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A CONSERVATIVE APPROACH TO ACCOUNT FOR USED FAST-NEUTRON REACTOR BLANKETS IN CRITICALITY-SAFETY STUDIES

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ABSTRACT

The current prospect of reprocessing the assemblies of the PHENIX Fast-neutron Reactor in France and the development of the 4th-Generation Fast-neutron Reactors (FR) enable research projects in relevant fuel cycle operations. Under these circumstances, the CEA and Orano Cycle have decided to investigate an approach to account for the depletion of the PHENIX reactor fuels in criticality-safety studies.

Nowadays FR fertile assemblies are considered as fresh fissile assemblies in criticality studies. Obviously, accounting for the fertile assemblies' depletion will offer substantial economic incentives, but it requires the use of a conservative approach. By definition, the fertile assemblies are more reactive after irradiation. That means the evaluation of the maximum of reactivity they can reach should be provided. The definition of such an approach is structured around two major points:

- 1- The first one concerns the determination of a set of penalizing conditions for the irradiation and depletion calculations. These conditions should conduct to a conservative fuel inventory, maximizing the reactivity of the irradiated fuel for the considered configuration;
- 2- The second one focuses on the definition of penalties to apply on the irradiated isotopic concentrations and on the reactivity worth of the isotopes. These penalties derive from the biases and uncertainties issued from the experimental validation of the involved calculation codes.

This paper focuses on the first point and so describes the different steps to define a conservative set of irradiation/depletion calculation options to account for the irradiation of fertile assemblies in criticality-safety analyses.

KEYWORDS: used fuel, fertile assemblies, fast-neutron reactors, irradiation calculation, criticality-safety

1. INTRODUCTION

The current prospect of reprocessing the assemblies of the PHENIX Fast-neutron Reactor in France and the development of the 4th-Generation Fast-neutron Reactors (FR) enable research projects in relevant fuel cycle operations. Under these circumstances, the CEA and Orano Cycle have decided to investigate an approach to account for the depletion of the PHENIX reactor fuels in criticality-safety study.

A preliminary study [1] has focused on the investigation on the use of burnup credit for used FR fissile fuel operations. It has highlighted the interest of a burnup credit approach for fissile FR fuels and shown that the highest contribution to the reactivity loss is mainly due to only one fission product: ^{149}Sm . This is highly promising and would considerably simplify the way to determine a penalized fuel inventory.

In the same field, this study focuses on fertile fuels. Nowadays the FR fertile assemblies are considered as fresh fissile assemblies in criticality-safety studies. Obviously, accounting for the fertile assemblies' depletion will offer substantial economic incentives, but it requires the use of a conservative approach. By definition, the fertile assemblies are more reactive after irradiation. Actually, they are composed of depleted or natural uranium and have two major functions. The first one is to limit the neutron-flux level in the core. For this, fertile assemblies axially and radially surround the fissile assemblies. The second one is to convert the fertile uranium into fissile plutonium, giving the fast-neutron reactor a breeder property. Hence, the evaluation of the maximum of reactivity reached by the fertile assemblies must be provided. The definition of such an approach is structured around two major points:

- 1- The first one concerns the determination of a set of penalizing conditions for the irradiation and depletion calculations. These conditions should conduct to a conservative fuel inventory, maximizing the reactivity of the irradiated fuel for the considered configuration;
- 2- The second one focuses on the definition of penalties to apply on the irradiated isotopic concentrations and on the reactivity worth of the isotopes. These penalties derive from the biases and uncertainties issued from the experimental validation of the involved calculation codes.

This paper is part of a larger work concerning the use of irradiated fertile assemblies instead of fresh fertile assemblies in criticality-safety studies. It focuses on the first part of the development of a criticality-conservative approach and so describes the different steps to define a conservative set of depletion calculation options and presents the resulting depleted isotopic concentrations of the fertile assembly.

First, the calculation tools, methods and models are described. Second, the way to define the conservative options is explained. Third, the depletion calculation results are presented and analyzed. Finally, the ongoing studies are highlighted.

2. CALCULATION TOOLS, METHODS AND MODELS

2.1. Fast-neutron Reactor depletion and criticality calculation chain

The PEPIN2 depletion solver of the DARWIN2.3 [2] package calculates the isotopic concentrations at the end of the irradiation or after a given cooling time. Then, these concentrations are used as input data in the Criticality-Safety package CRISTAL V2 [3] providing the effective multiplication factor (k_{eff}) for the calculated configuration.

Fig. 1 precisely describes the sequence between the depletion and the criticality calculations as well as the input and output data.

As this paper focuses on the definition of a set of conservative depletion options from the criticality point of view, a brief description of the DARWIN2.3 is essential. DARWIN2.3 is the French reference calculation package for fuel cycle applications, such as fuel inventories and decay heat. It performs the nuclide depletion calculation (PEPIN2 solver), involving nuclear data libraries on the one hand and neutronics data on the other hand (Fig. 1). All the decay data and fission yield values come from the JEFF-3.1.1 evaluation [4], whereas the self-shielded cross-sections and neutron spectra are provided by deterministic neutron transport code: ERANOS2 [5] resolving the Boltzmann equation on the whole reactor core for Fast-Neutron Reactor studies. Complementary cross-sections, missing from the transport

code libraries, are taken from JEFF-3.1.1 evaluation. It is to notice that DARWIN2.3 has been recently experimentally validated for FR fuels [6][7].

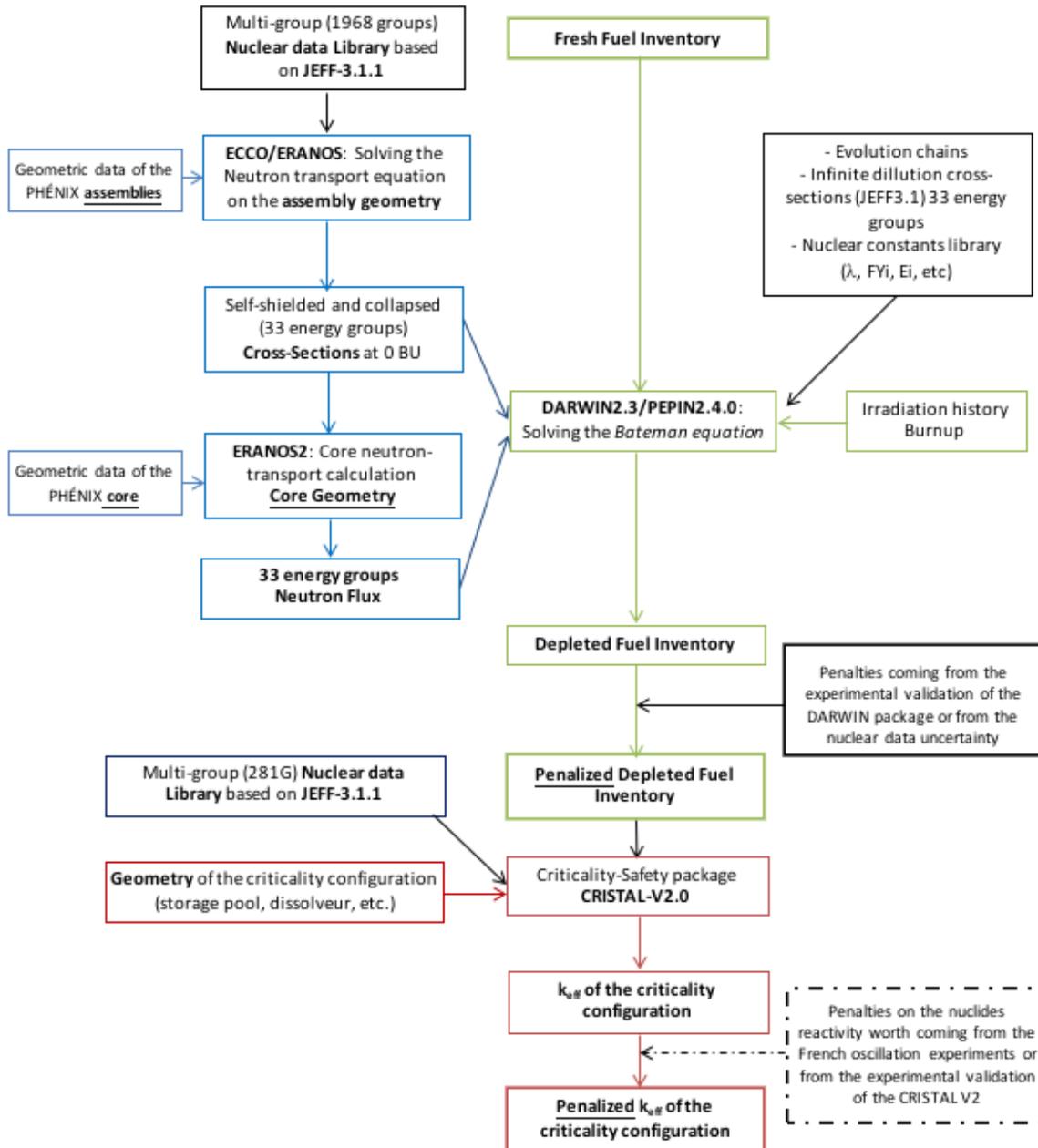


Figure 1. Overview of the Fast-neutron Reactor depletion and criticality calculation chain

2.2. Parameters of interest for criticality-conservative depletion calculations

The significant parameters to study arise directly from the calculation chain. Regarding the Fig. 1, three sets of data were studied to penalize the depletion calculation: the **neutronics data** resulting from the neutron-transport calculation, the **fresh fuel inventory** and the **irradiation history**.

The **neutronics data** as the neutron spectra, the self-shielded cross-sections and the neutron-flux level are the result of the neutron transport calculations (ERANOS2) on the whole reactor core. So, the irradiation

conditions have to be defined through the neutronics calculation stage and should cover all kinds of irradiation conditions encountered during the PHENIX reactor operation.

In this way, the goal is to define, first, the core arrangement carrying out the highest neutron-flux level and, second, the spatial position of the fertile assembly collecting the highest neutron-flux level. It is clear that the higher the neutron-flux level, the better the uranium to plutonium conversion and so the higher the “end of life” reactivity of the fertile assembly.

Finally, sensitivity studies are involved through the depletion calculations with PEPIN2 to define the conservative **fresh fuel inventory** and **irradiation history**.

2.3. The PHENIX reactor blankets

This study focuses on the radial and axial blankets of the French Sodium Fast Reactor, PHENIX.

As illustrated in Fig.2, two rings of **radial blankets** (fertile assemblies) surround the fissile internal cores (namely core 1 and core 2) inside the PHENIX core.

Moreover, the **axial fertile elements**, named Lower and **Upper Axial Blankets** (respectively LAB and UAB), are part of the fissile fuel pins (Fig. 2). It is to mention that, in order to be transported, stored and reprocessed, the Upper Axial Blanket is removed from the other part of the pin. This study focuses only on the UABs, as the LABs are treated together with the fissile part of the assembly.

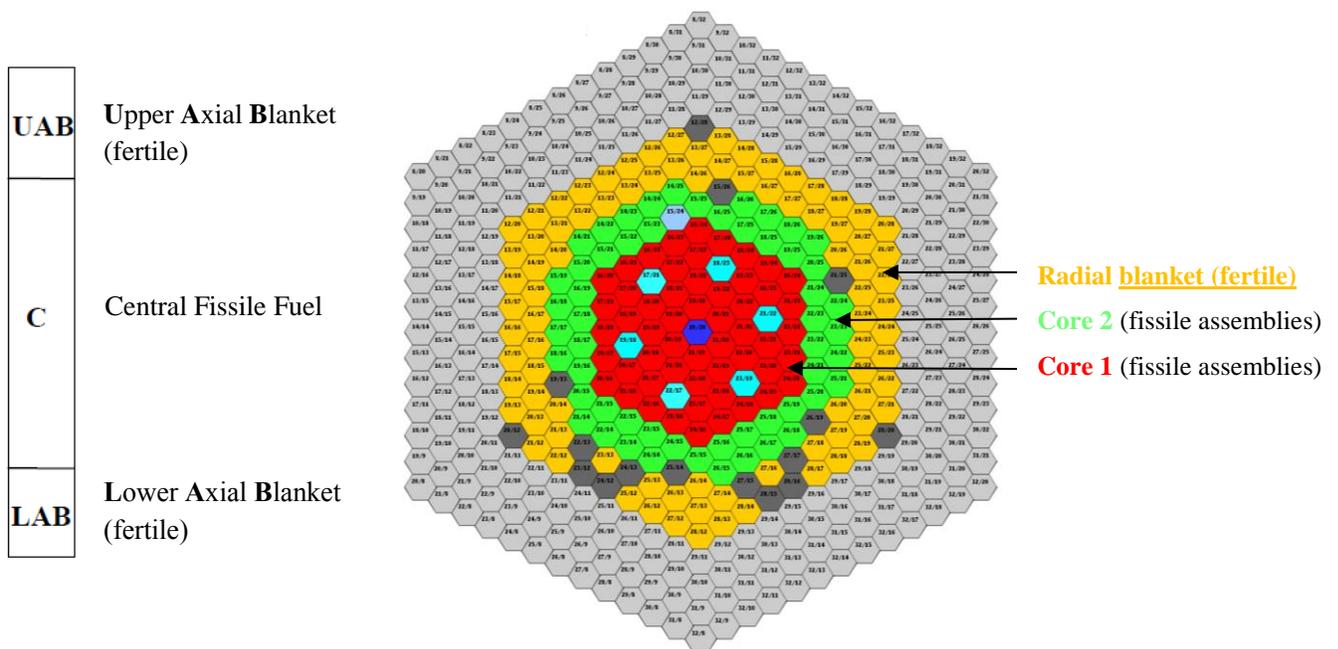


Figure 2. An illustration of a PHENIX fissile pin and an ERANOS2 model of the core

3. DEFINITION OF THE CRITICALITY-CONSERVATIVE OPTIONS

In order to obtain a conservative depleted blanket inventory, from a criticality point of view, irradiation parameters leading to maximizing the ^{239}Pu production are to be chosen. ^{239}Pu comes from the radiative capture of the ^{238}U . Then, the highest is the neutron-flux level, the most efficient is the ^{238}U capture and so the ^{239}Pu production. Thus, **the purpose is to determine the configuration maximizing the neutron-flux level received by the fertile assemblies.**

3.1. Neutronics Calculations Options

3.1.1. Core configuration

In order to define a conservative set of irradiation parameters, an analysis of all the core configurations of the PHENIX reactor was conducted. It appears that one core configuration, named “**little core**” configuration (Fig. 3.), leads to a higher-than-standard level of the neutron-flux in the fissile core. Actually, when the thermal power of the PHENIX reactor was reduced from 563 MWth to 350 MWth the neutron flux was not high enough to involve planned experimental programs. So, a decrease of the number of the assemblies was performed, keeping the same power and so rising the neutron-flux level. The rise of the neutron-flux level, compared with a “standard” core configuration, is of + 7.2% at the maximum in the fourth fissile ring and of +2.5% in the last fissile ring, just beside the fertile assemblies.

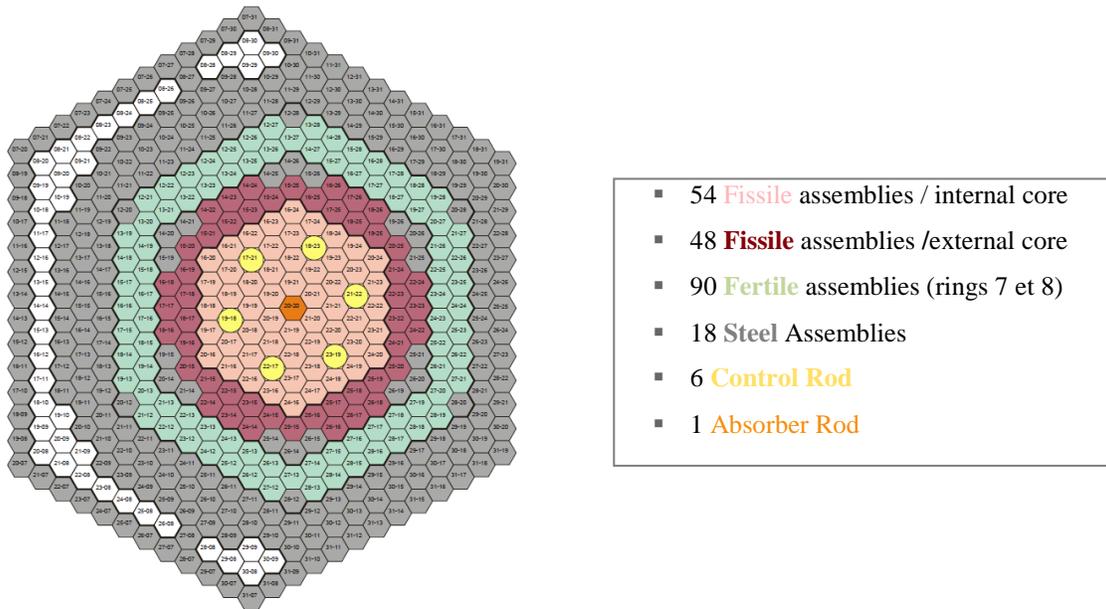


Figure 3. Overview of the « little core » penalizing configuration

Thus, the neutronics calculations were performed on the “little core” configuration.

3.1.2. Irradiation conditions

Parametric studies were conducted on the following irradiation parameters: the **temperature** of the fissile and fertile elements, the temperature of the coolant (sodium), the insertion of the **control rods** and the **spatial environment** of the fertile assembly.

Table I summarizes the irradiation parameter values involved in the parametric studies.

The values of the temperatures correspond to nominal values and to maximized values, retrieved from the Final Safety Report of the PHENIX plant.

Regarding the control rods, three positions were studied: fully axially inserted (530 mm); half axially inserted (700 mm); fully axially extracted (900 mm).

Concerning the spatial environment of the fertile assembly of interest, the composition of the surrounding fertile assemblies was penalized. It was assumed that all the surrounding fertile assemblies were used and composed of 4% $^{239}\text{Pu}/^{238}\text{U}$.

Finally, a conservative thermal power value of 563 MWth was taken into account. During operation it never reached more than 350 MWth in the “little core” configuration.

Table I. Irradiation Parameters

Pth = 563 MWth

Case n°	Control rods extraction (BDC) (mm)	Temperature (°C)			Environment
		Fissile assemblies	Coolant and Structures	Fertile assemblies	
e1	900	1200	460	450	Fertile - Standard
e2				2500	1200
e3		580			
e4					1200
e5		700			
e6	530	1200	460		
e7					

3.2. Depletion Calculation Options

3.2.1. Fresh fuel inventory

The radial and axial blankets of the PHENIX reactor were composed of:

- Depleted uranium ($0.2\% < ^{235}\text{U} < 0.4\%$),
- Natural uranium ($0.72\% ^{235}\text{U}$).

For the parametric study on the irradiation conditions, a depleted uranium fuel with $0.2\% ^{235}\text{U}$ enrichment was used.

Then, sensitivity study on the fresh inventory of a fertile assembly was performed. The conservativeness of the use of $100\% ^{238}\text{U}$ content and natural uranium initial content was evaluated.

3.2.2. Irradiation history and burnup

A **continuous irradiation history** (no inter-cycle) will be taken into account.

Regarding the **burnup**, two values have been retained: **1090 and 1700 Equivalent Full Power Days (EFPD)**. The higher value comes from the Final Safety Report of the PHENIX plant stipulating that the fertile elements is not allowed to be irradiated more than 1700 EFPD. It refers to a safety principle, regarding the nature of their hexagonal tubes. By the way, the CEA has a catalogue registering all the irradiation history of the PHENIX assemblies. It shows that the highest registered irradiation duration is 1090 EFPD for a first ring fertile assembly. Consequently, the 1700 EFPD value is conservative.

4. RESULTS AND ANALYSES

The 4.1 and 4.2 paragraphs focus on the radial blanket, necessarily more irradiated than the upper axial blanket. The study on the UAB is presented in the paragraph 4.4.

4.1. Conservative Spatial Position of the Fertile Assembly

For all of the computed cases, the radial position of the fertile assembly collecting the high neutron-flux level never changes. This is the “16/27” fertile assembly, located on the first blankets ring, just beside the fissile core. Figure 4 shows a map of the level of the neutron-flux reached inside the assemblies for the case n°e6 (cf. Table I). By the way, it indicates the penalizing radial position of the fertile assembly (red arrow).

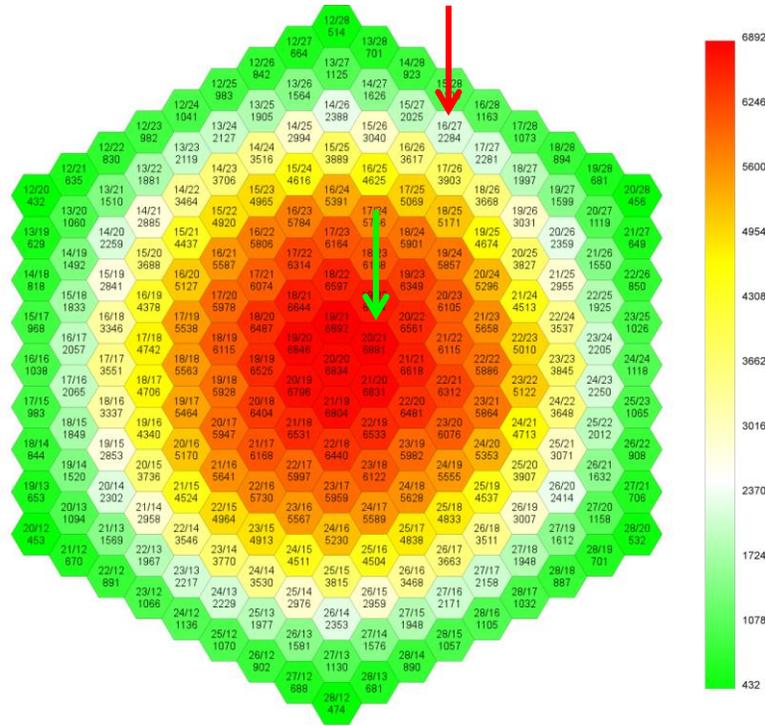


Figure 4. Example of a power map for the case e6 – Maximum values of the neutron-flux level $10^{12} \cdot n \cdot cm^{-2} \cdot s^{-1}$ (1 Energy-group, normalized with respect to the thermal power)

In the same way, for all of the computed cases, the axial position of the fertile assembly collecting the highest neutron-flux level never changes. It corresponds to the center of the assembly (see Figure 5).

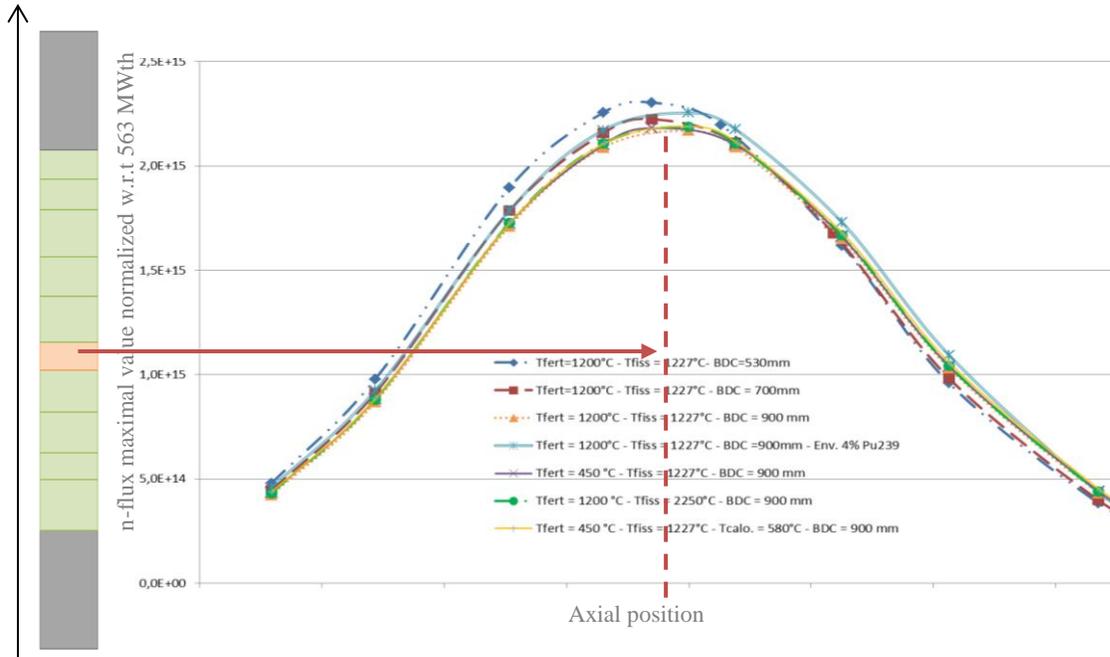


Figure 5. Maximal neutron-flux level along the fertile assembly “16/27”

4.2. Sensitivity Study on the Neutron-Flux Level

Table II. Maximal neutron-flux values on the conservative spatial position (r,z) of the radial fertile assembly as a function of the irradiation parameters

Pth = 563 MWth

Case n°	Control rods extraction (BDC) (mm)	Temperature (°C)			Environment	Max. n-flux values Normalized w.r.t Pth $10^{15} \text{ n.cm}^{-2}.\text{s}^{-1}$
		Fissile assemblies	Coolant and Structures	Fertile assemblies		
e1	900	1200	460	450	Fertile - Standard	2.193
e2				1200		2.182
e3		2500		Fertile - 4% ²³⁹ Pu	2.254	
e4		1200		2.200		
e5	700	1200	580	Fertile - Standard	2.209	
e6			460		2.231	
e7			530		460	2.302

As shown in Table II, the neutron-flux values are similar for all the studied cases. **The impact of the variation of the irradiation parameters on the neutron-flux level inside a fertile assembly is negligible** and should be insignificant on the depleted blanket inventory.

It is to note that the highest neutron-flux value is obtained when the control rods are fully axially inserted in the core (case e7).

These conclusions are well illustrated by the Figure 6 below.

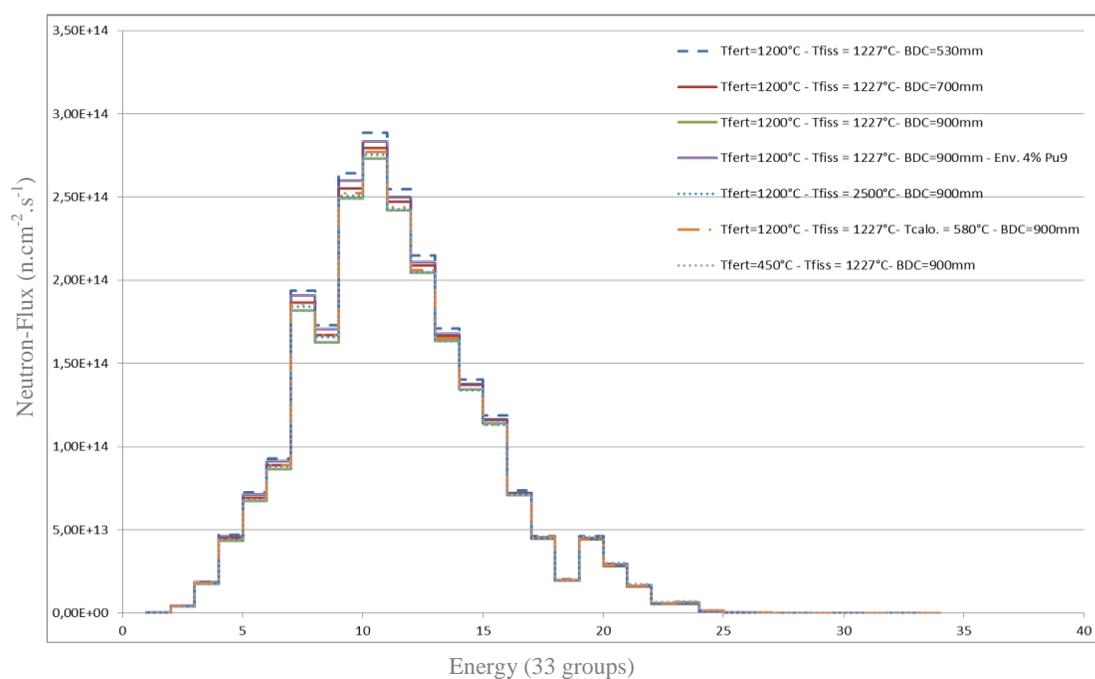


Figure 6. Mean neutron-flux of the “16/27” radial fertile assembly at the central axial position

4.3. Depleted isotopic concentrations

Finally, the neutron-flux and the self-shielded cross-sections are collected in the assembly at the previously defined conservative spatial (r, z) position. These data are involved in the depletion

calculations for the various case of interest (cf. Table I). The impact of the irradiation parameters can be directly analyzed on the depleted inventory of the fertile element.

The results are summarized in the Table III and IV below. Table IV focuses on the impact of the fresh fertile inventory to the final depleted inventory (cf. §3.2.1).

Table III. Depleted inventory of a radial blanket involved in spatial-conservative irradiation calculations

1090 EFPD							
Case number	e1	e2	e3	e4	e5	e6	e7
²³⁴ U	0.00	0.00	0.00	0.00	0.00	0.00	0.00
²³⁵ U	0.10	0.11	0.10	0.11	0.11	0.10	0.10
²³⁶ U	0.03	0.03	0.03	0.03	0.03	0.03	0.03
²³⁸ U	99.87	99.87	99.87	99.87	99.87	99.87	99.87
²³⁶ Pu	0.00	0.00	0.00	0.00	0.00	0.00	0.00
²³⁸ Pu	0.08	0.07	0.07	0.07	0.07	0.07	0.08
²³⁹ Pu	89.46	90.03	89.72	90.08	90.09	89.85	89.59
²⁴⁰ Pu	9.84	9.35	9.62	9.30	9.30	9.51	9.73
²⁴¹ Pu	0.59	0.53	0.56	0.52	0.52	0.54	0.57
²⁴² Pu	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Pu/(U+Pu)	5.8%	6.0%	6.2%	6.0%	6.0%	6.1%	6.2%

1700 EFPD							
Case number	e1	e2	e3	e4	e5	e6	e7
²³⁴ U	0.00	0.00	0.00	0.00	0.00	0.00	0.00
²³⁵ U	0.07	0.07	0.07	0.07	0.07	0.07	0.07
²³⁶ U	0.03	0.03	0.03	0.03	0.03	0.03	0.03
²³⁸ U	99.89	99.89	99.89	99.89	99.89	99.89	99.89
²³⁶ Pu	0.00	0.00	0.00	0.00	0.00	0.00	0.00
²³⁸ Pu	0.12	0.11	0.11	0.11	0.11	0.11	0.12
²³⁹ Pu	84.06	84.88	84.42	84.95	84.96	84.62	84.24
²⁴⁰ Pu	14.49	13.83	14.21	13.76	13.76	14.04	14.36
²⁴¹ Pu	1.24	1.11	1.17	1.10	1.10	1.15	1.20
²⁴² Pu	0.09	0.07	0.08	0.07	0.07	0.08	0.08
Pu/(U+Pu)	8.1%	8.4%	8.6%	8.5%	8.4%	8.5%	8.7%

Table IV. Impact of the fresh to the depleted inventory of a radial blanket involved in spatial-conservative irradiation calculations

Case number	e7			
Fresh inventory	100% ²³⁸ U		Natural Uranium (0.75% ²³⁵ U)	
Irradiation Time (EFPD)	1090	1700	1090	1700
²³⁴ U	0.00	0.00	0.00	0.00
²³⁵ U	0.00	0.00	0.38	0.26
²³⁶ U	0.00	0.00	0.10	0.13
²³⁸ U	100.00	100.00	99.52	99.60
²³⁶ Pu	0.00	0.00	0.00	0.00
²³⁸ Pu	0.07	0.11	0.09	0.15
²³⁹ Pu	89.60	84.25	89.58	84.21
²⁴⁰ Pu	9.73	14.36	9.73	14.36
²⁴¹ Pu	0.57	1.20	0.57	1.20
²⁴² Pu	0.02	0.08	0.02	0.08
Pu/(U+Pu)	6.2%	8.7%	6.2%	8.7%

The depleted blankets inventories are mostly composed of ²³⁸U, ²³⁹Pu and ²⁴⁰Pu. ²³⁹Pu coming from the radiative capture of ²³⁸U and ²⁴⁰Pu from the radiative capture of ²³⁹Pu. ²³⁹Pu and ²⁴⁰Pu are of interest for the criticality-safety analyses because of their reactivity worth in thermal spectrum conditions. The results show that the variation of the isotopic content is lower than 1% between the studied cases. By the way, the variation of the plutonium amount is limited to 0.6%.

In other words, the impact of the irradiation parameters on the depleted inventory is insignificant. This conclusion is consistent with the one resulting from the neutron-flux analysis.

In contrast, the irradiation time has a significant impact on the results. Between 1090 and 1700 EFPD, the plutonium amount rises by 2.5% on the one hand and, on the other hand, the ²³⁹Pu content decreases by 5% and the ²⁴⁰Pu content increases by 5%.

Finally, these results show that **the conservatisms introduced in the neutronics calculation** (core configuration, thermal power, spatial position, etc.) **are substantial**. They lead to a really high mean Pu/(U+Pu) value of 8.5% after 1700 EFPD. The CEA's experience feedback has shown that the PHENIX blankets plutonium amount does not exceed 4%. Nevertheless, the 6% mean plutonium amount calculated after 1090 EFPD is still conservative but more realistic. Regarding the needs, the burnup value selected for the criticality-safety study could be adjusted.

4.4. Focus on the Upper Axial Blankets (UAB)

The same study as for the radial blankets was done for the UAB.

First, the UAB collecting the high neutron-flux level was identified and correspond to the "21/20" position (cf. green arrow on the Figure 4). It is to note that **for all of the computed cases, the radial position of UAB collecting the high neutron-flux level never changes**.

Table V. Maximal neutron-flux values on the conservative spatial position (r,z) of the UAB as a function of the irradiation parameters

Pth = 563 MWth

Case n°	Control rods extraction (BDC) (mm)	Temperature (°C)			Environment	Max. n-flux values Normalized w.r.t Pth $10^{15} \text{ n.cm}^{-2} \cdot \text{s}^{-1}$	
		Fissile assemblies	Coolant and Structures	Fertile assemblies			
e1	900	1200	460	450	Fertile - Standard	1.023	
e2				1.022			
e3				Fertile - 4% ²³⁹ Pu	1.021		
e4					2500	1200	1.030
e5					580		1.036
e6	700	1200	460	Fertile - Standard	0.868		
e7	530				0.796		

As shown in Table V, the highest neutron-flux values ranges from 0.796 to $1.036 \cdot 10^{15} \text{ n.cm}^{-2} \cdot \text{s}^{-1}$. The spread of the results is significant in contrast with the radial blankets results, especially regarding the impact of the control rods insertion, which is easily understandable. However, the neutron-flux is around twice lower inside the UAB than in the center of the radial blankets. In these conditions, the conservativeness of the Radial Blankets depleted inventory instead of the UABs is easily demonstrable. As shown in Table VI, the plutonium amount reached after 1700 EFPD in the UABs is around 30% lower than in the radial blankets.

Table VI. Depleted inventory of a UAB involved in spatial-conservative irradiation calculations

Irradiation parameters case e2		
Irradiation Time (EFPD)	1090	1700
²³⁴ U	0.00	0.00
²³⁵ U	0.13	0.11
²³⁶ U	0.02	0.03
²³⁸ U	99.85	99.86
²³⁶ Pu	0.00	0.00
²³⁸ Pu	0.02	0.03
²³⁹ Pu	93.03	89.32
²⁴⁰ Pu	6.65	9.98
²⁴¹ Pu	0.29	0.64
²⁴² Pu	0.01	0.03
Pu/(U+Pu)	3.8%	5.5%

5. CONCLUSIONS

This paper is part of a larger work on the use of used fertile assemblies instead of fresh fertile assemblies in criticality-safety studies.

It focuses on the first part of the development of a criticality-conservative approach: **the determination of a set of penalizing conditions for the irradiation and depletion calculations**. These conditions should conduct to a conservative fuel inventory, maximizing the reactivity of the irradiated fuel for the considered configuration. In this way, the different steps to define a conservative set of depletion calculation options were described and analyzed.

In order to obtain a conservative depleted blanket inventory, from the criticality point of view, the irradiation parameters leading to maximizing the ^{239}Pu production have been chosen. ^{239}Pu comes from the radiative capture of ^{238}U . Then, the highest is the neutron-flux level, the most efficient is the ^{238}U capture and so the ^{239}Pu production. Thus, the idea has been to **determine the configuration maximizing the neutron-flux level received by the fertile assemblies**.

First a penalizing core configuration was defined, thanks to the valuable experience feedback of the CEA on the PHENIX plant operation. In this configuration, called “little core”, the neutron-flux is higher than in the standard core configuration.

Second, a set of parameters of irradiation was identified based on the experience feedback of the CEA on the development of conservative methods for burnup credit applications. It concerns: the fissile and fertile elements temperatures; the coolant and the structures temperature; the control rod insertion; the environment of the fertile assembly. For each neutron-transport calculation, the radial and axial positions of the fertile assembly collecting the highest neutron-flux have been calculated.

The results show that the radial and the axial positions are not impacted by the variation of the irradiation parameters. And so, **a unique radial and axial position collects the highest level of neutron-flux**. In the same way, the **neutron-flux values are not sensitive to the variation of the irradiation parameters**.

Parametric studies were done for the Radial Blankets and for the Upper Axial Blankets. The neutron-flux values reached in the UABs are twice lower than in the radial blankets. The conservativeness of the Radial Blankets instead of the UABs is easily demonstrable.

Third, the conservative neutronics data provided by the well-defined conservative ERANOS2 core calculations were involved in depletion calculations with the PEPIN2 code to obtain the conservative depleted composition of the blankets. Moreover, at this step, the impact of another set of parameters was studied: the fresh fertile inventory (100% ^{238}U and natural uranium) and two values of the irradiation time. The first one (1090 EFPD) is extracted from a CEA’s catalogue registering all the irradiation history of the PHENIX assemblies and the second one (1700 EFPD) is extracted from the safety report of the PHENIX plant.

As expected, since the neutron-flux is not sensitive to the variation of the irradiation parameters, neither the Pu vector nor the Pu content are significantly impacted. Actually, the variation of the isotopic content is lower than 1% between the studied cases and the variation of the plutonium amount is limited to 0.6%. In addition, the results are not sensitive to the initial variation of the fresh fertile inventory. In contrast, the irradiation time has a significant impact on the results. Between 1090 and 1700 EFPD, the plutonium amount rises by 2.5% on the one hand and, on the other hand, the ^{239}Pu content decreases by 5% and the ^{240}Pu content increases by 5%. At last, it is to note that the Pu/(U+Pu) amount can reach 6.2% after 1090 EFPD and 8.7% after 1700 EFPD. These amounts are really high for a PHENIX fertile assembly, meaning the conservatisms introduced in the neutronics calculation are substantial. If required in the criticality-safety studies, some conservatism could be relaxed as the burnup value.

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The next step of the study concerns the quantification of the impact of the conservative depletion calculation options in the criticality-safety calculations. Finally, the ongoing work will focus on the definition of penalties to apply on the depleted isotopic concentrations and on the reactivity worth of the isotopes. These penalties derive from the biases and uncertainties issued of the experimental validation of the involved calculation codes.

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