

# Flexblue<sup>®</sup> core design: optimisation of fuel poisoning for a soluble boron free core with full or half core refuelling

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**Abstract.** Flexblue<sup>®</sup> is a 160 MWe, transportable and subsea-based nuclear power unit, operating up to 100 m depth, several kilometers away from the shore. If being underwater has significant safety advantages, especially using passive safety systems, it leads to two main challenges for core design. The first one is to control reactivity in operation without soluble boron because of its prohibitive drawbacks for a submerged reactor (system size, maintenance, effluents, and safety considerations). The second one is to achieve a long cycle in order to maximise the availability of the reactor, because Flexblue<sup>®</sup> refuelling and maintenance will be performed in a shared support facility away from the production site. In this paper, these two topics are dealt with, from a neutronic point of view. Firstly, an overview of the main challenges of operating without soluble boron is proposed (cold shutdown, reactivity swing during cycle, load following, xenon stability). Secondly, an economic optimisation of the Flexblue<sup>®</sup> core size and cycle length is performed, using the QUABOX/CUBBOX code. Thirdly, the fuel enrichment and poisoning using gadolinium oxide are optimized for full core or half core refuelling, with the DRAGON code. For the specific case of the full core refuelling, an innovative heterogeneous configuration of gadolinium is used. This specific configuration is computed using a properly adapted state-of-the-art calculation scheme within the above-mentioned lattice code. The results in this specific configuration allow a reactivity curve very close to the core leakage one during the whole cycle.

## 1 Introduction

Flexblue<sup>®</sup> is a Small Modular Reactor (SMR) delivering 160 MWe to the grid. The power plant is subsea-based (up to 100 m depth and a few kilometers away from the shore) and transportable (Tab. 1). It is entirely manufactured in shipyard and requires neither levelling nor civil engineering work, making the final cost of the output energy competitive. Thanks to these characteristics and its small electrical output, Flexblue<sup>®</sup> makes the nuclear energy more accessible for countries where regular large land-based nuclear plants are not adapted, and where fossil-fuelled units currently prevail on low-carbon solutions. Immersion provides the reactor with an infinite heat sink – the ocean – around the containment boundary, which is a cylindrical metallic hull hosting the nuclear steam supply systems.

Several modules can be gathered into a single seabed production farm and operate simultaneously (Fig. 1). The

reactor is meant to operate only when moored on the seabed. Every 3 years, production stops and the module is emerged and transported back to a coastal refuelling facility which hosts the fuel pool. This facility can be shared between several Flexblue<sup>®</sup> modules and farms. During operation, each module is monitored and possibly controlled from an onshore control center. Redundant submarine cables convey both information and electricity output to the shore. A complete description of the Flexblue<sup>®</sup> concept, including market analysis, regulation and public acceptance, security and environmental aspects can be found in reference [1]. A more detailed description of the PWR reactor design and the thermal-hydraulic accident analysis can also be found in reference [2].

The purpose of this paper is to present a suitable design of the Flexblue<sup>®</sup> core, taking into account the specificities of the reactor. The first major option of this reactor is a soluble boron free control, which is analyzed in Section 2. The second main core characteristic is a three-year-long cycle. This duration together with the core size, enrichment and the refuelling scheme are justified, using an economic analysis, in Section 3. In the last part, an optimization of the burnable poison (gadolinium [Gd]) in the fuel assembly is performed, using an innovative heterogeneous configuration.

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**Table 1.** Flexblue<sup>®</sup> module main characteristics.

Parameter	Value
Unit power rating	160 MWe
Length	150 m
Diameter	14 m
Immersion depth	100 m
Lifetime	60 years

**Fig. 1.** Artist view of a Flexblue<sup>®</sup> farm.

## 2 Operating without soluble boron

### 2.1 Motivations

The use of soluble boron in the primary coolant is very common in large electricity generator PWR, such as French EDF or American ones. It is used there for three main purposes:

- cold shutdown: in these reactors soluble boron is the only system able to provide sufficient negative reactivity to achieve cold shutdown;
- reactivity swing during cycle: the use of soluble boron enables to mitigate the high reactivity of fresh fuel and to control the reactivity during the fuel depletion;
- load following: soluble boron is a convenient manner to control reactivity during short and limited variation of reactivity (load following, xenon transient).

Moreover, soluble boron has the advantage to be homogeneously distributed in the core, which is favorable to flatten the power distribution in order to reduce the power peak.

But, in the Flexblue<sup>®</sup> case, it has significant drawbacks. First of all, the use of soluble boron requires voluminous recycling systems, that cannot be afforded in the limited space available in an underwater reactor. Furthermore, these systems require frequent maintenance, which is hardly suitable for Flexblue<sup>®</sup>. Finally, operating without soluble boron also eliminates all the boron dilution accidents. This point is particularly important for severe accidents, if the flooding of the reactor compartment by seawater is considered; in such a case, if soluble boron is required to achieve cold shutdown, criticality may occur. This last point, even if associated to a very unlikely accident, prohibits the use of soluble boron for Flexblue<sup>®</sup>.

A soluble boron free reactor also has significant safety advantages, such as less primary corrosion, an increased

moderator coefficient (in absolute value) which is favorable for several accidents (uncontrolled control rod withdraw, unprotected loss of flow accident . . .),<sup>1</sup> and no criticality in case of main steam line break (in such an accident, the core cooling could be sufficient to make the core critical even with all the control rods inserted in reactors using soluble boron).

The manners to solve the cold shutdown and load following issues in a soluble boron free reactor are presented below, together with a consideration about the shutdown system redundancy. The way to solve the reactivity swing during cycle is analyzed in [Section 4](#).

### 2.2 Cold shutdown

Due to moderator effect, the reactivity strongly increases between the hot and cold shutdown (around 5,000 pcm), and a safety margin of negative reactivity of 5,000 pcm is also required [3,4]. In order to provide this negative reactivity without soluble boron, the only manner is to increase the control rod worth. Several ways can be investigated:

- use of particularly absorbing materials, such as enriched boron or Hafnium [5]; control rod using B<sub>4</sub>C with 90% of <sup>10</sup>B worth 40% more than with natural boron<sup>2</sup> in an infinite medium;
- an increased number of control rod pins: the use of 36 pins (compared to the classical 24 for 17 × 17 fuel assembly) can increase the control rod worth of 70%<sup>2</sup> (250%<sup>2</sup> using enriched B<sup>10</sup>) in an infinite medium. But these attractive results are not directly applicable, because in a real core, the control rods only cover a fraction of the core, and a space-shielding effect in controlled fuel assemblies strongly limits the negative reactivity of those solutions. For example, a 97 standard 17 × 17 fuel assembly's core, with half of them controlled with 24-pins control rods using enriched boron, with optimized poisoning ([Sect. 4.2](#)), does not achieve cold shutdown. With the most reactive rod stuck above the core, the reactivity is positive, around 2000 pcm;
- an increased number of control rods; another way to avoid this space-shielding effect is to increase the number of rodded fuel assemblies, above 50% possibly up to 100%

<sup>1</sup>A high moderator coefficient (in absolute value) is however unfavorable to overcooling accidents, such as main steam line break. But, this is not a drawback for soluble boron free reactor compared to reactor using soluble boron; indeed both have the same maximum moderator coefficient (in absolute value), at end of cycle when both do not have soluble boron in their primary coolant. The impact to be soluble boron free only reduces the moderator coefficient variation from approximately -40 pcm/°C in begin of cycle to -60 pcm/°C at end of cycle compared to ~0 pcm/°C to -60 pcm/°C for soluble boron reactors. As safety studies only consider the maximum coefficient, it has no impact. Moreover, concerning the main steam line break accident, as there is no criticality after automatic shutdown (thanks to the increased control rod worth) in soluble free reactor, it is much less an issue.

<sup>2</sup>These results have been obtained with QUABOX/CUBBOX, using cross-section libraries generated with DRAGON ([Sect. 4](#)).

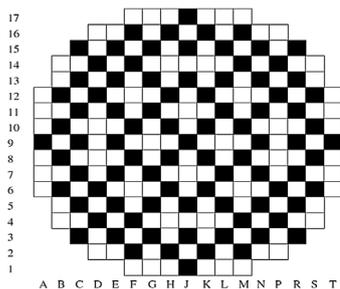


Fig. 2. Control rod position in the EPR Core.

of the core. Calculations performed for this paper show that for 100% of fuel assemblies rodded, even with 24 pins of natural  $B_4C$  or AIC, cold shutdown is easily achieved ( $-7,000$  pcm for the above-mentioned core, with the most reactive rod stuck).<sup>3</sup> But, this last solution has a major limitation: the current size of Control Drive rod Mechanism (CDM),  $\sim 30$  cm, is larger than the fuel assembly size (21.5 cm). That is why in current French PWR, the fraction of rodded fuel assemblies is always below 50% and diagonally spread in the core<sup>4</sup> (Fig. 2).

A way to solve this issue is to insert the control rod mechanism inside the reactor primary vessel; this exempts them to stand the pressure difference (155 bars – 1 bar), and enables to make them more compact. For example, Babcock and Wilcox have chosen this solution for the mPower integral reactor.<sup>5</sup> But it does not really suit the Flexblue<sup>®</sup> reactor, which is a loop type reactor. Furthermore, the development of such immersed CDM could be long, risky and costly.

For the Flexblue<sup>®</sup> case, another option has been preferred: it consists in using more compact external CDM. Indeed, the CDM size is mainly imposed by the control rod weight and the primary pressure. If immersed CDM use the lack of pressure to reduce CDM size, reducing the weight can also be an option. For a SMR concept such as Flexblue<sup>®</sup>, the reduced height (2.15 m of fissile height compared to around 4 m for large land-based PWR) automatically divides by two the control rod weight. The power required in the CDM is therefore also divided by two, and, for a constant height the CDM radial side could be reduced by approximately  $\sqrt{2}$ , and fitted with the fuel assembly dimensions. This solution, requiring less development than immersed CDM, is the reference for Flexblue<sup>®</sup> reactor.

Another way to cover 100% of fuel assemblies with classical CDM is to use bigger control rods, recovering several fuel assemblies. That is the idea developed by DCNS in four patent applications [6–9];

– adapted fuel assemblies: another way to cover 100% of the core with control rods is to use larger assemblies, in order

<sup>3</sup>It is not necessary to have 100% of rodded fuel assemblies; a fraction around 70–80% seems to be enough (function of the enrichment, size of the core and fuel refuelling strategy). But, this point should be more deeply studied.

<sup>4</sup>The CDM lattice is diagonally oriented compare to the fuel assembly lattice.

<sup>5</sup>[www.generationmpower.com](http://www.generationmpower.com).

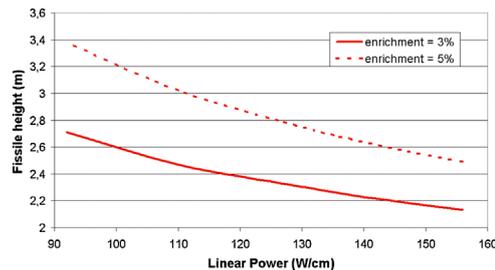


Fig. 3. Limit fissile height for axial xenon stability.

to have the same size for fuel assemblies and CDM. For example,  $21 \times 21$  fuel assemblies, with a moderator ratio of 3 (compared to 2 for current standard PWR, meaning more water between the pins) have a size of around 30 cm. But the change of a standard  $17 \times 17$  fuel assembly to a  $21 \times 21$  larger fuel assembly would have a significant impact on all the fuel facilities, and may raise criticality issues. That is why the reduced size CDM is preferred to this solution.

Several solutions can be combined in order to achieve cold shutdown. For example, reference [10] uses 28 control rods pins for a  $17 \times 17$  lattice, and a fraction of rodded fuel assemblies of 62%. Reference [5] uses Hf as absorber, an increased number of control rods pins, an increased moderator ratio (2.5) and a fraction of rodded fuel assemblies below 50%.

In conclusion, several ways are possible to achieve cold shutdown without soluble boron. Without significant modifications in the fuel assembly, a fraction of rodded fuel assemblies above 50% is required. The reference solution for the Flexblue<sup>®</sup> project is to keep a standard (but shortened)  $17 \times 17$  fuel assembly, and to adapt the design of the CDM in order to be able to insert a control rod in every assembly in the core. This solution has been chosen for its minimal required developments.

### 2.3 Xenon stability and load following

In large current PWR, boron is used in order to limit the control rod displacement and avoid the risk of axial xenon instabilities (increase of axial power oscillations due to xenon). For Flexblue<sup>®</sup>, the limited fissile height (2.15 m) is very favourable in terms of stability. In order to analyse the risk of xenon axial instability, a simplified conservative analytical model based on reference [11] has been used. The model estimates the maximum fissile height for which xenon oscillations are stable, for an axially uniform power profile (conservative hypothesis for stability), as a function of linear power (assuming a standard  $17 \times 17$  fuel assembly) and enrichment.<sup>6</sup> The results, presented in Figure 3, show that for a 5% enrichment, and a linear power below 125 W/cm (Flexblue<sup>®</sup> core), the stability limit is estimated above

<sup>6</sup>The xenon density, and neutronic worth are directly dependent on the fission rate (by producing  $^{135}I$ ), i.e. the linear power. The xenon density is also function of the neutron flux (for captures), which is strongly dependent on the enrichment for a given power density.

2.8 m. Accordingly, despite the uncertainty of the model, it can be assumed that xenon oscillations are stable in the Flexblue<sup>®</sup> core. Oscillations may occur consequently to a load follow, or a significant control rod movement, but they will decrease, without leading to safety concerns. Reference [10] even claims to be able to design a soluble boron free core, stable with 3.8 m of fissile height using axially heterogeneous poisoning.

Soluble boron is also currently used to manage significant reactivity variations due to xenon poisoning during a load follow. The way to manage it in a soluble boron free core has been well studied in references [12,13]. The idea is to adapt the average coolant temperature during a transient, in order to use moderator effect to balance the xenon variations. Control rod movements are also required during such a transient, in order to limit the temperature variations, but the study in reference [12] concludes that they are small enough to keep an acceptable form factor.

## 2.4 Other safety considerations

The soluble boron suppression also raises some other safety considerations. Firstly, a safety requirement of the European Utility requirements [3], similar to a requirement of the NRC in reference [14], is: ‘The control of the core reactivity shall be accomplished by means of at least two independent and diverse systems for the shutdown’. Usually, boron and control rods are these diverse shutdown systems. That is why, even if the reactor is soluble boron free in normal operation, the Flexblue<sup>®</sup> auxiliary systems include an emergency boron injection system, similar to VVER ones [15]. It consists of two tanks, full of borated water at the primary pressure, connected to the primary pumps (Fig. 4).

In case of an Anticipated Transient Without Scram (ATWS), the pump inertia provides the passive injection in the cold leg. After such an injection, the reactor must be transported back to a coastal maintenance facility in order to remove the boron.

Secondly, the reduced weight of control rods has also an impact on their falling time, which is expected to be slightly increased. The impact of this increase cannot be evaluated at this project phase but has to be carefully considered for future detailed transient studies.

## 2.5 Control rod ejection

For SMR reactors, the control rod ejection is much more problematic compared to large PWR. Indeed, due to the

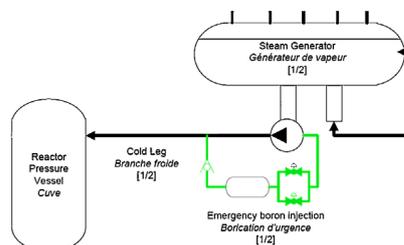


Fig. 4. Scheme of the Emergency Boron Injection.

small core size, the neutronic worth of each control rod is strongly increased, reaching 5,000 pcm for a 24 pins, natural B<sub>4</sub>C control rod, in a 77 assemblies core. This value has to be compared to approximately 600 pcm for the same control rod in a large PWR, which is high enough to lead to prompt-criticality, a power excursion up to 10 times the nominal power and an energy release of 75% of the safety related criterion of 200 cal/g [16]. Considering that the energy release is roughly proportional to  $\rho_{CR} \cdot \beta$  (where  $\rho_{CR}$  is the control rod worth and  $\beta$  the delayed neutron fraction)<sup>7</sup>, it is clear that the safety criterion cannot be respected with such insertion of reactivity (up to 30 times the criterion). Even with a control rod of 2000 pcm, the criterion is 10 times exceeded.

Furthermore, for Flexblue<sup>®</sup>, this point is emphasized by the soluble boron free conception; the control rods are inserted deeper and for a longer time in the core, for long-term reactivity variation and Axial Offset regulation. This makes the control rod ejection accident more likely and even more problematic. Additionally, a control rod ejection may deteriorate the third containment barrier (the module hull), if a dedicated protection is not added above the reactor. However, this place is very critical in terms of component arrangement, due to the module compactness. All these reasons make the control rod ejection a potential issue for safety. That is why, within the Flexblue<sup>®</sup> project, the strategy is to eliminate the possibility of a control rod ejection. This is achievable using anti-ejection devices, such as described in CEA or Combustion Engineering patents in references [17–19]. Many patents on preventing control rod ejection devices can be found, some associated with “nut screw” CDM, others with “pawl-push” ones. There are too many to be all listed and described here.

This problem is another reason why a re-design of a specific CDM is required for Flexblue<sup>®</sup>, taking into account two major issues: to be sufficiently compact to achieve one CDM by fuel assembly (to reach cold shutdown), and to eliminate the control rod ejection accident.

## 2.6 Conclusion

In conclusion, one of the main challenges to operate without soluble boron is achieving cold shutdown. In addition, one of the main challenges of designing a SMR core, especially a soluble boron free one, is control rod ejection accident. These two issues can be solved, keeping a standard 17 × 17 fuel assembly, by using an adapted CDM, more compact, in order to be able to insert one control rod per assembly, and integrating an anti-control-rod-ejection device. The following assumes that such CDM is achieved. The reduced fissile height of the core ensures the stability of axial xenon oscillation, and the load follow can be managed by adapting the coolant average temperature. In order to fit safety requirements, a passive emergency boron injection is added.

The last main challenge for operating a Flexblue<sup>®</sup> without soluble boron is to manage the reactivity swing

<sup>7</sup>[www.cea.fr/energie/la-neutronique/](http://www.cea.fr/energie/la-neutronique/) (in French).

during cycle. This last point will be presented in Section 4. Meanwhile the next part describes the core design strategy and results.

### 3 Core design

#### 3.1 QUABOX/CUBBOX calculations and control rods regulation

QUABOX/CUBBOX is a diffusion 3D code, developed by GRS (in German “Gesellschaft für Anlagen- und Reaktor-sicherheit”). It is integrated in all the GRS reactor physics chain, and especially coupled to ATHLET code for neutronic/thermal-hydraulic transients. It has been validated by benchmark (see for example Refs. [20,21]).

In this study, QUABOX/CUBBOX uses library cross-sections generated by DRAGON (Sect. 4.3). The coupling between the two codes has been developed by DCNS in Python. A validation of this new calculation chain has been performed on standard and Cyclades refuelling strategies on 900 MWe French PWR, with a few percents of discrepancy on burn-up and cycle length.

Cycle calculations have been performed with imposed temperature profile and moderator density (no thermal-hydraulic feedback). For the soluble boron free operation, the current version of the code uses a very simplified control rod regulation; all groups are inserted or withdrawn at the same time, keeping a constant relative distance. These simplifications have a quite small impact on the cycle length, but strongly limit the ability of the current version to estimate precise form factors. Despite these limitations, some optimizations of the refuelling scheme have been performed, and some 3D form factors are presented below, in order to evaluate the performance of poisoning optimization. These values are not very accurate, but give a good idea of what kind of performance can be achieved.

In order to control the Axial Offset, a fuel with heterogeneity has been used, considering a layer of 21.5 cm for two-batch cycle and 18 cm for single-batch without Gd at the top of the core.

#### 3.2 Methodology

Considering that the transportation, between the production site and the refuelling facility, might have an impact on the average availability, the focus has been placed on the following features. Firstly, the conception of the module and the maintenance planning are optimized to shorten the maintenance duration, especially using standard exchange for some components. Secondly, and that is this paper’s objective, the core has been designed to optimize the cycle length in order to minimize the Levelized Cost of Energy (LCOE).

The optimized cycle is a compromise between the availability (which is improved by increasing the cycle length), the fuel cost (which is dependent on the enrichment and the refuelling strategy: single or two-batch) and the core size (to increase the reactor vessel size increases the reactor investment).

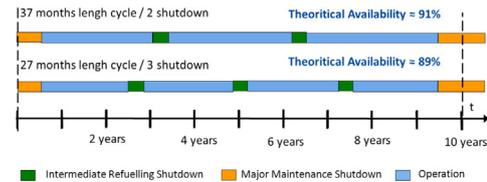


Fig. 5. Examples of 10 years Flexblue<sup>®</sup> cycles.

One major parameter is the refuelling strategy. Indeed, a single-batch refuelling (100% of fresh fuel at each refuelling) enables to reach a long duration cycle, but misuses the fuel with typical burn-up below 30 GWd/t<sub>UO<sub>2</sub></sub> for 5% enrichment. On the other hand, a two-batch refuelling reduces the cycle length by approximately one third, compared to a complete refuelling, but increases the final fuel burn-up by one third,<sup>8</sup> reducing the fuel total cost.

Another key parameter is the core size. Indeed, a bigger core reduces the power density, and linear power. As a result, it increases the cycle length (thus the availability) for a given burn-up. But it also increases the reactor-vessel cost, and the initial investment to build a module. Taking into account the financial aspect of this investment, with an 8% actualization rate, it has an impact on the LCOE. The linear power is also limited by safety considerations, especially for a soluble boron free core, in which the form factor is expected to increase (Sect. 3.3).

Considering a major shutdown for maintenance of several months every 10 years adds another aspect to take into consideration, because the fuel cycle length should be close to a fraction of this 10-year cycle. It is worthless to achieve a 32-month cycle, because it is not long enough to have only two intermediate refuelling shutdowns, and 27 months are sufficient to have three intermediate shutdowns (Fig. 5). A margin is useful to provide flexibility for the shutdown operation date (function of electricity consumption) but is already provided by stretching possibilities and burn-up economy realized during load following.

All these parameters have been included in a general economic model in order to evaluate the LCOE of several Flexblue<sup>®</sup> farms. This model takes into account some operation hypotheses (maintenance and transportation durations), cost evaluation (module, fuel, transportation, decommissioning, maintenance facility cost including its own investment and cost strategy), and models for a progressive development and investment in each farm, all the financial fluxes, planned shutdowns and electricity production. In order to evaluate the maximum cycle length for a given core size, enrichment and refuelling strategy (single, two or three batches), polynomial interpolations sets on several hundreds of QUABOX/CUBBOX calculations are used. These calculations are performed assuming a standard 17 × 17 fuel assembly, with a fissile height of 2.15 m. The average quadratic discrepancy between the interpolations and the calculation is 2%. The model also optimizes the core enrichment in order to adapt the cycle length to the number of refuelling shutdowns required, and

<sup>8</sup>Using the well-known approximation  $Bu(n) = \frac{2n}{n+1} Bu$  (1), where  $n$  is the refuelling strategy (1 for single batch, 2 for two batch), and  $Bu$  the burn-up [22].

**Table 2.** Reference core main characteristics.

General characteristics	Number of fuel assemblies	77
	Fissile height	2.15 m
	Equivalent diameter	2.13 m
	Height/Diameter ratio	1.01
	Thermal power	550 MW <sup>a</sup>
	Average linear power	126 W/cm
	Internal/External vessel diameter	3.2/3.5 m
	Reflector	Iron
Single batch refuelling (reference cycle)	Enrichment	4.95%
	Gadolinium content	44 pins/8%w
	Radial assembly form factor	1.24
	3D core form factor	3.0
	Maximum linear power	< 465 W/cm
	Cycle length	38 months
	Burn-up	27 GWd/t <sub>UO<sub>2</sub></sub>
Two-batch refuelling	Enrichment	4.95%
	Gadolinium content	32 pins/9%w
	Radial assembly form factor	1.16
	3D core form factor	2.2
	Maximum linear power	< 322 W/cm
	Cycle length	27 months
	Burn-up	38 GWd/t <sub>UO<sub>2</sub></sub>
	ΔLCOE (compared to single batch)	+2 €/MWh

<sup>a</sup>The thermal power is, in this study, considered to be 550 MWth, including 20 MWth of margin (conservative on the cycle length and DNBR), compared to the reference 530 MWth [2].

reduces fuel costs. A 5% maximum enrichment is imposed, mainly because most industrial enrichment capabilities cannot reach higher values.

This paper does not deal with the evaluation of the LCOE of Flexblue<sup>®</sup>, and only focuses on the impact of core design on the LCOE, in order to guide core pre-conception. The results presented below are subsequently only relative between themselves, and to a certain extent functions of the economical hypotheses, and distance between the production site and maintenance facility.

### 3.3 Core design results

One of the first results obtained with this model is the fact that, achieving a very long cycle of 55 months (4 years and half), in order to maximise the availability, by doing only one refuelling shutdown, is not the economic optimum. Indeed, despite the fact that it would be quite difficult from a maintenance point of view, the gain in terms of availability is annihilated by the fuel misuse and increased investment due to the pressure vessel size.

Another result concerns the decision to use a heavy reflector (iron, like the EPR<sup>®</sup>) or water like current French PWR. The model shows, with the considered hypotheses, that the use of a heavy reflector is always interesting. The iron reflector reduces the neutron leakage (by  $\approx 1800$  pcm compared to a water reflector, for such small cores), therefore

the enrichment ( $\approx 0.2$ – $0.3\%$  for a given cycle length) and fuel cost, enough to compensate for its own cost. It also reduces the vessel neutronic damages and flattens the radial-core-power distribution. Consequently, a heavy reflector is today the reference design option for the Flexblue<sup>®</sup> project.

Every core size (between 69 and 121 fuel assemblies<sup>9</sup>) and refuelling strategy has been evaluated, and among all the results two particular core designs have been selected. More detailed neutronic calculations have been performed for these ones.

The first one, which is the reference core for the Flexblue<sup>®</sup> project, is a 77 fuel assemblies core whose main characteristics are presented in Table 2.

One of the main characteristics of this core is its quite low average linear power (126 W/cm, compared to 175 W/cm for current French PWR). Such a low power density has been chosen in order to ensure enough safety margins, especially on the DNBR, despite the degraded power distribution in the core due to soluble boron free operation (more control rods inserted) and the scale effect on DNBR (Sect. 3.4). The H/D ratio is almost 1, corresponding to minimum leakage.

This core can be used with a single batch refuelling. It enables to reach cycles longer than 37 months and only two intermediate refuelling shutdowns (Fig. 5), increasing the availability. This is the current reference cycle. On the

<sup>9</sup>Odd geometries only, for better symmetry of the control rod scheme.

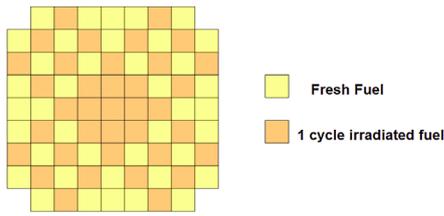


Fig. 6. Two-batch refuelling scheme of the reference core.

contrary, with a two-batch refuelling (Fig. 6) the cycle length is limited to 27 months, requiring three intermediate refuelling shutdowns. In this specific situation, the LCOE increase due to reduced availability is bigger than the fuel economy, indeed LCOE is increased by about 2 €/MWh. But, even with a slightly increased LCOE, this cycle is quite attractive, because it has an increased burn-up, meaning less waste management. In addition, if for regulatory or maintenance reasons, the 37-month cycle could not be achieved at the beginning, it offers an interesting alternative.

Moreover, a two-batch refuelling has significant advantages in terms of reactivity management (Sect. 4.2) and power distribution flattening, with a very low 3D form factor (2.2 compared to 3.0 for single-batch). Especially, it has to be noticed that current single-batch duration cycle is limited by the ability to control the power distribution (the axial offset and form factor increase up to +35% and 3.5 after 38 months), while two-batch cycles are only limited by fuel depletion.

The second selected core is a 97-fuel-assemblies core (Fig. 7) whose main characteristics are presented in Table 3. Its very low linear power (100 W/cm) enables to reach a 37-month cycle, with only two intermediate refuellings, with a two-batch cycle. With the best availability, and a quite good fuel economy (burn-up of 40 GWd/t<sub>UO<sub>2</sub></sub>), this core has a reduced LCOE of 2 €/MWh compared to the reference one, and is the cheapest among all studied cores. Moreover, the very low linear power provides significant safety margins. Its main drawback is its size, but such a primary vessel could still be integrated in Flexblue<sup>®</sup> containment.

### 3.4 Concerning the maximal linear power and DNBR

Low linear powers are required for Flexblue<sup>®</sup> core, because of two main safety reasons. First, the soluble boron free operation increases the power-distribution heterogeneity in the core, due to an increased use of neutron poison and control rods, especially for a single batch refuelling. Reference [12] shows that it can be managed for a 3-batch

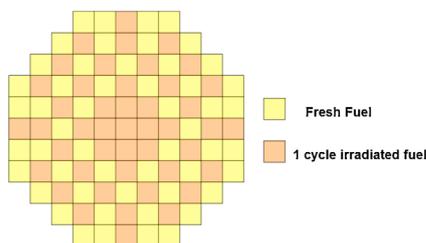


Fig. 7. Two-batch refuelling scheme of the 97 fuel assemblies core.

Table 3. Ninety-seven fuel assemblies core main characteristics.

General characteristics	Number of fuel assemblies	97	
	Fissile height	2.15 m	
	Equivalent diameter	2.39 m	
	Height/Diameter ratio	0.9	
	Thermal power	550 MW <sup>a</sup>	
	Average linear power	100 W/cm	
	Internal/External vessel diameter	3.4/3.7 m	
	Reflector	Iron	
	Two-batch refuelling	Enrichment	4.95%
		Gadolinium content	32 pins/9%w
Radial assembly form factor		1.16	
3D core form factor		2.4	
Maximum linear power		< 278 W/cm	
Cycle length		38 months	
Burn-up		40 GWd/t <sub>UO<sub>2</sub></sub>	
$\Delta$ LCOE (compared to single batch reference core)		- 2 €/MWh	

<sup>a</sup>The thermal power is, in this study, considered to be 550 MWth, including 20 MWth of margin (conservative on the cycle length and DNBR), compared to the reference 530 MWth [2].

refuelling, but it is quite different from a single-batch, with longer cycle, higher reactivity swing and initially uniform fuel assemblies. In Tables 2 and 3, the maximum linear power is below 330 W/cm for two-batch cycles, which is acceptable for normal operation compared to 430 W/cm for current PWR, but slightly above the large reactor reference for a single-batch operation (465 W/cm). This last cycle still requires an optimized power distribution.

Secondly, one of the main safety core parameters is the Departure from Nucleate Boiling Ratio. Considering it, SMR are slightly disadvantaged, compared to large PWR. Indeed, with an approximately half fissile length, for similar core-coolant temperature variation, the flow is roughly divided by two. This has a significant impact on flow turbulence and DNBR, and this single effect approximately reduces by 30% the DNBR (for Flexblue<sup>®</sup> case compared to a 1300 MWe PWR), and so the acceptable maximum linear power (Fig. 8).

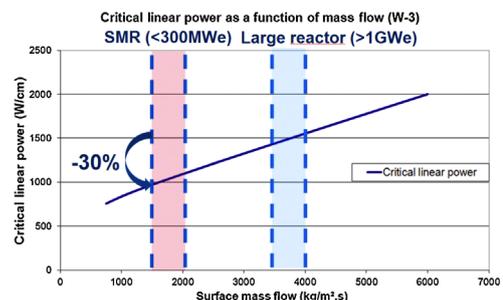


Fig. 8. Scale effect on the DNBR.

Other parameters must be taken into account such as outlet temperature, but this scale effect implies a roughly 30% lower linear power for SMRs. And, as shown in Tables 2 and 3, the above-mentioned two-batch cycles, with unoptimized core power distributions, show a minimum 25% reduction of maximal linear power, which is considered sufficient to have an acceptable DNBR. It is not the case for the single batch cycle, which requires a better power distribution optimization. For future work, this will have to be verified by dedicated thermal-hydraulic codes.

### 3.5 Conclusion

An economic study has explored the most suited core for Flexblue<sup>®</sup>, and two particular cores of 77 and 97 fuel assemblies have been selected. The reference one (77) shows good economic characteristics for a single batch but unsatisfactory 3D form factor and has to be optimized with a better control rods regulation. This core also shows acceptable economic features for a back-up 27-month-cycle with enough safety margins. The 97 one has a reduced LCOE of 2 €/MWh and improved safety characteristics, but its size is a limitation.

This study highlights the fact that with different economic features (particularly a longer shutdown for refuelling), the optimum refuelling strategies are very different from current French PWR (3-batch and 4-batch ones). Lower linear power is also required, not only in order to achieve long cycles, but also for safety reasons.

## 4 Fuel optimisation for 1- and 2-batch refuelling

In this last part, the fuel optimisation for the above-mentioned cycles is performed, considering a standard  $17 \times 17$  fuel assembly and Gd homogeneously dispersed in fuel pellets as neutron burnable poison. The optimisation aims to obtain a reactivity curve close to the leakage in order to minimise the control rods insertion.

### 4.1 Influence of gadolinium on reactivity

Gadolinium is a burnable neutron poison. It means that once it has absorbed a neutron, it becomes almost transparent to them. Therefore, it brings negative reactivity at the beginning of irradiation, which decreases with Gd depletion. An example of the influence of Gd on reactivity, in rods homogeneously distributed in an assembly, is displayed on Figure 9.

Two major parts are present in this graph. First, reactivity increases along with Gd depletion to reach, around 18 GWd/t on Figure 9, a “Gd reactivity peak” when almost all the Gd has been burnt. In a second part, the linear decrease of reactivity is very close to the one that would have been noticed without Gd. Reactivity is then slightly below what it would have been without Gd, owing to the lower uranium enrichment in poisoned rods and to the residual absorption of Gd.

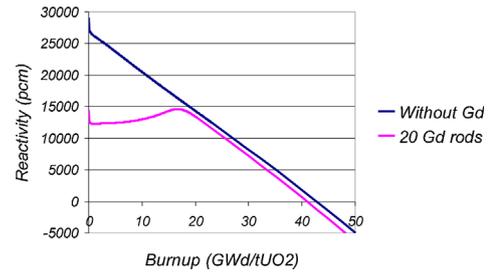


Fig. 9. Influence of gadolinium poisoning on fuel reactivity.

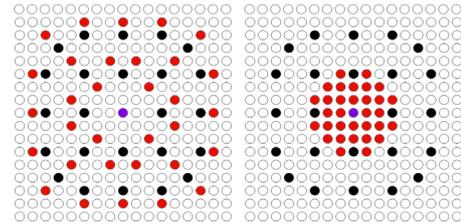
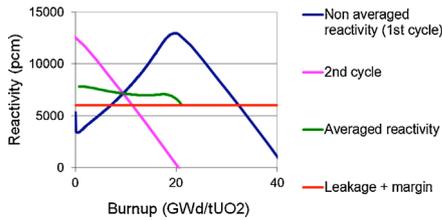


Fig. 10. Fuel bundles containing 32 poisoned rods homogeneously distributed (left) and gathered in a cluster (right). White: fuel, red: poisoned fuel, black: control rods, purple: instrumental rod.

In a homogeneous core of PWR containing one type of assembly made of homogeneous pellets, there are mostly three ways to modify the reactivity using Gd. The first option is to change the number of poisoned rods, keeping the Gd ratio in the poisoned rods the same. Since the effective surface is modified, negative reactivity at the beginning of irradiation is accordingly modified. But the ratio being the same, the burn-up of the Gd peak does not change. The second option is to increase the Gd ratio in the fuel. Since more Gd is available with the same effective surface, it remains longer in the fuel and the Gd peak is shifted to higher burn-up values. Actually, this ratio is limited because gadolinium oxide strongly lowers the fuel thermal conductivity and it could become a safety issue if Gd were to be used in too high proportions. Indeed, when Gd is burnt, what stays is a rod with fresh uranium, almost no fission products to mitigate reactivity and deteriorated thermal conductivity. Hence it increases the risk of fuel melt once Gd has been consumed. This phenomenon explains why the enrichment of poisoned rods has to be lower than the one of the other rods.<sup>10</sup> Industrially in France, gadolinium oxide has never exceeded 9%w, with an 8% standard value. The last option is to modify the poisoned rods distribution in the assembly to make clusters of them (Fig. 10). This way the inter-rods spatial self-shielding protects Gd of the inner rods which will be available later in the cycle. Hence, the Gd peak is delayed. At the same time, the effective layer being in a first approach the one of the external layer of the poisoned cluster and not the sum of all

<sup>10</sup>In this paper, an interpolated maximum enrichment in poisoned fuel pellets is used:  $e_{Gd} (\%) = 1.8965 + 0.6207e - 0.25r_{Gd}$ . Where  $e$  is the enrichment in other pellets (%), and  $r_{Gd}$  the gadolinium content (%w). This interpolation has been set on open data on irradiated fuel.



**Fig. 11.** Reactivity profile of first- and second-cycle fuel, along with the averaged reactivity.

the poisoned rods surfaces, initial negative reactivity is much lower than the one of a homogeneous distribution of the poisoned rods. This kind of configuration has been presented by Soldatov [23], but with questionable parameters (8% enriched uranium even in poisoned rods). What is presented in the present paper (Sect. 4.3) is an improved application of this interesting idea.

### 4.2 Fuel optimisation for 2-batch fuel management

In order to optimise the fuel for a half refuelling management, the averaged reactivity of the first cycle and second cycle fuel has been studied. This assumption has proven being a good approximation for a core where first- and second-cycle fuel bundles are positioned alternatively.

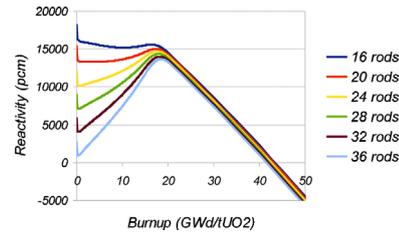
If the refuelling happens during the Gd peak, namely around 20 GWd/ $t_{UO_2}$  with 8%w of Gd, the reactivity of first-cycle fuel increases (burn-up before the Gd peak) and the reactivity of the second-cycle fuel decreases (normal reactivity decrease with fuel consumption). With an optimisation of the number of homogeneously distributed poisoned rods and the ratio of Gd in them, it was possible to obtain a flat reactivity curve up to 21 GWd/ $t_{UO_2}$ <sup>11</sup> above the leakage (considered as constant around 3,000 pcm) and margins for operations (Fig. 11). This assembly, enriched up to 4.95% and containing 32 homogeneously distributed rods poisoned with 9%w of Gd, is the one used in the two-batch cycle of Section 3.

### 4.3 Fuel optimisation for full refuelling management

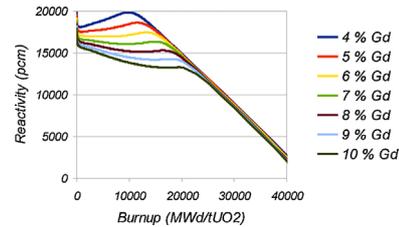
In case of full refuelling management, no assembly shows a reactivity decrease to compensate for the reactivity increase linked to Gd consumption. Hence, fuel reactivity has to follow the leakage without being averaged on the core.

For this kind of fuel management, a phenomenon usually negligible for 3- or 4-batch fuel management must also be considered. The fuel burns at different speeds according to its location in the core (faster in the middle than on its edges). To neutron leakage (around 3,000 pcm), it adds a reactivity penalty (up to 4,000 pcm at 25 GWd/ $t_{UO_2}$ ) compared to reactivity in an infinite medium  $\rho_{inf}$ , due to the fact that the fuel assemblies which have the most impact on core reactivity are at higher burn-up than the average burn-up of the core. To optimise  $\rho_{inf}$ , these two phenomena have to be considered. Therefore, the reactivity

<sup>11</sup>Cycle length, which means a final burn-up of 42 GWd/ $t_{UO_2}$ .



**Fig. 12.** Influence of the number of poisoned rods on reactivity (U enrichment: 4.95%, Gd ratio: 8%).

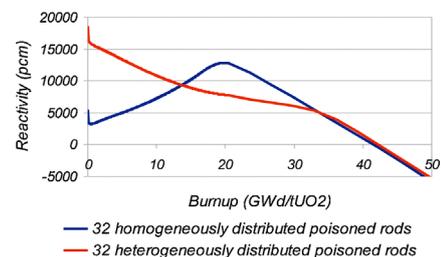


**Fig. 13.** Influence of gadolinium in poisoned rods on reactivity (U enrichment: 4.95%, 16 poisoned rods).

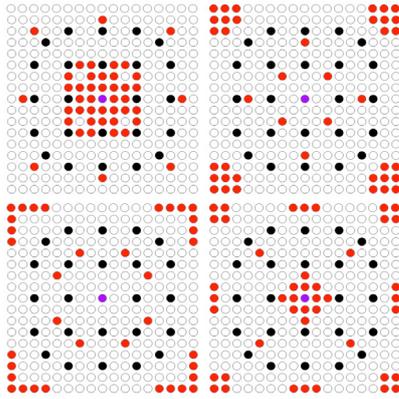
of the optimised fuel should increase with the burn-up in order to follow this evolution (Fig. 16).

For the considered cycle, Gd peak cannot be compensated at the core scale if the study includes only homogeneous poisoned rods distributions. It would imply an important resort to control rods to mitigate the reactivity and this would penalise the core form factor. And from that observation, two contradictory parameters had to be considered. First, the initial reactivity should not be too high, so the poisoned rods should be numerous enough (to increase the effective surface of the poison), as displayed on Figure 12. Secondly, the reactivity when all the Gd is burnt (during the Gd peak) should not be too high. Using only homogeneous distributions, one would have to increase the Gd ratio in poisoned rods (Fig. 13). However, as evoked previously, this resort to the Gd ratio is limited to 9% percent of gadolinium oxide, so that all the poison is burnt at around 20 GWd/ $t_{UO_2}$  and reactivity is still very high (Fig. 13). In other words, to control that peak, another way to preserve Gd negative reactivity after 20 GWd/ $t_{UO_2}$  has to be found.

A solution to answer that question and keep negative reactivity after 20 GWd/ $t_{UO_2}$  is to group the poisoned rods in clusters, as described in Soldatov's Ph.D. thesis. In this kind of configuration called heterogeneous distribution, Gd



**Fig. 14.** Comparison of reactivity of two assemblies with 32 poisoned rods (U enrichment: 4.95%, Gd ratio: 8%).



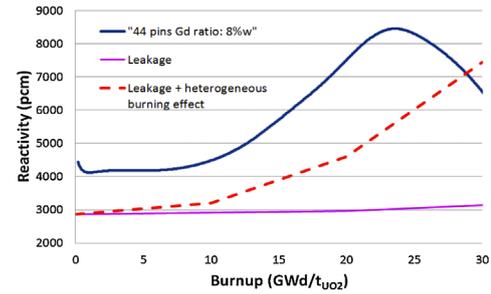
**Fig. 15.** Examples of mixed assemblies (white: fuel, red: poisoned fuel, black: control rods, purple: instrumental rod).

is burnt from the edge of the cluster to the center. The effective surface is reduced: it is no more the summation of all the poisoned rods' areas but the area of the rods constituting the external layer of the cluster. Because of that, initial negative reactivity is much lower than the one of a homogeneous distribution with the same number of poisoned rods. At the same time, this inter-rods spatial self-shielding enables to use more poisoned rods. Owing to these two aspects (the protection given by the cluster and the increased number of poisoned rods), Gd is preserved after 20 GWd/ $t_{UO_2}$ , with Gd ratios lower than or equal to 8%. Reactivity is then mitigated below 10,000 pcm and there is no more Gd peak. The problem of such a configuration, as displayed on Figure 14 for the fuel displayed on Figure 10, is that initial reactivity is too high. This is due to the reduced amount of poisoned rods initially subjected to the neutron flux. Besides, the radial form factor in the assembly can be relatively high (1.2–1.3).

To summarise the last two paragraphs, homogeneous distributions enable an interesting reactivity mitigation at the beginning of irradiation but with the price of an intense Gd peak afterwards ( $> 10,000$  pcm), when heterogeneous ones display high reactivity at first, mitigated in a second time owing to the absorption of initially protected Gd.

Another solution, called “mixed” was considered. Inspired of both, it has been designed to ensure reactivity mitigation all the irradiation long. In this idea, the assembly contains cluster(s) of poisoned rods and isolated poisoned rods homogeneously distributed amongst the other rods (see some examples on Figure 15, from the DCNS patent [24]). The distribution of the isolated rods has to take into account the presence of clusters. In addition, considering that an assembly is not alone in a core, it should be kept in mind that the clusters on the edge are adjacent to the ones of other assemblies.

This kind of configuration has very promising properties on the control of reactivity. In parallel, the presence of clusters enables to keep negative reactivity longer without using too high Gd ratio, which is a strong point for the fuel safety. A last interesting aspect is that if the radial form factor in an assembly is higher than the one of a homogeneous configuration, it is still lower than the one



**Fig. 16.** Reactivity of a mixed configuration made of 44 poisoned rods: 40 in 9 small clusters and 4 isolated.

of a heterogeneous distribution, owing to the isolated poisoned rods which mitigate the fluxes in the areas where it is the highest in heterogeneous configurations.

The reactivity at the beginning of irradiation can be set by the number of isolated poisoned rods and the peak reactivity by the size of the cluster (or the number of clusters). Therefore, by adjusting the number of poisoned rods, their Gd ratio and their repartition, the fuel designer can model reactivity at any time of the fuel's life.

To study a mixed configuration, a 44 poisoned rods assembly, with a distribution of poisoned rods shown on bottom right on Figure 15, with a 4.95% enrichment and 8%w Gd, has been selected. Its reactivity curve is displayed on Figure 16. This fuel assembly has been used to evaluate the reference single-batch cycle of the reference core.<sup>12</sup> Compared to homogeneous or heterogeneous configurations, reactivity is indeed much closer to the summation of the leakage and heterogeneous burning effect, from the beginning of irradiation to the end (around 30 GWd/ $t_{UO_2}$ ). This leads to the insertion of fewer control rods in the core, and the ability to a better optimisation of the core power distribution. However, due to the simple control rods regulation and the lack of thermal-hydraulic feedback, current calculations do not achieve to manage the core power distribution in this particular case, and the maximum 3D form factor reaches 3.0. Furthermore, it is the increase of the axial offset and the form factor at the end of cycle which requires limiting the cycle length at 38 months. For future work, an optimisation of the control rods regulation, including thermal-hydraulic feedback, is required in order to confirm the interest of this solution.

A drawback of such a configuration is an increased assembly form factor. For the considered 44 poisoned rods it reaches 1.24 at the beginning of cycle, compared to typically 1.06 for an assembly without poison, and 1.18 for the 36 poisoned rods used for the two-batch cycles. But such an increase may be acceptable if it enables a significant reduction of the core form factor. Moreover, this form factor decreases with irradiation and is about 1.10 at the end of cycle. Another issue might be the thermal difference between the rods inside and outside the poisoned cluster.

<sup>12</sup>The fact that reactivity is at the beginning very close to the leakage (low margin) is to be compensated by the non-poisoned layer of fuel on the top of the core.

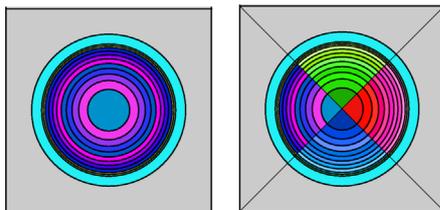
### 4.4 Calculation strategy for heterogeneous and mixed assemblies

Calculations were led with DRAGON, a freely available calculation code developed by École Polytechnique de Montréal. DRAGON has been designed to solve the neutron transport equation considering every prominent physical phenomenon [25,26]. Evolution calculations have been performed using the interface current tracking method and the JEFF-3.1.2 cross-sections library, with 281 energy groups. The energy self-shielding is done by the subgroups method on the isotopes of Zr, U, Pu, Am and Gd.

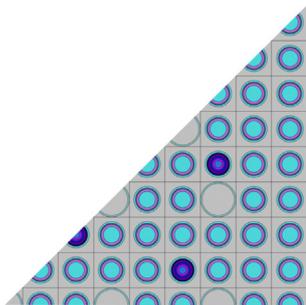
For homogeneous fuel configurations, each rod (being fuel or poisoned fuel) evolves in a quasi-isotropic medium regarding neutron flux; hence a discretisation of the rods in concentric rings is sufficient (4 rings for fuel and 11 for poisoned fuel owing to the importance of spatial self-shielding).

For heterogeneous or mixed configurations, this isotropy hypothesis is not valid anymore. Actually, the interest of that kind of configuration lies in its anisotropy that guarantees the inter-rods self-shielding. For that reason, a pellet discretisation according to its diagonals is required to describe adequately the fuel (cf. example on Fig. 17).

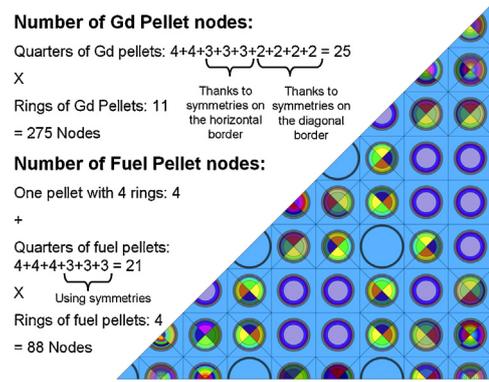
With this new calculation scheme, each quarter of ring, corresponding to one side of the pellet, is calculated with his own flux, and own isotopic depletion (energy self-shielding being the same). Consequently, a single Gd pellet requires 44 nodes, compared to 11 for a homogeneous configuration.



**Fig. 17.** Poisoned rod discretisation. On the left: without azimuthal discretisation, acceptable description for homogeneous distributions, and on the right: with azimuthal discretisation adapted to heterogeneous or mixed distributions.



**Fig. 18.** Example of a standard assembly discretisation for homogeneous distributions.

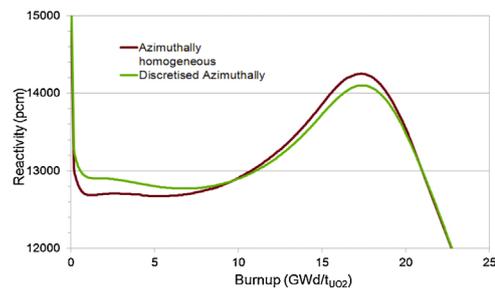


**Fig. 19.** Example of assembly discretisation for “mixed” distributions.

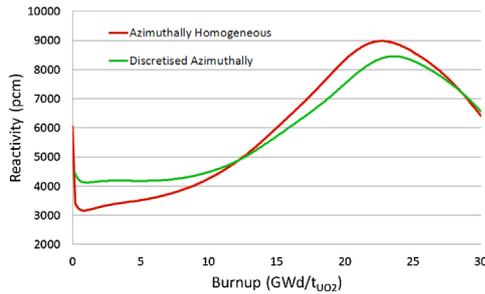
Furthermore, on the assembly scale, the same issue is raised; in a homogeneous distribution (Fig. 18) every fuel pellet without Gd can be assumed to have the same isotopic depletion. The same hypothesis can be done (and is done in standard calculation scheme) for the Gd pellet. The total number of fuel nodes is then:  $11 + 4 = 15$  nodes.

But for a heterogeneous or mixed distribution, such assumptions cannot be done, and each Gd pellets, with surrounding fuel pellets, has to be differentiated. In Figure 19, corresponding to the previously mentioned 44 poisoned rods assembly, 88 depletion nodes are required for fuel pellets and 275 for Gd pellets. Such calculation scheme drastically increases the computation time and memory.

Comparisons between calculations, with and without azimuthal discretisation, have been performed for a 20-poisoned-pins homogeneous configuration (Fig. 20) and the 44-poisoned-pins mixed configuration mentioned above (Fig. 21). The results show a discrepancy up to 260 pcm for the homogeneous one, and around 1,000 pcm for the mixed one. In order to analyse precisely the impact of azimuthal discretization, according to heterogeneous or homogeneous configurations, another calculation has been performed for a heterogeneous configuration with 20 poisoned rods in a central single cluster; the discrepancy is about 425 pcm, to be compared to the 260 pcm for the homogeneous one.



**Fig. 20.** Reactivity with or without azimuthal discretisation for a homogeneous configuration with 20 rods poisoned with 8% of Gd.



**Fig. 21.** Reactivity with or without azimuthal discretisation for a mixed configuration with 44 rods poisoned with 8%w of Gd.

In each case, without the azimuthal discretisation the reactivity is under-estimated at beginning of cycle (due to an artificial over-consumption of Gd) and over-estimated during the Gd peak.

Therefore, for a preliminary optimisation of fuel assemblies, if the azimuthal discretisation is not strictly necessary for homogeneous configurations, it is clearly required, and used in this paper, to study heterogeneous and mixed configurations with such number of Gd rods.

The use of the interface current tracking method is also a discrepancy source, especially for heterogeneous and mixed geometries, because this method is not very accurate for treating the strong flux gradients of such configurations. Reference [27] shows an impact of around 300 pcm for a homogeneous configuration. It is expected that the impact is increased for a heterogeneous configuration. However, it is assumed that the impact is lower than the azimuthal discretisation one.

## 4.5 Conclusion

For two-batch cycle, the classic homogeneous configurations of Gd poisoning are well suited and enable to achieve quite good safety performances.

For the specific case of single-batch long-cycle core, new heterogeneous configurations of Gd inside the fuel assembly are proposed. They offer a powerful manner to control reactivity during the whole cycle. But, in order to adequately model such geometries, the calculation scheme has to be adapted to take into account an azimuthal discretisation.

## 5 Conclusions

Within the Flexblue<sup>®</sup> project, a soluble boron free core has been designed. Several manners to achieve cold shutdown have been explored and a compact CDM, including an anti-ejection device has been selected. An economic optimisation of core design and fuel has been performed, with two selected cores, functions of the size available in the containment. For the specific case of single-batch long-cycle, a new kind of heterogeneous fuel-assembly poisoning is proposed, which may enable an improved reactivity regulation, and so, power distribution in the core. These

configurations require adapted calculation scheme including an azimuthal discretisation of poisoned rods.

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