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Advanced reactor models for plutonium multirecycling scenario studies using artificial neural networks

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Abstract. This paper presents an innovative way to identify the plutonium content in MOX fresh fuel according to its isotopic composition in fuel cycle dynamic simulations. In those calculations, the fuel fabrication is a challenge to model as the plutonium stock status (quantity and quality) is unknown and the fuels that are loaded in reactors should ensure criticality throughout the wanted cycle length. This model is based on metamodeling full core depletion simulation of PWRs with artificial neural networks to predict efficiently the cycle length and power factors as a function of the MOX fresh fuel composition. An exploration of the plutonium phase space has shown the impact of plutonium isotopic composition on power factors and fuel cycle length variability. Moreover, the sensitivity of the cycle length to the plutonium content have led us to propose a model that links the plutonium content to its isotopic composition by a constant step function, while accepting an uncertainty of the order of 1 GWd/t on the cycle length. The impact of this new model on PWR loaded with plutonium recovered by UOX and MOX spent fuel reprocessing is assessed in this paper. Pu content estimator based on this new approach leads to standard deviation of the cycle length discrepancies distribution lower than 150 MWd/t for a Pu fissile quality range size of 4%.

1 Introduction

The possible strategies for the future of nuclear energy are studied thanks to nuclear scenario simulations that model possible future developments of the nuclear fleet. These calculations make it possible to quantify the impact of industrial and political choices concerning the recycling of materials from spent fuel reprocessing on resource consumption or waste production, for example. Recently, French stakeholders have particularly studied the strategy that consists in recycling plutonium from spent MOX fuels in future EPRs (Evolutionary Power Reactors) [1,2]. Several options for the design of new fuel assemblies have been studied but ultimately, efforts seem to be on the MOX-MR technology (MOX MultiRecycled): a fuel assembly similar to MOX fuels but with plutonium coming from spent MOX and MOX-MR fuels. In those studies, the degraded fissile quality of this plutonium has to be compensated by mixing it with plutonium coming from UOX spent fuels.

These studies rely on reliable fuel cycle simulation tools that model each fuel cycle unit: deactivation pool, fuel reprocessing unit, fresh fuel fabrication unit and reactors, to name a few. Among all the challenges raised by these simulations, one difficulty focuses a great part of research efforts: the fuel fabrication. Indeed, it is necessary to determine the composition of the fresh fuel to be loaded into the reactors, which satisfies relevant criterion (such as the reactor criticality throughout the irradiation campaign for example) depending on the isotopic composition of the materials contained in the available stocks, which are calculated and updated throughout the simulation. The construction of different estimators of reactor properties as a function of the fresh fuel compositions allows us to invert the problem, that is to identify the plutonium content of fresh MOX fuels at each loading. This paper is dedicated to the construction of a new model for fuel fabrication of MOX-MR fuels to be used in fuel cycle simulations. This model is designed to be implemented in the dynamic fuel cycle simulation codes COSI [3], developed by CEA, and CLASS [4], developed by CNRS. It was built by using

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artificial neural networks (ANN) that predict different reactor properties such as the irradiation length and the power distributions. To do so, a database of depletion simulations had to be built with a full core calculation scheme designed for this work.

The first part of this paper presents the core characteristics considered for this work. The configuration is taken from the Pre-Construction Safety Report of the Hinkley point EPR [5]. The calculation scheme and the definition of different observables are defined in this part. The second section of this paper presents the construction of the depletion database and illustrates the possible links between the different observables. This database is then used for ANN construction, presented in the third section of this paper, that allows a phase space exploration under several constraints such as the cycle length to identify the plutonium content as a function of its isotopic composition, exactly as in fuel cycle simulations. This is the topic of the fourth section. Finally, seeing the results and specially the sensitivity of the cycle length to the plutonium content in full core depletion simulations, the fifth section presents a new model for fuel fabrication and how it may impact the results of fuel cycle dynamical simulations.

2 Full core depletion calculation scheme

2.1 Core definition

The core studied here corresponds to the MOX version of the UK EPR design that is described in the Pre-Construction Safety Report given in reference [5]. It is composed of 3 types of UOX assemblies (differing in their number of gadolinium poisoned rods) and one type of MOX assemblies, each assembly being unloaded after 3 or 4 irradiation cycles. The configuration of each assembly is given in Figure 1 and the loading pattern in Figure 2. For this work, only the fresh fuel composition of MOX fuels is considered as a variable (^{235}U enrichment of the UOX fuel is then kept to 5.0%). The MOX assembly is divided into three zones depending on their plutonium content to reduce power peaks at UOX/MOX interfaces and the Pu content cannot exceed 12% (in one fuel rod) due to fabrication constraints and void reactivity feedback [5]. This limit leads to a maximum of 11.3% for the average plutonium content in MOX fuel assemblies.

The core modelling is performed using two-step deterministic calculations. The first step is the resolution of the neutron transport equation with 2D infinite lattice calculations using the code APOLLO2 [6]. The second step is the resolution of the diffusion equation at the core level with CRONOS2 [7]. Fuel pins and guide thimbles are precisely described and the SHEM 281-group energy mesh is considered. Nuclear data for this calculation are provided by the library JEFF-3.1.1 [8]. Using a different nuclear data library instead of JEFF would have a minimal impact on the reactor simulation results, negligible compared to other numerical biases introduced by our computational scheme [9].

2.2 Calculation scheme

Our previous work [9] was dedicated to the development of an optimized EPR 30% MOX core calculation scheme to set up a depletion simulations database. Several options for the calculation scheme were compared in terms of numerical costs and numerical biases. For this work, we chose to consider a transport calculation scheme based on the REL2005 standard [10], with a pin-by-pin cross section homogenization tabulated as a function of the fuel temperature and the moderator density. Additional information on this calculation scheme is available in [9]. The core calculation scheme, performed with CRONOS2 [7], is based on the neutron diffusion equation with thermal-hydraulics feedbacks. The geometrical mesh considers a pin-by-pin discretization with 21 axial subdivisions, leading to a unitary element that is defined by 20 cm of fuel pins (or guide thimble), its cladding and its associated moderator. No boron concentration follow-up is considered for criticality monitoring, as this computational option proved to have minimal impact on the estimation of the cycle length in our work on calculation scheme optimization [9]. Depending on the MOX fresh fuel compositions, 8–10 iterative irradiation simulations are needed to identify the equilibrium core (defined when the burn-up of each assembly at end of cycle corresponds to the same burn-up of the corresponding assembly at beginning of cycle). The end of irradiation is determined when the fuel cannot sustain the chain reaction any longer. For this work we considered a criticality penalty of 1000 pcm at end of cycle (meaning that the irradiation stops when $k_{\text{eff}} = 1.01$).

The temperature distribution calculation at each time step allows a precise estimation of the power distribution's evolution during irradiation. For this work, two different power factors are considered to quantify the flatness of this distribution. The first one, quoted F_{2D} , identifies the hottest assembly and is defined as the ratio of the maximal power delivered by one assembly over the average power delivered by all the assemblies. The second one, quoted F_{3D} , is a quantification of the maximal linear power delivered by one fuel pin and is defined by the ratio of the maximal power delivered by one element of the geometrical grid over the average value.

With such a calculation scheme, it is then possible to calculate 3 core properties as a function of the fresh MOX fuel composition: the natural cycle length (performed at nominal power), and the 2 power factors. However, fuel cycle simulations cope an inverted problem: the fresh MOX fuel composition is actually an unknown and the plutonium content has to be calculated as a function of the reactor wanted cycle length (which is not a variable value) and the plutonium isotopic compositions. Hence, numerical meta-models are often used to estimate efficiently those properties.

3 Artificial neural network on core depletion simulations

For this work, artificial neural networks have been considered to predict reactor properties as a function of the

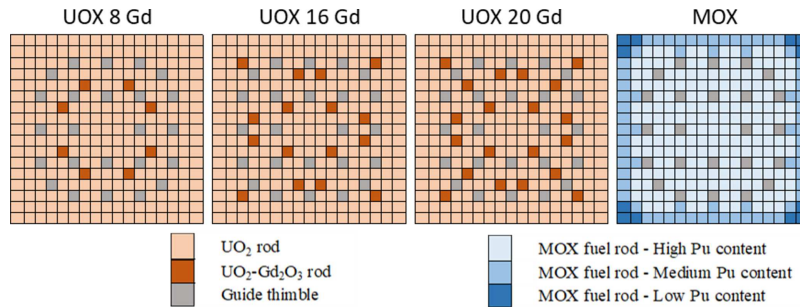


Fig. 1. Lattice definition of the different fuel assemblies loaded in the core.

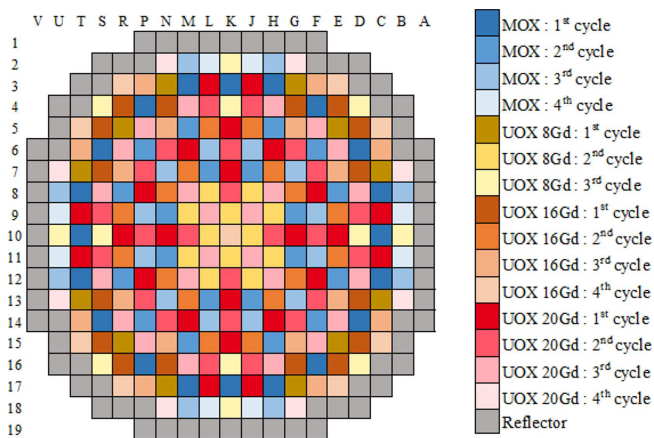


Fig. 2. Core loading pattern definition.

MOX fresh fuel composition. Two databases were then built, first to train the neural networks then to assess their accuracy.

3.1 Database construction

The sampling of MOX fresh fuel compositions should be chosen carefully, as it will define the validity domain of the metamodels and their use. As the goal is ultimately to use them to explore possibilities to load EPR MOX with degraded plutonium, the phase space should cover all possible plutonium isotopic composition coming from UOX and MOX spent fuels with various cooling times. Those compositions were taken from [11] and Table 1 presents the limits chosen in this work. The ^{240}Pu proportion is considered as a buffer (as the sum of all the isotopes should be equal to 100%) and is consequently not an independent random variable. Plutonium content in the MOX fresh fuel is also sampled. 500 random initial compositions have been identified with a Latin Hyper Square sampling, leading to 500 different depletion simulations.

Cycle length (or the average core burn-up within one irradiation cycle), F_{2D} and F_{3D} power factors are tabulated as a function of the initial MOX composition. The results of all the depletion simulations are presented in Figure 3. It can be noted that, among all possibilities of the phase space determined by Table 3, the cycle length varies from 13.1 GWd/t to more than 17.2 GWd/t approx-

imately. It seems that an anti-correlation can be seen between F_{2D} and the cycle length. Low fissile content in fresh MOX fuel leads to hot UOX fuel assemblies and a low average burn-up. The 2D and 3D power factors seem to be correlated showing that a distributed power radially leads to minimal lineic power in the hottest fuel assemblies.

3.2 Artificial neural networks training and precision estimation

The database is used to train artificial neural networks (ANN) to predict the observables (cycle length, and the two power factors) as a function of the fresh MOX fuel composition. ANN are widely used for this purpose, as they can provide more accurate estimates of the variables of interest than other methods, such as polynomial regression, while offering reasonable training times (within a few dozen minutes) and near-instantaneous execution [12]. The library used is TMVA [13] and an empirical approach was considered to identify adequate ANN configurations. To do so, the depletion database was separated in two, the first one, called the training database, gathers 75% of the simulations and allows the ANN training. The second one, called the testing database, is used to compare the simulation results to the ANN's estimations. The network architectures (number of neurons per hidden layer and number of hidden layers) are adapted as long as the bias introduced by the ANN estimator remains reducible. Table 2 gathers the architectures and the precisions of all observables considered for this work.

4 Use of neural networks for phase space exploration

Based on the ANN estimators presented in the previous section, an exploration of the input parameter space leading to acceptable values of core parameters is carried out. Indeed, in the context of plutonium multi-recycling in PWRs, managing plutonium isotopic composition is a major issue. This isotopy varies significantly between high-quality plutonium extracted from slightly cooled spent UOX fuels and more degraded plutonium from MOX fuels already stored for several decades. Depending on the available Pu isotopic composition and the reactor target cycle length, the Pu content in the MOX fresh fuel is calculated

Table 1. MOX fresh fuel composition phase space definition. The proportion of plutonium 240 is defined as the buffer to reach 100% in the plutonium vector definition

	Plutonium content	^{238}Pu	^{239}Pu	^{241}Pu	^{242}Pu	^{241}Am
Min	5.3%	0.7%	40.0%	2.0%	4.0%	0.0%
Max	12.0%	5.0%	65.0%	14.0%	12.0%	3.0%

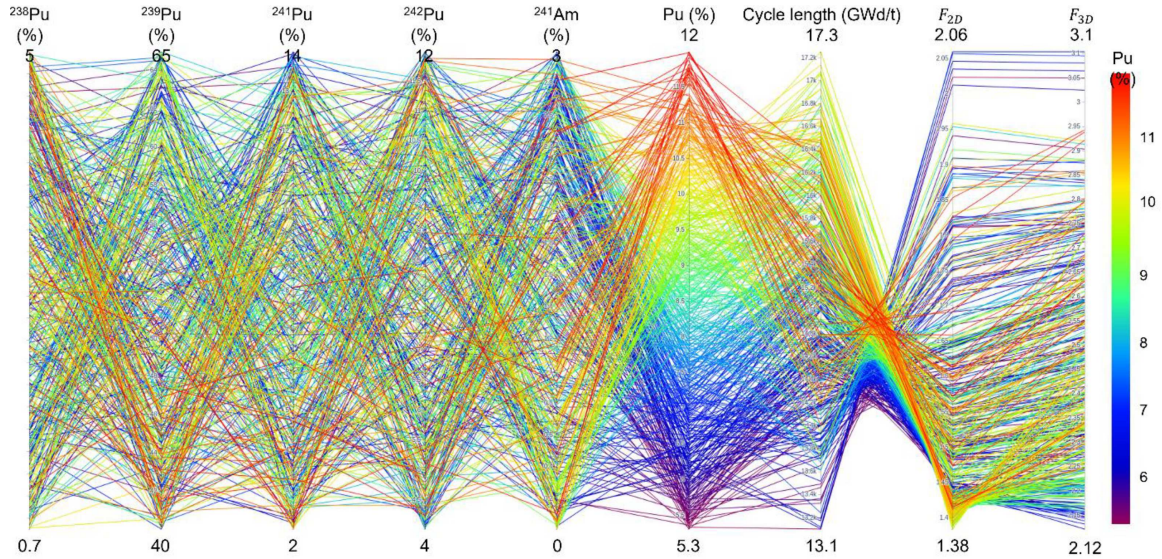


Fig. 3. Representation of different core observables as a function of the plutonium isotopic vector and the plutonium content in fresh MOX fuels. The colorization is function of the plutonium content.

Table 2. Artificial Neural Networks (ANN) architecture and precision estimated on a testing data set to compute standard deviations

Observable	Neural network architecture	Input variable	Mean deviation	Standard deviation
Cycle length	2 hidden layers of 4 neurons each	MOX fresh fuel composition	-0.005%	0.09%
F_{2D}	2 hidden layers of 16 neurons each	MOX fresh fuel composition + Irradiation time	-0.006%	0.21%
F_{3D}	3 hidden layers of 16 neurons each	MOX fresh fuel composition + Irradiation time	-0.008%	0.24%

accordingly. The Pu content in MOX fresh fuel should remain below a specified limit (12% in this case). For a given core configuration (fixed loading pattern and UOX assemblies), the objective of this phase space exploration is to determine the range of plutonium isotopy fluctuations leading to a satisfactory Pu content and estimate the F_{2D} and F_{3D} power factors that depend on the reactor target cycle length (as the plutonium content is also dependent to this parameter). No constraints were considered here for the power factors, but safety studies may legitimate some exclusions in the phase space that would lead to inadequate power distributions.

4.1 Global phase space exploration

5000 plutonium isotopic compositions have been sampled within the range defined in Table 1 using the LHS method. For each isotopic composition, the Pu content required to reach a given reactor target cycle length is calculated with the ANN estimator. Two target values are considered in this work: 15 GWd/t and 16.2 GWd/t, the latter being the reference value for the reference MOX fresh fuel composition [5] and the optimized calculation scheme. For both target values, the resulting 2D and 3D power factors are then calculated. Pu isotopic compositions, in terms of Pu

Table 3. Plutonium isotopic vector for average UOX and MOX spent fuel extracted from an APOLLO2/CRONOS2 simulation with the MOX reference composition given in [5]

	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Spent UOX	3.23%	50.5%	24.0%	14.5%	7.73%
Spent MOX	5.33%	36.7%	28.2%	15.6%	14.1%

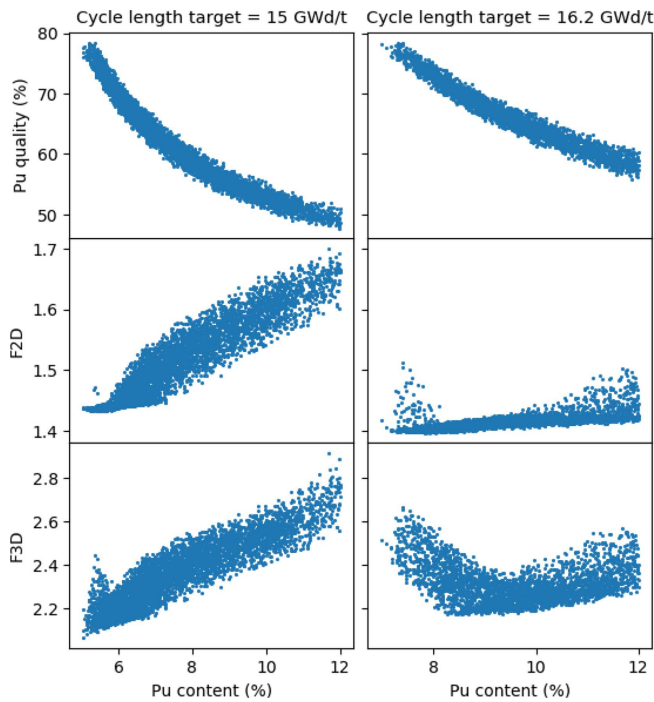


Fig. 4. Identification of the phase space that allows acceptable solutions for a cycle length of 15 GWd/t (on the left) and 16.2 GWd/t (on the right).

fissile quality (sum of ^{239}Pu and ^{241}Pu fractions in Pu vector), lead to an acceptable range of Pu and the associated F_{2D} and F_{3D} are presented on Figure 4.

Figure 4 first highlights a dispersion of required Pu content in fresh fuel (up to 1% absolute variation) for a given Pu fissile quality, for both target cycle lengths. A cycle length target value of 15 GWd/t allows to accept lower Pu fissile quality within the limit of 12% Pu content in fresh MOX fuel. However, F_{2D} values are higher and more spread out in this case. Indeed, the EPR 30% MOX core configuration is optimized for a cycle length of 16.2 GWd/t. Decreasing the cycle length and therefore the required Pu content in MOX fresh fuel results in UOX assemblies carrying higher power values lead to a power distribution showing strong variability. The optimization of the core configuration at 16.2 GWd/t also leads to a reduced variation of F_{3D} in this case compared to a cycle length imposed at 15 GWd/t, especially for Pu fissile quality around 60%, corresponding to the reference MOX fresh fuel composition [5].

4.2 Potentialities of spent MOX dilution in spent UOX for plutonium recycling

4.2.1 Plutonium vector definition

To deepen this analysis using compositions being more representative of the spent fuel mixtures at reprocessing that could be implemented in a Pu multi-recycling strategy in PWR, MOX and UOX average spent fuel Pu isotopies (presented in Tab. 3) have been extracted from the reference EPR 30% MOX case calculation [5]. To consider the effect of cooling and fabrication durations, it is subsequently assumed that the spent UOX and MOX fuels associated with these Pu isotopies undergo either 5 or 30 years of cooling, followed by 2 years of aging for the manufacturing stage, resulting in two spent UOX Pu isotopies ($\text{Pu}_{\text{UOX}}^{5y}$ and $\text{Pu}_{\text{UOX}}^{30y}$) and two spent MOX Pu isotopies ($\text{Pu}_{\text{MOX}}^{5y}$ and $\text{Pu}_{\text{MOX}}^{30y}$). These four resulting isotopies are systematically combined to form all possible binary mixtures between Pu_{UOX} and Pu_{MOX} (i.e. $\text{Pu}_{\text{UOX}}^{5y} + \text{Pu}_{\text{MOX}}^{5y}$, $\text{Pu}_{\text{UOX}}^{5y} + \text{Pu}_{\text{MOX}}^{30y}$, $\text{Pu}_{\text{UOX}}^{30y} + \text{Pu}_{\text{MOX}}^{5y}$ and $\text{Pu}_{\text{UOX}}^{30y} + \text{Pu}_{\text{MOX}}^{30y}$). For each type of mixture, the proportion of Pu_{MOX} is varied from 0% to 100%, with the remaining fraction corresponding to the respective Pu_{UOX} .

4.2.2 Results

For each resulting Pu isotopic composition, the Pu content required to reach the reactor target cycle length (15 GWd/t or 16.2 GWd/t) is calculated, as well as the associated 2D and 3D power factors. Pu isotopic compositions leading to Pu content higher than 12% are discarded. The resulting data, presented on Figure 5, first demonstrate that among the possible constraints, the limit on the Pu content is the most restrictive.

Indeed, the required Pu content in MOX fresh fuel to reach a target cycle length is very sensitive to Pu fissile quality variation. Regardless of the cooling time of Pu_{UOX} and Pu_{MOX} , increasing Pu_{MOX} fraction in the mixture results in an increase of the Pu content to compensate the degradation of the Pu fissile quality. Figure 5 also reveals that the maximum proportion of Pu_{MOX} acceptable in the mixture is reduced with the increase of the spent fuel cooling time. Indeed, the increase of spent fuel cooling time enhances ^{241}Pu decay, reducing the Pu fissile quality and increasing the required Pu content to reach a given cycle length. For the reference reactor cycle length of 16.2 GWd/t, a maximum of 40% of $\text{Pu}_{\text{MOX}}^{5y}$ can be introduced in a mixture with $\text{Pu}_{\text{UOX}}^{5y}$. Decreasing the target cycle length to 15 GWd/t allows to reach a mixture composed solely of $\text{Pu}_{\text{MOX}}^{5y}$, at the cost of an increase of the 2D and 3D power factors (whose values may be minimized via a core configuration optimization).

5 Definition of a new model for MOX fresh fuel fabrication in dynamic fuel cycle simulations

Evaluating Pu multi-recycling in PWR strategy can rely on nuclear fuel cycle scenario. Nuclear scenario studies

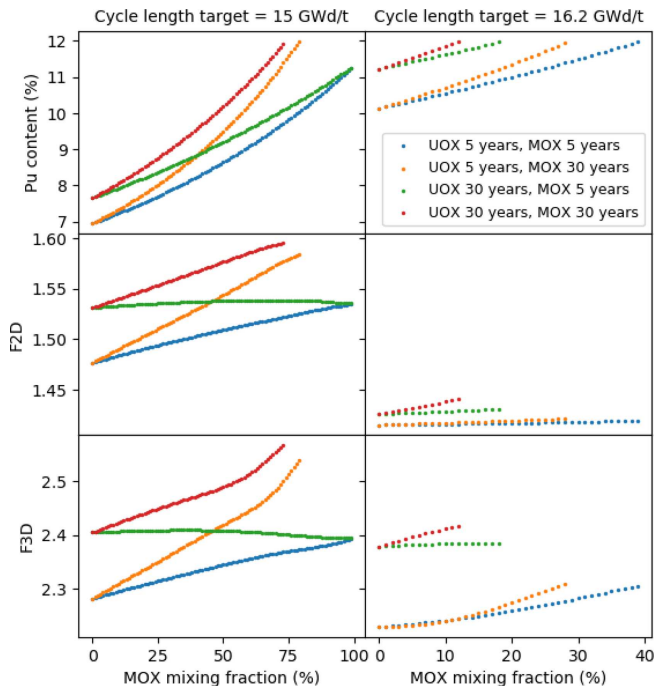


Fig. 5. Plutonium content, 2D and 3D power peaks as a function of the mixing fraction of plutonium coming from MOX spent fuel in plutonium from UOX spent fuel.

usually rely on a fuel cycle simulation tool modeling evolving reactors and fuel cycle units and calculating isotopic material fluxes and inventories overtime. Reactor modeling is then ensured by a fuel loading model and an irradiation model, built on a depletion calculation database prior to the scenario simulation. In this work, the EPR 30% MOX 3D full core calculation database presented in the previous sections and the associated ANN estimators are used to build a fuel loading model following a new approach detailed in this section.

5.1 General presentation of the fuel loading model

In nuclear fuel cycle scenario codes, fuel loading models are used to build a fresh fuel meeting the reactor requirements, at each reactor loading, depending on the available fissile material. In the case of Pu recycling in PWR, fuel loading models commonly calculate the Pu content required in the fresh MOX fuel to reach a target cycle length using the available Pu inventory [11]. MOX fresh fuel loading models usually rely on a fresh fuel Pu content estimator (often ANN-based) built on a depletion calculation database built from 2D infinite lattice calculations, without considering core scale phenomena (core geometry, fuel loading pattern, assembly neighborhood, etc.).

5.2 Introduction to the new MOX fuel loading model

Performing 3D full core calculations in this work enables a comprehensive understanding of Pu isotopy impact on

the full core reachable cycle length, the Pu MOX fresh fuel content and additional core features, such as 2D and 3D power factors. The analysis carried out in the previous sections have shown that for a given Pu fissile quality, the Pu fresh fuel content adjusted to reach a given target cycle length can vary up to 1% in absolute (up to 10% relative variation on the 2D and 3D factors). In addition, further work has demonstrated the strong influence of the MOX fresh fuel fabrication criterion (power distribution optimization or target cycle length) on the required fresh fuel Pu content (absolute variation of Pu content up to 3% for a given Pu isotopy). This additional study also revealed the impact of the core configuration (fuel loading pattern and MOX assembly fraction in the core) on the required fresh fuel Pu content to reach a target cycle length (absolute variation of Pu content up to 2% for a given Pu isotopy) [14].

Moreover, the ANN-based estimators produced in this work indicate that an absolute 1% variation of Pu fresh fuel content causes at most a 3% variation of reachable cycle length (approximately 500 MWd/t), irrespective of Pu fissile quality. Considering a constant Pu content in the fresh fuel, a 5% absolute change in the Pu fissile quality results in a maximum bias of 1 GWd/t on the cycle length. The biases affecting the cycle length are comparable in magnitude to those arising from the choice of full core computational settings [14]. From the reactor operation perspective, the cycle length may also undergo variations resulting from load-following operations or stretch-out up to 1.5 GWd/t [15]. On the other hand, PWR MOX fuel managements in France are usually designed for a fixed Pu content and a permissible variation around a reference Pu isotopy, notably facilitating the MOX fabrication process.

Given the low sensitivity of the Pu content to the cycle length, the biases associated with the modeling choices (computational schemes and fabrication criterion), but also the acceptable margins on the cycle length, it appears justified to propose a fuel loading model based on fixed Pu content values, within a range of Pu fissile quality, while accepting an uncertainty on the order of 1 GWd/t on the cycle length.

5.3 Results

According to this analysis, a new MOX fuel loading model has been defined. It relies on the definition of Pu fissile quality ranges characterized by a fixed Pu content that guarantee a variation of the cycle length lower than 1 GWd/t. For each of the 5000 Pu isotopic compositions previously sampled, the Pu content required to reach a given reactor target cycle length is calculated with the ANN estimator. For each Pu fissile quality range, the Pu content value that, on average, yields the closest approximation of the target cycle length across all Pu isotopic compositions in this range is calculated. Two target cycle lengths are considered (15 GWd/t and 16.2 GWd/t). Three Pu fissile quality range sizes have been evaluated (1%, 2% and 4%).

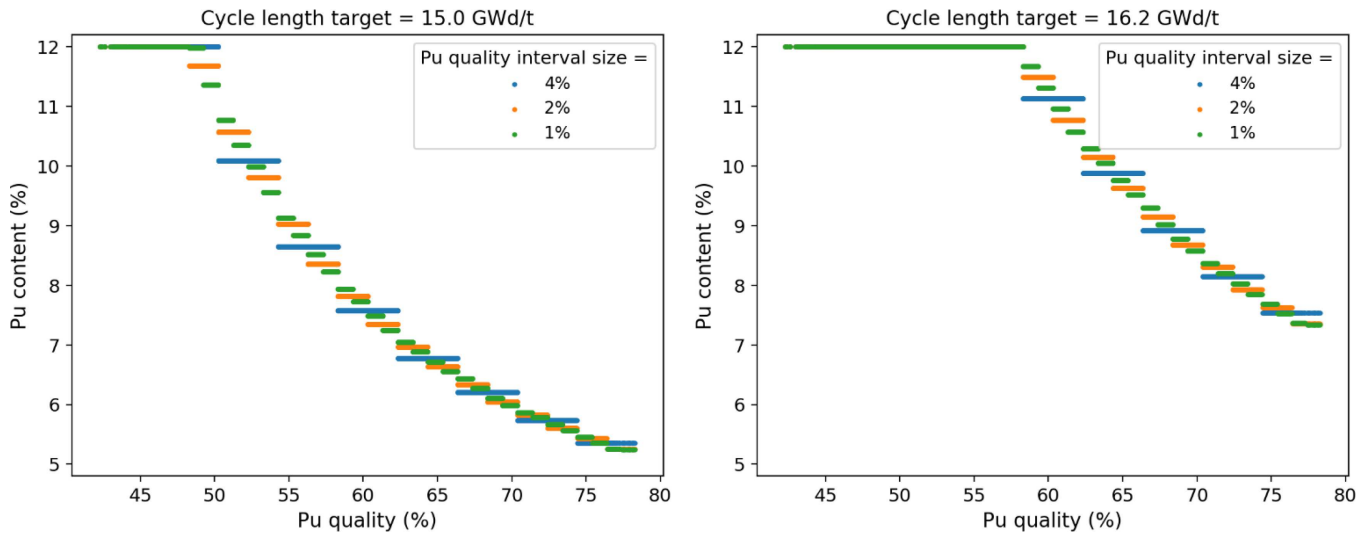


Fig. 6. Plutonium content as a function of the plutonium fissile quality for 3 different sizes of plutonium quality intervals to reach a cycle length of 15 GWd/t (on the left) or 16.2 GWd/t (on the right).

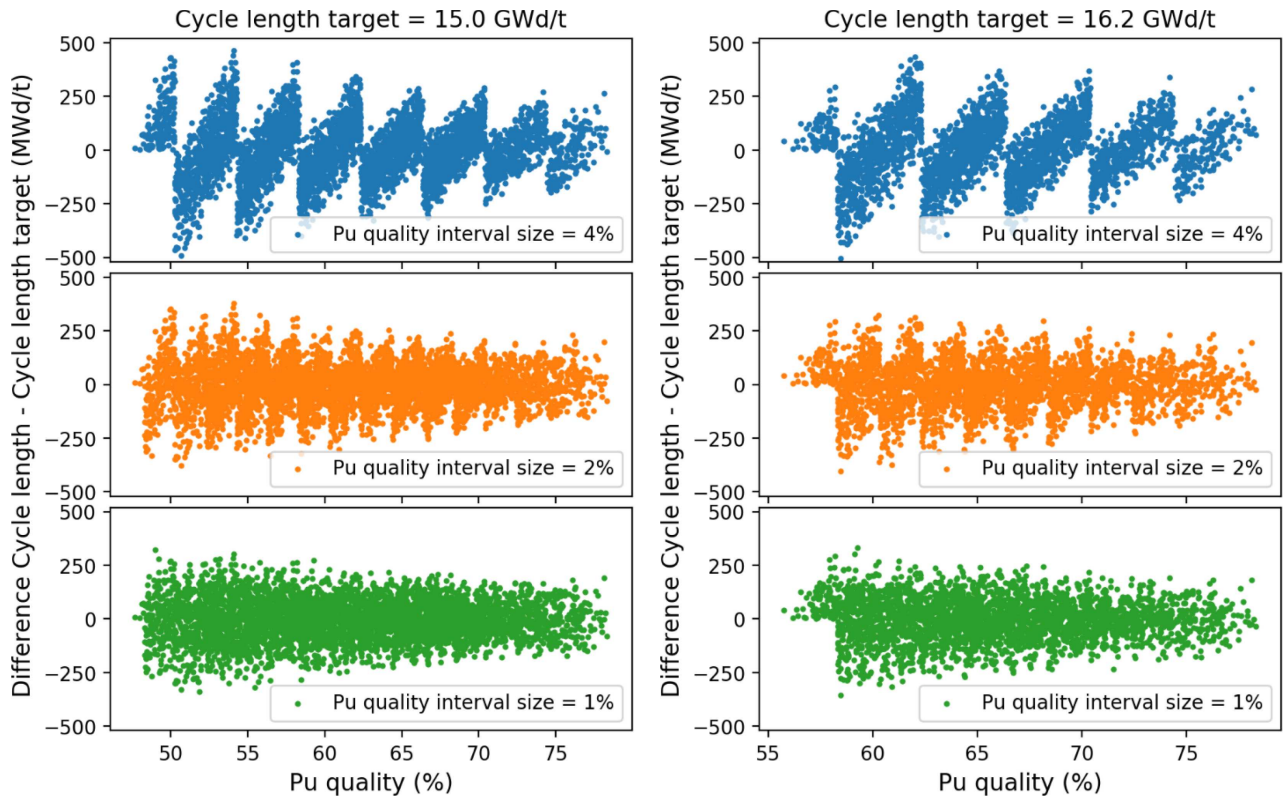


Fig. 7. Absolute differences between the cycle length reached by MOX fuel compositions estimated with the new fuel loading model and the cycle length target (15 GWd/t on the left and 16.2 GWd/t on the right) for 3 different sizes of plutonium quality intervals.

Figure 6 presents the two target cycle lengths of the Pu content calculated for each Pu fissile quality range. Pu isotopic compositions lead to a cycle length lower than the target with a Pu content of 12% are displayed as a range of Pu content of 12%. Figure 6 confirms that this piecewise approach preserves the trend of the Pu content as a function of the Pu fissile quality for a given

cycle length, regardless of the Pu fissile quality interval size.

For each resulting MOX fresh fuel composition (Pu isotopy and Pu content of the range), the cycle length is then calculated. Figure 7 shows the deviation of these values to the target cycle length. Pu isotopic compositions lead to a cycle length lower than the target with a Pu

Table 4. Mean and standard deviations to the cycle length targets 15 GWd/t and 16.2 GWd/t for 3 different sizes of plutonium quality intervals

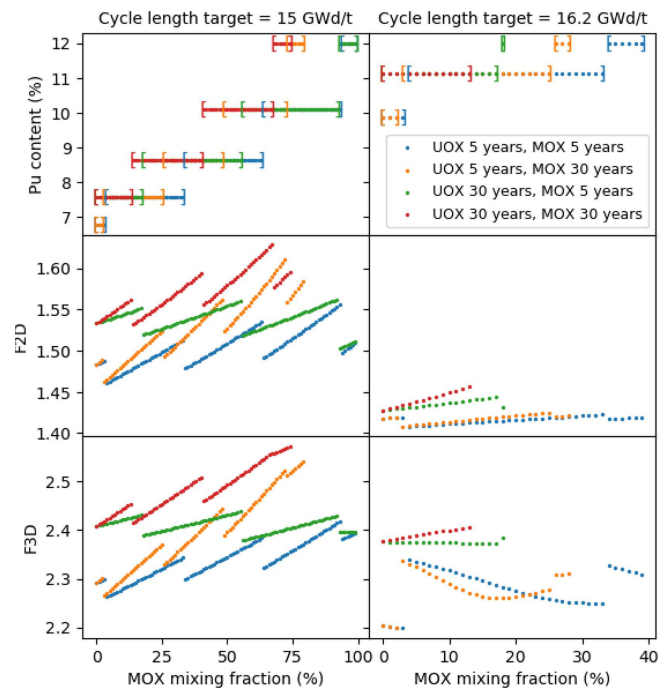
Pu quality interval size	Cycle length target = 15 GWd/t		Cycle length target = 16.2 GWd/t	
	Mean deviation (MWd/t)	Standard deviation (MWd/t)	Mean deviation (MWd/t)	Standard deviation (MWd/t)
4%	-6.9	134	-4.2	146
2%	-2.3	105	-5.4	109
1%	-3.6	95	-5.2	99

content of 12% are excluded. For the three evaluated Pu fissile quality range sizes, a maximum absolute deviation of 500 MWd/t is observed, below the acceptable margin of 1 GWd/t. Figure 7 shows that for a Pu fissile quality range of 1%, the variations around zero in the deviations from the target cycle length value appear to be primarily due to variations in Pu isotopy at a given Pu fissile quality. As the size of the Pu fissile quality intervals increases, the deviations exhibit a more pronounced “sawtooth” pattern with respect to Pu fissile quality. This indicates that the variations in cycle length caused by the interval size of Pu fissile quality (variation along the x -axis) have become greater than those induced by variations in Pu isotopy at fixed Pu fissile quality (variation along the y -axis). Table 4 presents the mean and standard deviation for each scatter plots displayed on Figure 7. Pu content estimator based on this new approach leads to standard deviation of the cycle length discrepancies distribution lower than 150 MWd/t for a Pu fissile quality range size of 4%.

5.4 Potentialities of spent MOX dilution in spent UOX for plutonium recycling

Using this new MOX fuel loading model, an analysis based on mixtures of Pu extracted from UOX and MOX cooled spent fuel has been performed. Pu mixtures defined in Section 4.2 are reproduced. The new fuel loading model based on Pu fissile quality ranges of 4% is used in this case. For each resulting Pu isotopic composition, its Pu fissile quality range is identified. The resulting Pu content is deduced using the new fuel loading model. F_{2D} and F_{3D} ANN estimators are then run using the Pu isotopic composition and the Pu content. Pu isotopic compositions leading to a cycle length lower than the target with a Pu content of 12% are excluded. The resulting data are presented in Figure 8.

Compared to the application of the previous fuel loading model presented in Figure 5, the dependence of the Pu content on the fraction of the different Pu_{MOX} in the Pu mixture (and thus on the resulting Pu isotopy) no longer results in a continuous increasing curve but rather a series of discrete intervals. However, the minimum and maximum values of the Pu content and the fraction of the different Pu_{MOX} in the Pu mixture remain comparable for a given target cycle length. Compared to the

**Fig. 8.** Plutonium content estimated with the new fuel loading model and corresponding 2D and 3D power peaks as a function of the mixing fraction of plutonium coming from MOX spent fuel and plutonium from UOX spent fuel.

previous fuel loading model, the Pu content assigned at each Pu fissile quality interval leads to a maximum absolute discrepancy of 400 MWd/t on the target cycle length.

In contrast to the previous fuel loading model, this new approach produces discontinuous segments of F_{2D} and F_{3D} for each fissile quality interval. These discontinuities are explained by the fact that a change of Pu fissile quality interval corresponds to a change of Pu content. Nevertheless, the values remain comparable to those previously obtained with a maximum relative difference compared to the previous model of 3%.

Consequently, this new MOX fuel loading model enables to maintain the Pu content over extended intervals of Pu fissile quality, with a minor bias on the cycle length and F_{2D} and F_{3D} .

6 Conclusion

This paper focuses on the development of a new MOX fresh fuel loading model, dedicated to Pu multi-recycling in PWR, for nuclear scenario codes. The deployment of Pu multi-recycling in PWRs requires precise management of Pu isotopy, due to its high variability resulting from the mixing of various spent fuels that may have been recycled multiple times and cooled for different durations. This significant variability in Pu isotopy requires studying its impact on reactor fuel managements dedicated to Pu recycling.

To this end, the methodology proposed in this work relies on core-level calculations of an EPR 30% MOX, to accurately capture the effects that occur at this scale (core geometry, loading pattern, assembly neighborhood, etc.). A EPR 30% MOX 3D core calculation scheme, based on the APOLLO2/CRONOS2 neutron transport codes, was therefore developed. Using this scheme, a core calculation database gathering key results (power factors and cycle length), comprising several hundred calculations with varying isotopic compositions of fresh MOX assemblies, was built. Several ANN were then trained on this database to predict the cycle length and power factors for given MOX input compositions.

Based on these ANN estimators, the exploration of the possible Pu isotopic space and its impact on the results of interest highlighted the strong sensitivity of the required Pu content in fresh MOX fuel to Pu isotopic variability for a given target cycle length. In contrast, the cycle length achievable by the reactor is less sensitive to variations in Pu content. Furthermore, reactor operations can also lead to adjustments in cycle length to accommodate operational conditions. These findings challenge the conventional approach in MOX fuel loading models, which consists in adjusting the Pu content based on Pu isotopy to reach a target cycle length. A new MOX fuel loading model has been proposed. It relies on the definition of Pu fissile quality ranges characterized by a fixed Pu content that guarantee a limited variation of the cycle length (lower than 500 MWd/t).

The outlooks of this work focus on the implementation of this new MOX fresh fuel loading model into the nuclear scenario code, together with the integration of a dedicated irradiation model. These new MOX physics models will then enable the simulation of nuclear scenario dedicated to Pu multi-recycling deployment in PWR. Material management in the multi-recycling fleet can subsequently be analyzed with respect to the characteristics of Pu fissile quality intervals.

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Conflicts of interest

The authors have nothing to disclose.

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