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AN ALTERNATIVE SIMPLE APPROACH FOR THE MODELLING OF FUEL ASSEMBLIES WITH MISSING FUEL RODS

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ABSTRACT

This paper presents a discussion about an alternative calculation scheme that can be used to model nuclear fuel assemblies under water.

In criticality Monte-Carlo multigroup calculations performed by French industrials, heterogeneous media (such as fuel assemblies or more generally any type of arrays of fissile material in water) are mostly modelled as a homogeneous medium whose nuclear cross sections are adjusted to match those of the original heterogeneous system. These cross sections are obtained using a preliminary flux calculation based on deterministic methods. For a fuel assembly, the simplest deterministic method is to consider a simple cell (fuel oxide cylinder surrounded by clad and water) with a moderation ratio determined by considering that the water around fuel rods and inside empty slots is homogeneously distributed all over the assembly section. This simplified calculation scheme, very useful for parametric studies and for modelling missing fuel rods which position is not known, allows fast multigroup calculations and only requires knowing the number of fuel rods in the section. However, in some cases, this simplified approach can lead to underestimate the assembly reactivity. Indeed, the moderation ratio is generally heterogeneous within the assembly section, particularly for boiling water reactor types assemblies for which empty slots are unequally dispatched within their section. Moreover, the modelling of the water located outside of the assembly section can lead to mis-estimate the moderation of the external fuel rods.

The purpose of this paper is to present an alternative simple approach to use preliminary deterministic calculations to generate homogeneous cross sections for multigroup Monte Carlo codes, in order to avoid two dimensional deterministic calculations which limit the parametric studies possibilities and are computer-time consuming.

This paper will firstly remind generalities about the problematics regarding missing fuel rods in fuel assembly modelling. Then, results obtained with the alternative calculation scheme will be presented, with an explanation of the discrepancies compared to other calculation schemes. At last, a discussion about the bounding trait of this alternative scheme and the parameters that can have an influence on its behaviour will be presented.

KEY WORDS

Fuel assembly, missing fuel rods, calculation scheme.

1. INTRODUCTION

Fuel assemblies of light water reactors, in particular after irradiation, may have some missing fuel rods for several reasons (removal of damaged rods for instance). Guide tubes (for control rods) and missing fuel rods can lead locally to a significant variation of the moderation ratio. Taking into account these local variations is quite challenging for criticality codes since the number and location of the missing fuel rods may vary greatly, which results in a huge number of possible rods arrangements.

In the following paragraphs, different options for fuel assembly modelling will firstly be described, with the associated pros and cons, especially regarding the consideration of empty slots and missing fuel rods. An alternative simple approach for fuel assembly modelling with any number of missing fuel rods will be described. The results obtained with these different methods will then be compared for two fuel assembly designs and the discrepancies will be discussed. Finally, a global discussion about other possible studies will be made before concluding this paper.

2. FUEL ASSEMBLY MODELLING

Two approaches can be adopted for the modelling of fuel assemblies:

- A continuous energy Monte Carlo code modelling, for which each rod is modelled individually ;
- A homogenized modelling, using a deterministic code to generate multigroup cross sections file then used in the multigroup Monte Carlo transport code. This approach is the one preferred in France for its ease of use and speed.

a. Modelling of each fuel rod using continuous energy Monte Carlo codes

In continuous energy Monte Carlo codes, for each isotope, nuclear cross sections are linearly interpolated from a specific nuclear data library. This method for estimating cross sections is as accurate as achievable at the present time. With such codes, the fuel rods within the assembly have to be modelled individually. So, when missing fuel rods can be randomly distributed within the assembly section, the number of configurations to be calculated can rise significantly. This constraint makes difficult to find easily and within a reasonable time the bounding configuration with continuous energy Monte Carlo codes without specific optimization algorithms. Consequently, such codes are not systematically used in France to justify the subcriticality of configurations involving missing fuel rods. An example of assembly section filled with fuel rods modelled with a continuous energy Monte Carlo code is shown in Figure 1.

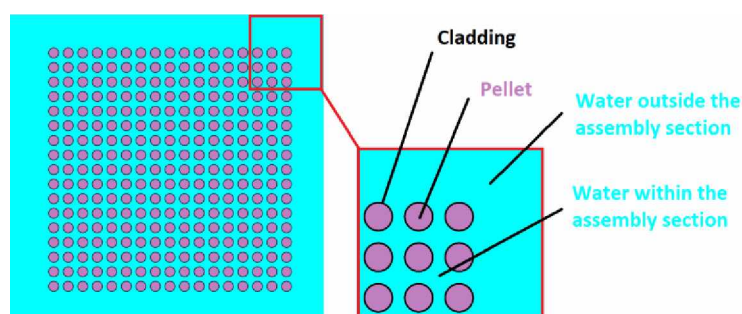


Figure 1. Example of assembly section modelled with a continuous energy Monte Carlo Code

Thanks to its accurate treatment of geometry and nuclear cross section data, even if slower in terms of calculation time, the continuous Monte Carlo simulation method still represents an invaluable tool to validate the bounding configuration when this one has been found by other ways. Its results can be considered as a reference for results comparison with multigroup deterministic approaches.

b. Homogenized modelling using deterministic and Monte Carlo codes

Multigroup deterministic codes use, for each isotope, a neutronic flux-weighted mean of nuclear cross sections from a pointwise nuclear data library in predefined energy intervals (or groups). Thanks to this simplification

of modelling, the computing time associated with deterministic codes is lower than those of the reference codes. However, a compromise has to be found between the number of energy groups, leading to more precise results when increased, and the need to optimize computing time. Nuclear cross section as a function of the neutron energy takes the shape of a histogram, as shown in Figure 2.

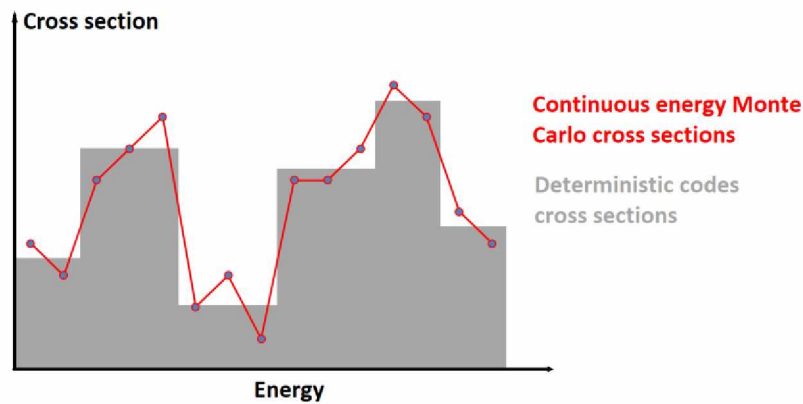


Figure 2. Shape example of nuclear cross section as a function of neutron energy in a multigroup deterministic code

In such codes, fuel rods can be represented by a unique cell entirely reflected to simulate an infinite regular array of several concentric cylinders corresponding to pellet, gap between pellet and cladding, cladding and surrounding water. The quantity of water in the external part of this cell is tuned to match with the overall moderator-to-fuel ratio of the assembly, or with the optimum of moderation when the number of missing fuel rods is undefined. By using this cell, a homogeneous medium of equivalent cross sections is computed using a preliminary flux calculation based on deterministic methods (P_{ij} method for instance). Then, this homogenized material is used in a 3D calculation with a multigroup Monte-Carlo code. An example of assembly section modelled with a multigroup deterministic code using a “one zone” calculation scheme is shown in Figure 3.

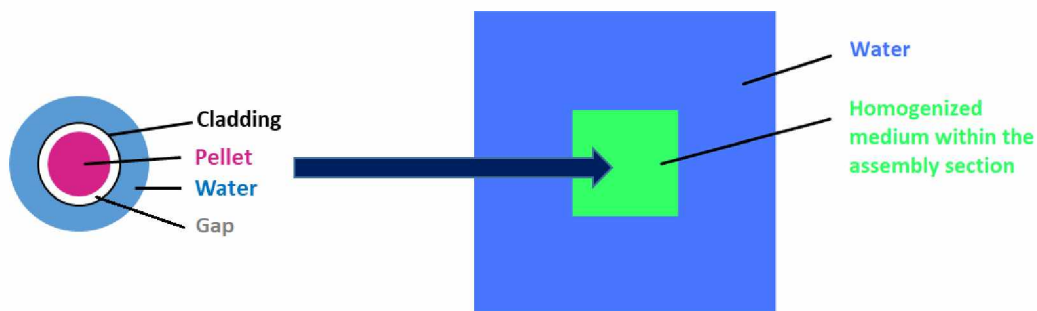


Figure 3. Example of assembly section modelled with the “one zone” calculation scheme

The advantage of this simple calculation scheme is that there is theoretically no need to know where the prospective missing fuel rods are located. They are accounted for solely by adjusting the cell moderation ratio. Contrary to continuous energy Monte Carlo models, finding the bounding configuration does not require to study all possible missing rod locations, which, in addition to computing time save, is a real asset.

However, weaknesses can be identified with this calculation scheme. It assumes that the additional water within the assembly due to empty slots and missing fuel rods is equally dispatched all over its section. Nonetheless, heterogeneous distributions of water holes can be found for real assemblies (in particular boiling water reactor types assemblies) or can be supposed if the assembly properties are not precisely known, and may lead to more reactive assembly configurations. Moreover, the water surrounding the assembly brings more moderation to external fuel rods than internal ones: applying a unique moderation ratio to both of these rod

types within the assembly section is most likely not leading to the most reactive configuration regarding moderation. This last effect is all the more important as the fuel assembly section is small.

c. “Two zones” homogenized modelling

The use of a “two zones” scheme aims at being a compromise between the “one zone” modelling and the reference code modelling. It aims at both avoiding the previously described drawbacks of the one zone scheme and the difficulty to account for all missing fuel rods configurations in continuous energy Monte Carlo codes, while remaining bounding in terms of assembly reactivity. The assembly section modelled, following the two zones scheme, takes the shape of two concentric squares, as shown in Figure 4.

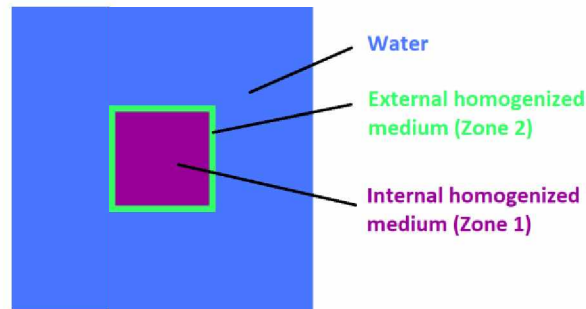


Figure 4. Example of assembly section modelled with the “two zones” calculation scheme

The size of both zones and their moderation ratio can all vary independently and account for some of the possible heterogeneous distributions of missing fuel rods within the assembly section. The number of variables is thus increased compared to the study of the one zone modelling, but this method remains far simpler to implement than a Monte Carlo detailed model accounting for every single rod and water hole positions.

3. CALCULATION CODES

To compare the three approaches previously presented, the following calculations codes have been used:

- The MORET continuous energy code as a reference code [1] ;
- The APOLLO-MORET route of the CRISTAL V2.0.2 package [2] for the homogenized modelling in one or two zones. The APOLLO code generates the cross-sections file that will be used in the MORET transport calculation code.

The JEFF 3.1.1 nuclear data library has been used for all calculations.

4. STUDY OF A PWR 17X17 UO₂ ASSEMBLY UNDER WATER

a. Description of the PWR assembly study hypothesis

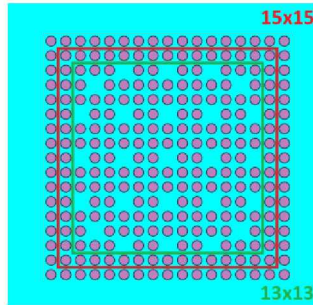
The calculations have been performed with the following assumptions:

- Fuel:
 - Uranium oxide density of 10.96 ;
 - 5% ²³⁵U mass enrichment ;
 - Pellet radius of 0.4102 cm ;
- No gap was considered between the pellet and its cladding
- Cladding:
 - Zirconium density of 6.506 ;
 - Cladding thickness of 0.053 cm ;
- PWR assembly design:
 - 17x17 array (264 fuel rods and 25 water holes) ;
 - Rods pitch of 1.262 cm ;
 - Assembly section of 21.45 cm x 21.45 cm ;
 - Infinite height modelled.

The studied PWR fuel assembly has 25 initial water holes that are dedicated to reactor core control rods, as shown in Figure 5. In addition, in the calculations, missing fuel rods are considered, their location in the assembly being not pre-defined, unlike the 25 water holes.

Two calculation configurations have been studied:

- An isolated fuel assembly in water, surrounded by 20 cm of water ;
- An infinite array of fuel assemblies in water with a gap edge to edge ranging from 2 to 20 cm.



**Figure 5. Rods distribution for the studied 17x17 PWR assembly type
Initial assembly configuration (25 water holes, no missing fuel rods)**

This figure shows that two different modelling options seem relevant when using the two zones scheme:

- An internal zone whose size matches with an internal 13x13 array of rods (the external zone being the two outer arrows of rods) ;
- An internal 15x15 array of rods (the external zone being the outer arrow of rods).

b. Calculation schemes comparison for the initial PWR assembly configuration

The results obtained with the different calculation schemes for the initial assembly configuration (25 water holes) are presented in Table I. The Δk_{eff} value is defined as the difference between the k_{eff} obtained with the reference modelling (MORET) and the k_{eff} obtained with the one zone or two zones modellings (APOLLO-MORET). Negative values mean overestimation and positive values mean underestimation.

Table I. Δk_{eff} values for the initial PWR assembly configuration

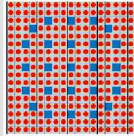
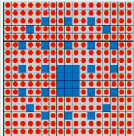
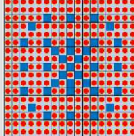
Δk_{eff} ($\sigma=100$ pcm)	Isolated	Array with a 8 cm gap
Δk_{eff} 1 zone	+ 800 pcm	+ 600 pcm
Δk_{eff} 2 zones 15x15	+ 200 pcm	- 200 pcm
Δk_{eff} 2 zones 13x13	- 200 pcm	- 500 pcm

These results highlight that the one zone modelling results are below the reference modelling results and the two zones modelling (13x13 and 15x15 internal arrays) are statistically equivalent or bounding compared to the reference modelling results.

c. Calculation schemes comparison for 10 missing fuel rods within the PWR assembly

In French Nuclear Criticality Safety assessment of operations and transport of used fuel assemblies, it is usual to consider the possibility of having at most 10 missing fuel rods, which is less penalizing than considering the optimum of moderation. The modelling of this configuration is complex with continuous energy codes because the positions of missing fuel rods are unknown or not ensured, hence the number of modelling possibilities is important. IRSN studied several missing fuel rods distributions which results are summarized in the Table II.

Table II. Δk_{eff} values for the initial assembly configuration and for 10 missing fuel rods

$\sigma=100$ pcm		Fuel assembly modelling		
		 Initial configuration	 10 missing fuel rods Configuration #1	 10 missing fuel rods Configuration #2
Δk_{eff} 1 zone	Isolated	+ 800 pcm	- 400 pcm	+ 400 pcm
	Array with a 8 cm gap	+ 600 pcm	< 100 pcm	+ 600 pcm
Δk_{eff} 2 zones 15x15	Isolated	+ 200 pcm	- 1100 pcm	- 300 pcm
	Array with a 8 cm gap	- 200 pcm	- 1200 pcm	- 600 pcm
Δk_{eff} 2 zones 13x13	Isolated	- 200 pcm	- 1600 pcm	- 800 pcm
	Array with a 8 cm gap	- 500 pcm	- 1300 pcm	- 700 pcm

The assembly reactivity obtained with the one zone modelling for configurations #1 and #2 is the same since the moderation ratio within the whole assembly section remains identical due to the method used. This is also the case for the two zones modelling: the moderation ratios in the internal and external zones remain the same between configurations #1 and #2.

On the one hand, the assembly reactivity obtained for configuration #1 with the reference code is lower than with the one zone modelling because of the highly heterogeneous distribution of missing fuel rods. The one zone modelling tends to homogenize this water distribution within the assembly section which, in this case, leads to the higher assembly reactivity. On the other hand, the assembly reactivity obtained for configuration #2 with the reference code is higher than with the one zone modelling because, in this case, the heterogeneous missing fuel rods distribution seems to be adequate in terms of increase of assembly reactivity. For configuration #2, the one zone modelling leads to a missing fuel rods distribution which is too homogeneous and thus a slight underestimation of the assembly reactivity.

Regarding the two zones modelling, conservative results have been obtained for configurations accounting for 10 missing fuel rods.

d. Calculation schemes comparison for any number of missing fuel rods within the PWR assembly

In this study, the number of missing fuel rods in the PWR fuel assembly is not defined. In order to limit the number of studied configurations, the assumption was made that the number of fuel rods leading to the maximum $k_{\text{eff}} + 3\sigma$ value in the MORET calculations is likely to be in the same range as the number of fuel rods leading to the maximum $k_{\text{eff}} + 3\sigma$ value for the one zone and two zones schemes. The Δk_{eff} value is defined as the difference between the maximum k_{eff} obtained with the reference modelling and the maximum k_{eff} obtained with the one zone or two zone modellings. The Δk_{eff} results obtained and the associated number of fuel rods that led to the maximum k_{eff} values for the different calculation schemes are presented in Figure 6.

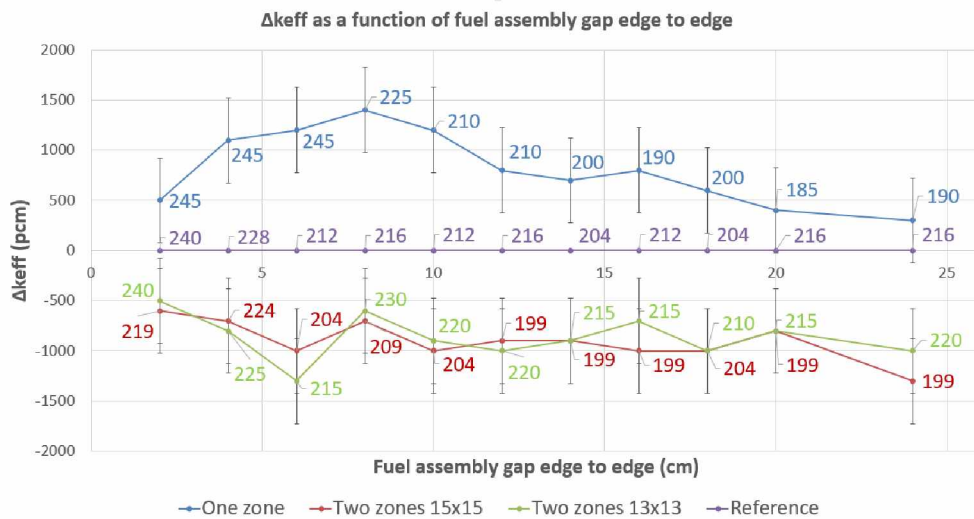


Figure 6. Δk_{eff} as a function of fuel assembly gap edge to edge for the different modelling options

The maximum k_{eff} values were obtained for fuel assemblies containing between 185 and 245 fuel rods, that is to say with 19 to 79 missing fuel rods. It is not ensured that the $k_{\text{eff}} + 3\sigma$ calculated with the reference modelling are the highest that can be obtained, considering all the given possibilities of rod arrangements. Nevertheless, reference calculations leading to a higher reactivity than one zone modelling have been found for almost all the studied configurations shown in Figure 6. Meanwhile, the two zones modelling has systematically led to conservative results compared to reference calculations, even though it seems to be quite penalizing for some cases. Another interesting point is that the highest reactivity using the two zones scheme, for both 13x13 and 15x15 internal arrays of rods, was obtained for configurations where the external zone was filled with the maximum number of fuel rods.

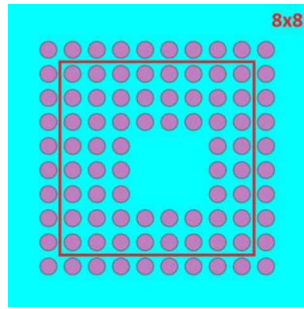
5. STUDY OF A BWR 10X10 UO₂ ASSEMBLY UNDER WATER

a. Description of the BWR assembly study hypothesis

The calculations have been performed with the following assumptions:

- Fuel
 - Uranium oxide density of 10.5 ;
 - 5% ²³⁵U mass enrichment ;
 - Variable pellet radius (from 0.4 to 0.6 cm) ;
- No gap was considered between the pellet and its cladding
- Cladding
 - Zirconium density of 6.506 ;
 - Cladding thickness of 0.053 cm ;
- BWR assembly design
 - 10x10 array (91 fuel rods and 9 water holes) ;
 - Rods pitch of 1.345 cm ;
 - Assembly section of 13.45 cm x 13.45 cm ;
 - Infinite height modelled.

The studied BWR fuel assembly has 9 initial water holes which implies locally a high moderation discrepancy, as shown in Figure 7. In addition, in the calculations, missing fuel rods are considered and their location in the assembly is not pre-defined, unlike the 9 empty slots. At last, a reflexion by 20 cm of water is modelled around the fuel assembly.



**Figure 7. Rods distribution for the studied 10x10 BWR assembly type
Initial assembly configuration (9 water holes, no missing rods)**

For this particular study, the only internal zone considered when using the two zones scheme is the one whose size matches with the internal 8x8 array of rods (the external zone being the outer arrow of rods).

b. Calculation schemes comparison for the initial BWR assembly configuration

For the initial assembly configuration, the Δk_{eff} values are presented in Figure 8 as a function of pellet radius. In the modelling named “1 zone + hole”, the water zone corresponding to the 9 water holes is explicitly modelled in the MORET code, and is not considered for the determination of the moderator-to-fuel ratio of the homogenized zone.

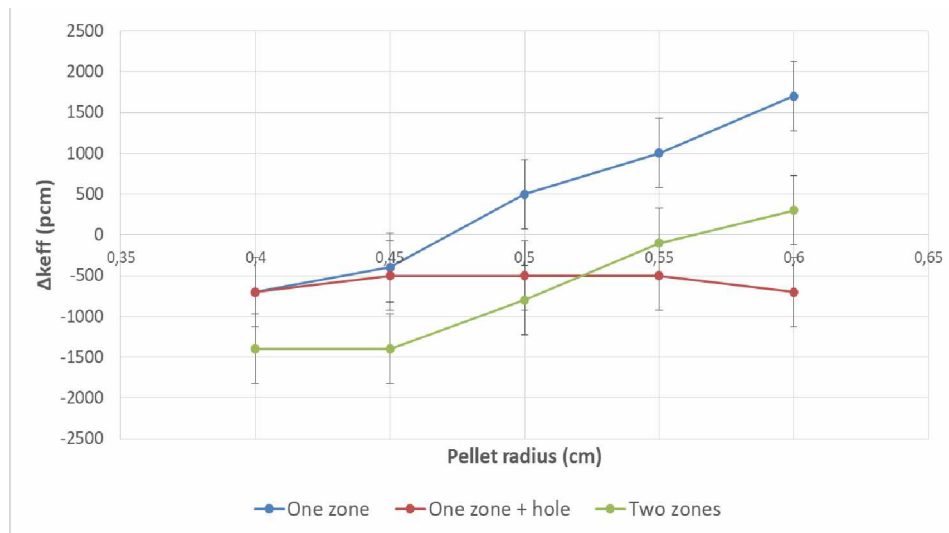


Figure 8. Δk_{eff} values depending on pellet radius for different modelling options of the initial BWR assembly configuration

These results highlight that the one zone modelling remains conservative or equivalent to the reference modelling as long as the pellet radius remains low enough or, in other words, as long as the moderation ratio within the assembly section remains high enough. The one zone approach can be considered for all pellet radius if the water zone corresponding to the 9 initial water holes is taken into account. At last, the two zones modelling appears to be conservative or equivalent to the reference modelling in any cases.

c. Calculation schemes comparison for any number of missing fuel rods within the BWR assembly

In this study, the number of missing fuel rods in the BWR fuel assembly is not defined. In order to limit the number of studied configurations, as in paragraph 4d, the assumption was made that the number of fuel rods leading to the maximum $k_{\text{eff}} + 3\sigma$ value in the MORET calculations is likely to be in the same range as the number of fuel rods leading to the maximum $k_{\text{eff}} + 3\sigma$ value for the one zone and two zones modellings. The

Δk_{eff} results obtained and the associated number of fuel rods that led to the maximum k_{eff} values for the different calculation schemes are presented in Figure 9.

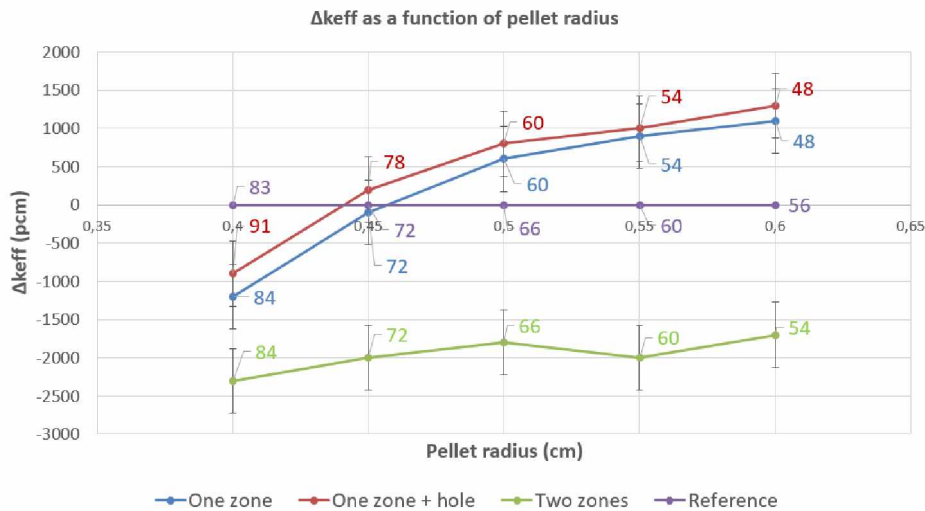


Figure 9. Δk_{eff} values depending on pellet radius for different modelling options of the BWR assembly with any number of fuel rods

The maximum k_{eff} values were obtained for fuel assemblies containing between 48 and 91 fuel rods, that is to say with none to 43 missing fuel rods. It is not ensured that the $k_{\text{eff}} + 3\sigma$ calculated with the reference modelling are the highest that can be obtained, considering all the given possibilities. Nevertheless, reference calculations leading to a higher reactivity than one zone modelling have been found when the pellet radius is higher or equal to 0.5 cm. Meanwhile, the two zones modelling has systematically led to conservative results compared to reference calculations, even though it seems to be quite penalizing.

The bigger the pellet, the lower the moderation ratio can be in the modelled cell. This leads to more moderation ratio discrepancy possibilities between the internal and external zones when using the two zones scheme, which can account for the differences observed compared to the reference modelling. Just like the study made on the PWR assembly in paragraph 4d, the highest reactivity using the two zones scheme was obtained for configurations where the external zone was filled with the maximum number of fuel rods.

6. DISCUSSION AND FURTHER MODELLING OPTIONS

For the studied assemblies, the use of the two zones calculation scheme is simple to implement while remaining bounding in terms of reactivity compared to the reference modelling. It can be a suitable solution when the study of an assembly containing any number of fuel rods has to be made. However, it seems to be quite penalizing: one might be careful when using the two zones scheme for assembly configurations whose reactivity is expected to be close to the defined k_{eff} criteria.

The studies made in this paper are limited to a couple of assembly designs, and should be extended to more designs in order to estimate if the two zones scheme remains a bounding modelling option. Hereafter is a list of parameters that are expected to have an influence on discrepancies obtained between the two zones scheme and other calculation schemes:

- The nature of the fuel: this can influence the neutronic spectrum and the distribution of reaction rates within the internal and external zones ;
- Pitch between rods: the lower the pitch, the lower the moderation ratio can be. Just like the size of the fuel pellet, this leads to more moderation ratio discrepancy possibilities ;
- Size of the assembly array of rods: the proportion of “external” rods compared to “internal” rods when using the two zones scheme may be a source of bias.

As far as continuous energy Monte Carlo codes are concerned, algorithms can be implemented in order to determine which missing rods configuration leads to the highest assembly reactivity. IRSN intends to work further in the R&D field of such algorithms, which development and performance justification are challenging.

7. CONCLUSION

The purpose of this paper was to describe and comment on an alternative simple approach for the modelling of fuel assemblies with missing fuel rods. This alternative two zones modelling is based on a deterministic calculation approach with the use of distinct cells in order to generate homogenized cross sections for the two distinct areas defined within the assembly section. This scheme can account for a heterogeneous distribution of missing rods within the assembly section and maximize the moderation brought by the water around the immersed assembly or the water gap between assemblies.

Compared to the one zone and continuous energy Monte Carlo modellings, the use of the two zones scheme for the studied assemblies remained simple to implement and yet led to bounding results. However, its potential penalizing trait requires a cautious use in order not to create excessive operating constraints. The calculations presented in this paper should be extended to more assembly designs in order to estimate its bounding behaviour, especially regarding the nature of the fuel, the pitch between rods and the size of the assembly array of rods.

ACKNOWLEDGMENTS

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