on inner positions is evident. Despite their smaller presence in outer positions (0.9 % and 50 % respectively), the impact on reactivity is more substantial. Combining all control rods, total insertion matches the temperature defect, yet using all six CRA raises reactivity by 200 pcm more. This could be due to neutron flux redistribution due to the effect of CRA insertion.

For radial power distribution analysis and comparison with HFP's reference core, fission rate ratios were computed (Figure 5). Each position's ratio and uncertainty were shown. As expected, ratios are < 1 where control rods are placed. Lowest is 0.798/0.799 (purple), at outer CRA spots. Around control rod positions, neutron flux drops (green, turquoise), reducing fission reactions in this core's outer region. Neutron flux shifts toward the core center, raising fission rate ratios beyond 1. Flattening radial distribution warrants designing new configurations.

3.5 Configuration 2

In the second configuration, the selected positions for the control rods keep a more homogeneous distance to the center core. These positions are 35, 43, 47, 63, 67 and 75. Again, two different CR materials concentrations were considered. The results from the simulations as well as the CRA composition are shown in Table 4.

Regarding the control rods composition, it can be noted the similar zirconium weight fraction for both compositions: 99.52 % and 99.43 %. This choice is due to the uniform distance

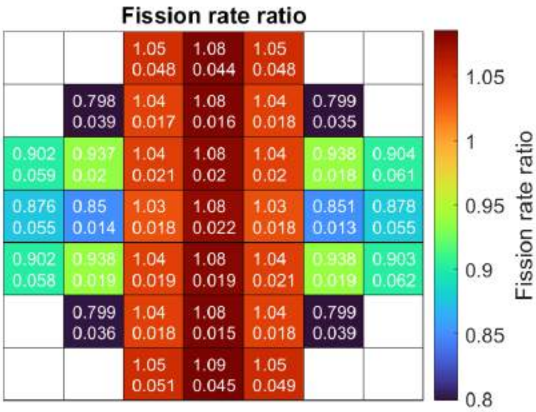


Figure 5: Fission rate ratio of Configuration 1 with respect to the ARO configuration.

Table 4: Composition and results of Configuration 2.

CRA inserted positions	Composition				Reactivity [pcm]
	Ag	In	Cd	Zr	
35	0.001	0.002	0.0018	0.9952	-149 (2)
43-47-63-67	0.001	0.002	0.0027	0.9943	-130 (2)
75	0.001	0.002	0.0018	0.9952	-149 (2)
SUM					-818 (5)
6 CRA inserted					
43-47-63-67	0.001	0.002	0.0027	0.9943	
35-75	0.001	0.002	0.0018	0.9952	-1040 (2)

to the core center and the absence of gadolinium in the selected positions. Hence, similar reactivity is inserted. Summing all control rod contributions maintains the total inserted reactivity close to the temperature defect. However, when all six control rods are inserted together, a reactivity increase of about 320 pcm emerges. For fission rate ratio (see Figure 6), Configuration 2 exhibits a more uniform profile than Configuration 1. Control rods cause a less significant fission rate drop, with ratios ranging from 0.905 to 0.947 for both compositions (purple and sky blue colour). The surrounding positions values also approach 1. This limits the neutron flux displacement towards the core center compared to Configuration 1. Thus, Configuration 2 notably enhances the fission rate ratio range.

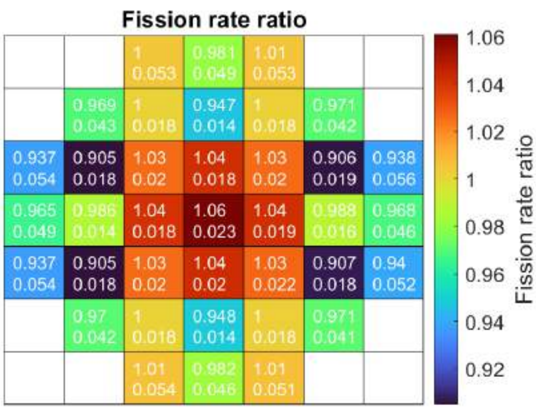


Figure 6: Fission rate ratio of Configuration 2 with respect to the ARO configuration.

4 CONCLUSIONS

A model of the NuScale reactor core was considered in the Monte Carlo Serpent code to study the feasibility of low absorption control rods for reactor operation under load-following mode. The results showed the influence that different parameters of the control rod assemblies (position, materials composition, concentration of neutron absorber materials, etc.) have on important reactor physics parameters. Furthermore, different control rod configurations were analysed and the interference between the clusters could be partially reduced.

As a future research line, the optimization of these non-linear effects can be further studied aiming to achieve a solid design of grey control rod clusters that would allow the reactor operation under load-following mode under safe and reliable circumstances.

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