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**ARTICLE**

# Assessment of Enriched Uranium MOX Fuels for Plutonium Multi-Recycling in LWRs

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Since 2019, the French government has adapted its mid-term nuclear energy policy, introducing a milestone to demonstrate the industrial feasibility to manage successive recycling of the plutonium issued from PWR spent fuels. This work presents some prospective core studies, focusing on the introduction of a specific multi-recycling fuel, called MIX (for MOX, with enriched uranium support fuel), into the future EPR2 French fleet. Assessment of both 100% MIX and partial 60% MIX/UOX cycles is presented, and discussion of the associated equilibrium cycle characteristics is given. We showed that the MIX fuel can be very easily adapted to more degraded Pu vectors, without any need to change the core loading pattern.

***KEYWORDS: MIX, enriched uranium MOX, plutonium multi-recycling, PWRs***

## I. Introduction

The French fuel cycle currently implements the mono-recycling strategy, which consists in recovering reusable materials from spent Enriched Natural Uranium fuels (ENU), as Plutonium (Pu) and Reprocessed Uranium (RepU), so that they can be irradiated once again in some dedicated Pressurized Water Reactors (PWR) of the EDF fleet.

Uranium-Plutonium Mixed Oxide (MOX) and Enriched Reprocessed Uranium (ERU) are thus irradiated, resulting in around 20% natural uranium savings with respect to the open cycle. Nowadays, spent ERU and MOX fuels are stored awaiting later use, as strategic stock for Fast Neutron Reactor (FNR) deployment.

Since 2019, the French government has adapted its mid-term plutonium management policy, introducing a milestone to demonstrate the industrial feasibility of the plutonium multi-recycling in PWRs, while preserving the capability to deploy a future FNR fleet.[1)] An R&D program, involving the main French nuclear actors, was then organized to address the potential of new PWR fuel concepts (generically called MOX2 fuels) to manage successive recycling of the plutonium issued from PWR spent fuel, while reprocessed uranium continues to be recycled through ERU fuel.[2)] This option is called multi-recycling in PWR.

The expected benefits for plutonium multi-recycling in PWR are:

- The stabilization of the Pu inventory by choosing the appropriate reactor fleet equilibrium amongst Pu generation in UOX fuels and Pu consumption in MOX2 fuels.
- A solution for the recycling of spent MOX and ERU in current reactor technologies enabling to pilot the plutonium inventory with lower technological and planning risks, costs effectiveness. By reprocessing all types of spent fuels (ENU, ERU and MOX), to stabilize or adjust spent fuel inventories, thus decreasing the required interim storage capacities.
- A further reduction in the need for natural uranium resources compared to the current French mono-recycling option by over 20% more, corresponding to a saving of 40% compared to the open cycle. This also reduces carbon emissions of the nuclear industry as mining constitutes the main contributor, thus minimizing the environmental footprint.
- A significant step forward in the development of fuel cycle skills and technologies such as MOX reprocessing at industrial scale, or manufacturing of MOX fuels containing Pu from spent MOX.

The main difference when considering PWR multi-recycling compared to the current mono-recycling scheme is that the plutonium fissile content decreases along the multi-recycling process. Indeed, if the Plutonium used in currently loaded MOX comes from ENU spent fuel (with a fissile content at around 60-65%), spent MOX fuel assembly (FAs) exhibit a lower fissile content (around 51%), and MOX2 spent fuels can even reach lower fissile quality (around 47%). Due to its low fissile quality, the direct recycling of Pu from spent MOX is incompatible with an efficient and economic fuel cycle, resulting in shorter cycle length and/or larger number of fresh FAs to be loaded in the core. Therefore, the retained strategy consists in mixing Pu from both ENU and MOX/MOX2 spent FAs to reach a targeted Pu fissile quality.

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Two MOX2 fuel assembly options have been investigated: a standard MOX fuel with a lower plutonium fissile quality (<55%), known as MOX-MR for "MOX-Multi-Recycling" [2,3] and the MIX concept (a MOX with enriched uranium support), which is specifically considered in this paper[a]. Thanks to its similarities with the existing MOX standard technology, and the benefits from extensive manufacturing and reactor operation experience, the MOX-MR was chosen as the reference design, and extensively described in *C. Evans et al.* and G. *Vaast et al.*[2,3] The MIX concept, which requires a higher fuel qualification effort, is then considered as a longer-term multi-recycling option.

This work presents some prospective core modelling studies for plutonium multi-recycling in PWR, focusing on the introduction of the MIX fuel into the future EPR2 French fleet. After a short presentation of the work hypothesis and methods, this paper describes a few core cycles ranging from fully loaded 100% MIX cores to partial 60% MIX/UOX cores and highlights some of the main reactor challenges related to the introduction of MIX fuels. More precisely, this work showed that the core shutdown margin is one of the most challenging design criteria for MOX2 fuels, which may result in some reactor material modifications on the reactor reactivity control and the core shutdown system.

## II. Work Hypotheses and Input Data

**Figure 1** shows the radial structure of MIX FA, under an 8% Pu content (FA average) hypothesis. It recovers the structure of standard MOX fuel with a three enrichment zones to flatten the pin power map, in the case MIX fuels are placed close to UOX fuel. To be noted that even for cores fully loaded with MIX fuels, there is still an interest to keep this 3-zone structure, for instance in case of the unavailability of the MIX fuel (e.g. disruption of the fuel supply chain), requiring the replacement of fresh MIX fuel by fresh UOX fuel.

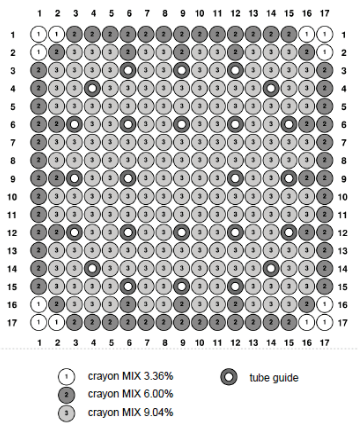


**Fig. 1** Schematic representation of the MIX FA

[a] The specific $^{235}$U enrichment depends on the initial Pu content and fissile quality, the core pattern and the desired discharge burnup. The range can vary from <1% up to 3.5% (2.1%<$^{235}$U<3.25% in this study).

**Table 1** gives the Pu characteristics for two kinds of MIX fuels. The MIX1 vector is representative of a better Pu fissile quality (beginning of the multi-recycling process), whereas the MIX2 one is more representative of the multi-recycling equilibrium phase. The Pu content was limited to 8% to significantly reduce the risk associated the to void coefficient feedback. For comparison purposes, the EPR2 FA MOX characteristics are also given in the last column. The fraction of fissile isotopes is calculated as follows: $(Pu^{239}+Pu^{241})/(Pu + Am)$.

**Table 1** Pu vector and MOX characteristics

| | MIX1 | MIX2 | MOX |
|---|---|---|---|
| Pu fissile quality | 53% | 49.5% | ~61% |
| Pu content (average) | 8% | 8% | 9.54% |
| Pu content (high) | 9.04% | 9.04% | 10.78% |
| Pu content (medium) | 6.00% | 6.00% | 7.15% |
| Pu content (low) | 3.36% | 3.36% | 4.04% |

Core loading pattern were established for 100% MIX cores (**Fig. 2**) and partial 60% MIX/UOX cores (**Fig. 3**).

In order to limit the pin internal pressure, the most irradiated MIX FAs (3rd cycle) were placed on the core periphery. The final arrangement resulted from an iterative optimization process taking into account several target design criteria, such as power pin factor, reactor shutdown margins, cycle length, Boron Concentration (BC), and Pu consumption (see. **Table 2**).

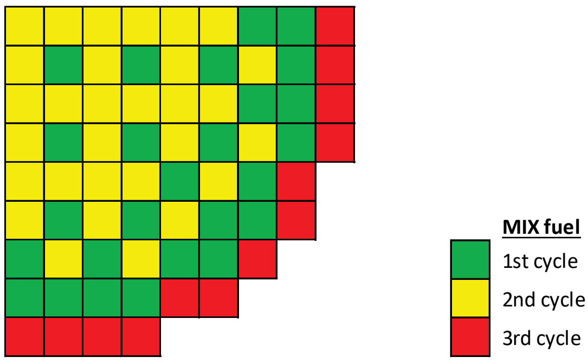


**Fig. 2** Core loading pattern for a 100% MIX core

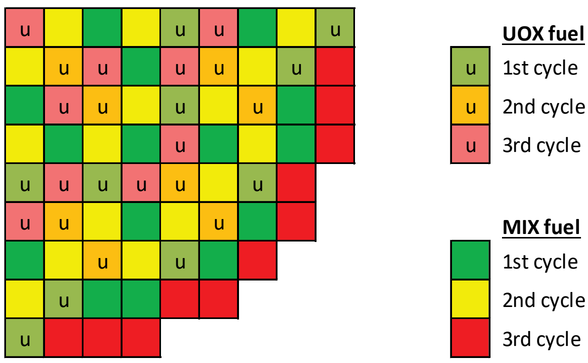


**Fig. 3** Core loading pattern for a 60% MIX core

**Table 2** Design criteria for core pattern with MOX2 fuels

| Criteria | target |
|---|---|
| Cycle length (including stretch) | > 470 EFPD |
| Radial power peaking factor (Fxy) | < 1.50 |
| Boron Concentration @BOCX | < 1500 ppm |
| Shutdown Margins @CZP / ARI-1 | > 4000 pcm |
| FA discharge burnup MIX | < 52 GWd/t |
| FA discharge burnup UOX | < 56 GWd/t |
| Pu consumption | > 0 kg/cycle |

Several core loading patterns and fuel characteristics were assessed:

- **100% MIX1** - A loading pattern with 100% MIX FA (MIX1 Pu vector).
- **60% MIX1** or **60% MIX2** - Two 60% loading patterns with MIX FA (with both MIX1 and MIX2 Pu vector).
- **60% ERU** - The same 60% MIX1 core loading pattern, where ENU was replaced by ERU.
- **60%_short MIX1** or **60%_short MIX2** - A shorter cycle length version for 60% MIX1 and MIX2 cycles.

## III. Results and Discussion

Core calculations were based on the CEA spectral code APOLLO2 and the EDF core code COCAGNE.[4,5)]

Main characteristics of the equilibrium cycles mentioned in the previous section, are given in **Table 3**. Colors in the figures have the following meaning: red indicates the physical quantity exceeds the limit given in Table 2, and green, indicates it complies with the design criteria.

In the case of mixed UOX/MIX core loadings (Fig. 3), ENU FA were set to 4.2% (standard $^{235}$U enrichment for EPR2) when targeting long cycle lengths (around 505 Equivalent Full Power Days) and to 3.7% for short ones (around 465 EFPD). Then, as the Pu content in MIX fuels is also fixed to 8%, the only variable parameter is the $^{235}$U enrichment of the MIX fuel, which was determined to meet the target cycle length. Finally, concerning the ERU variant (4$^{th}$ column of the table), the replacement of 4.2% ENU required a 4.95% ERU FA enrichment to keep the same cycle length, as the reprocessed Uranium contains larger amounts of $^{236}$U, a neutronic poison for PWR.

All the equilibrium cycles comply with the design criteria Fxy<1.50. Thanks to a specific choice of the Gadolinium poisoning (up to 16 Gd poison fuel pins), all the 60% MIX cycles fulfill the BC<1500ppm requirement. The MIX/ERU core pattern is slightly above the criteria, but it could be fixed by increasing the Gd content on some ERU-Gd FA. On the contrary, as the introduction of burnable poisons in MIX fuels is not allowed, this lever cannot be applied to the 100% MIX core pattern, which fails to comply with the BC limit.

Spent fuel discharge burnup is obviously related to the core cycle length, the average residence number of cycles, and the core loading pattern. For instance, although the cycle length is almost constant for all long cycle configurations, the MIX discharge burnup for 100%MIX is lower than for 60% MIX configuration due to a different average residence time (~2.5cycles vs ~2.87cycles). Consequently, for the considered 60%MIX core patterns, the MIX and UOX discharge burnup may not meet the French design requirements, which may lead to considerably shorter 60% MIX cycle (5$^{th}$ and 6$^{th}$ column).

Spent fuel composition mainly depends on cycle length and fresh fuel characteristics. Pu content from MIX spent fuel decreases from 8% to 6.7/6.9%. Also, the Pu fissile quality varies from 47.2% to 48.3% for the 60% MIX core patterns (depending on the initial MIX1/MIX2 vector), and 49.3% for the 100% MIX1 core pattern (here, the lower Pu degradation must be related to a lower discharge burnup). The residual $^{235}$U enrichment for spent MIX FA may still be quite high. It varies from 1.2% to 1.8% depending on the initial $^{235}$U content. In particular, the MIX2 cases which need a higher $^{235}$U support, still contain 1.7%-1.8% $^{235}$U, which however, will be recovered at the recycling phase.

The Pu consumption is, as expected, particularly high for the 100% MIX configuration (~740kg/cycle) and decreases to ~200/240 kg/cycle for the MIX/UOX cycle.

At first sight, the difference in plutonium consumption between the 100% MIX core and the 60% MIX core may appear larger than what might be anticipated from the MIX FA core fraction value. This discrepancy arises because, in the case of the 100% MIX core, all fuel assemblies contribute to plutonium consumption, whereas for the 60% MIX core, 40% of the core is loaded with ENU fuel assemblies which are net producers of plutonium. Indeed, in the 60% MIX core case about 440 kg/cycle of Pu are burned in the MIX fuel assemblies (~60% of the amount burned in a 100% MIX core), but at the same time, ~210 kg/cycle of Pu are produced in the 40% core fraction loaded with ENU FA.

When comparing the mono-recycling strategy using standard MOX FAs to multi-recycling strategy using MIX FA with similar core performances (approximatively the same cycle length and discharge burnup), the main difference concerns the characteristics of the spent MOX and MIX fuels, and obviously, the level of Pu consumption or production associated to the specific fuel core pattern. Indeed, the standard MOX fuel management (30% MOX and 70% ENU) exhibits a net Pu production (~50/60 kg/cycle) to be compared to a large net Pu consumption for MIX FA.

Secondly, the MOX spent fuel is quite different to the spent MIX fuel. The Pu fissile quality is higher (~51/52%, to be compared to ~47/49% for MIX1 or MIX2 Pu vector), and still exhibits a global Pu content of ~7.8% (to be compared to ~6.8% for MIX spent FA). This is related to the characteristics of the fresh fuel (see **Table 1**).

On the contrary, ENU spent fuels are not very different when discharged from 60% MIX or 30% MOX fuel core patterns. The Pu fissile quality is ~64/65%, for a global Pu content of ~1.3%.

**Table 3** Main characteristics of the Equilibrium cycles

| | | 100% MIX1 | 60% MIX1 | 60% MIX2 | 60% ERU | 60%_short MIX1 | 60%_short MIX2 |
|---|---|---|---|---|---|---|---|
| **Fresh MIX fuel** | Pu content | 8% | 8% | 8% | 8% | 8% | 8% |
| | Pu fissile quality | 53% | 53% | 49.5% | 53% | 53% | 49.5% |
| | $^{235}$U enrichment | 2.10% | 2.75% | 3.25% | 2.75% | 2.40% | 3.00% |
| **Fresh UOX fuel** | natural/reprocessed U | - | ENU | ENU | ERU | ENU | ENU |
| | $^{235}$U enrichment | - | 4.20% | 4.20% | 4.95% | 3.70% | 3.70% |
| | Cycle Length [MWd/t] | 18129 | 17946 | 18125 | 18124 | 16591 | 16527 |
| | Cycle Length [EFPD] | 507 | 503 | 507 | 507 | 464 | 463 |
| | Fxy max (> 150 MWd/t) | 1.48 | 1.49 | 1.45 | 1.45 | 1.47 | 1.44 |
| | BC @BOCX [ppm] | 1864 | 1440 | 1349 | 1559 | 1237 | 1143 |
| **Spent MIX fuel** | av. burnup [GWd/t] | 45.3 | 51.1 | 50.7 | 50.3 | 46.8 | 46.6 |
| | max. burnup [GWd/t] | 49.5 | 55.1 | 55.0 | 54.3 | 50.6 | 50.5 |
| **Spent UOX fuel** | av. burnup [GWd/t] | - | 52.0 | 54.1 | 54.8 | 48.9 | 48.7 |
| | max. burnup [GWd/t] | - | 55.9 | 57.3 | 58.0 | 51.8 | 51.7 |
| **Spent MIX fuel** | Pu content | 6.84% | 6.72% | 6.88% | 6.76% | 6.77% | 6.93% |
| | Pu fissile quality | 49.3% | 48.3% | 47.2% | 48.4% | 48.3% | 47.3% |
| | $^{235}$U enrichment | 1.17% | 1.47% | 1.77% | 1.49% | 1.34% | 1.70% |
| **Spent UOX fuel** | Pu content | - | 1.36% | 1.36% | 1.53% | 1.28% | 1.28% |
| | Pu fissile quality | - | 64.2% | 64.4% | 62.6% | 64.7% | 64.7% |
| | $^{235}$U enrichment | - | 0.79% | 0.80% | 1.20% | 0.73% | 0.73% |
| | Pu consumption [kg/cycle] | 738 | 241 | 215 | 207 | 234 | 204 |
| | Pu consumption [kg/TWhe] | 92 | 35 | 31 | 30 | 37 | 32 |

Finally, shutdown margins were computed at Cold Zero Power (CZP) conditions (**Table 4**) under the assumption that All Rods are Inserted beside the most efficient one (ARI–1). Aside the reference Rod Cluster Control Assemblies (RCCA) pattern with natural boron for the hybrid AIC/$B_4C$ rods, an alternative option with 50% $^{10}$B enrichment of shutdown RCCA was also assessed.

**Table 4** Shutdown Margins [pcm] - CZP (T=303°C) / ARI-1

| | 100% MIX1 | 60% MIX1 | 60% MIX2 | 60% ERU | 60%_short MIX1 | 60%_short MIX2 |
|---|---|---|---|---|---|---|
| natural $B_4C$ | 2018 | 3103 | 3152 | 2998 | 3292 | 3287 |
| 50% $^{10}$B $B_4C$ | 2686 | 3715 | 3760 | 3611 | 3900 | 3885 |

For the 100% MIX cycle it was impossible to meet the shutdown margins design criteria (set to approx. 4000 pcm at CZP conditions), even with the 50% $^{10}$B enrichment option. Indeed, all the shutdown rods are inserted – without any other possible choice – into a MIX FA, where the neutronic spectrum is harder and the absorber efficiency significantly reduced. The situation is different for the 60% MIX cycles, where the UOX FA can be placed under the RCCA positions, resulting in an enhanced shutdown efficiency. However, despite of those placement measures, it was still difficult to comply with the design criteria when considering the reference EPR2 RCCA with natural $B_4C$. On the contrary, the 50% enriched $B_4C$ option allows to improve by the initial shutdown margins by +600pcm, reaching ~3700/3900 pcm margin, which was considered by expert judgement to be enough at his stage.

Due to the insufficient core shutdown margins, the impossibility to master the BC at usual values, the 100% MIX core configuration was then abandoned. The 60% MIX configurations are so retained for better core management opportunities, higher shutdown margins, and lower BC during the reactor operation.

## IV. Conclusion

This work presented some prospective core studies, focusing on the introduction of the MIX fuel (MOX, with enriched uranium support fuel) into the future EPR2 French fleet.

Both 100% MIX and partial 60% MIX/UOX cycles were assessed, by optimizing the FA position, the fuel characteristics, the Gadolinium poisoning, and the reloading scheme.

Assessment of core shutdown margins revealed the difficulty to meet design criteria, mostly for the 100% MIX core, that was then abandoned. One 60% MIX/UOX core pattern, associated with the 50% $^{10}B$ enriched $B_4C$ option for shutdown RCCA was then retained.

We showed that the MIX fuel can be very easily adapted to more degraded Pu vectors (such as MIX2). Indeed, one just need to increase the $U^{235}$ support, without any need to change a proven core loading pattern, making it as a feasible option to address a longer-term multi-recycling strategy in PWRs.

## Nomenclature

AIC : Silver/Indium/Cadmium absorber
ARI : All Rod In
BOCX : Beginning Of Cycle – Xenon at Equilibrium
BC : Boron Concentration
CZP : Cold Zero Power
EDF : Electricité de France
EFPD : Equivalent Full Power Days
ENU : Enriched Natural Uranium
EPR : Evolutionary Pressurized Reactor
ERU : Enriched Reprocessed Uranium
FA : Fuel Assembly
FNR : Fast Neutron Reactor
MOX : (Uranium-Plutonium ) Mixed Oxide
MOX2 : Advanced MOX fuel for multirecycling
NatU : Natural Uranium
PWR : Pressurized (Light) Water Reactors
RCCA : Rod Cluster Control Assemblies
RepU : Reprocessed Uranium

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### References

1) Ministère de la Transition écologique et de la Cohésion des territoires, *Programmation pluriannuelle de l’énergie 2019-2023, 2024-2028*, (2020). [in French]
2) C. Evans et al, “Advances in Developing a LWR Multi-recycling System,” *Proc. IAEA Int. Conf. on the Management of Spent Fuel from Nuclear Power Reactors*, Vienna, Austria, June 10-14, 2024, paper IAEA-CN-323/113 (2024).
3) G. Vaast et al, “MOX and UOx Fuel Recycling in Pressurized Water Reactors,” *Proc. IAEA Int. Conf. on the Management of Spent Fuel from Nuclear Power Reactors*, Vienna, Austria, June 10-14, 2024, paper IAEA-CN-323/112 (2024).
4) R. Sanchez et al., “Apollo2 : year 2010,” *Nucl. Eng. and Technol.*, **42**[5], 474-499 (2010).
5) A. Calloo et al., “COCAGNE: EDF new neutronic core code for ANDROMÈDE calculation chain,” *Proc. Int. Conf. on M&C*, Jeju, Korea, April 16-20, 2017 (2017).