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PLUTONIUM RECYCLING IN PWR

G. YOUINOU, R. GIRIEUD, B. GUIGON
Commissariat à l'énergie atomique,
Saint-Paul-lez-Durances, France

Abstract

Two concepts of 100% MOX PWR cores are presented. They are designed such as to minimize the consequences of the introduction of Pu on the core control. The first one has a high moderation ratio and the second one utilizes an enriched uranium support. The important design parameters as well as their capabilities to multirecycle Pu are dicussed. We conclude on the potential interest of the two concepts.

1. INTRODUCTION

Recycling plutonium in standard PWRs using 100% MOX loadings brings about a degradation of the control mean efficiency. Different solutions exist, in order to mitigate this effect, and have to be analyzed and compared. One possibility could be to increase the moderation ratio (Highly Moderated Reactor concept). Another way of improvement, while using a standard PWR, is to limit the plutonium content in the reactor, which means that to reach the target burnups, enriched uranium must be used (MIX concept). Other possibilities, like the APA [1] (Advanced Plutonium Assembly) concept are, as well, under study at CEA. This paper presents the analysis of the MIX and HMR concepts performed with the codes APOLLO2 (preparation of the group constants) and CRONOS2 (3D diffusion and fuel management).

One must notice that the MIX and HMR belongs to different strategies. The MIX belongs to a 'dilution' strategy, i.e. each reactor of the park contains Pu. In particular, it is shown that a PWR core with a 100% MIX loading characterized by a 2% Pu content has a zero Pu mass balance. On the other hand, the HMR is designed to burn as much Pu as possible and must be fed with Pu coming from UOX cores.

2. HYPOTHESIS

The MIX has been developped so that Pu can be recycled in a standard 1300 MWe reactor without any modifications, whereas the HMR has been designed so that it is compatible with the 1450 MWe EPR (European Pressurized Reactor) vessel.

A 3x18 months fuel management is considered, corresponding to average discharge burnups of, respectively, 45 Gwd/t and 66 Gwd/t for the MIX and for the HMR. The Pu isotopic composition considered (Table I) represents the average Pu that will be available in France around 2015; it takes into account the Pu coming from UOX as well as MOX. The results obtained with different fuel managements and Pu isotopic compositions are presented in Ref. [2] and [3].

TABLE I. PLUTONIUM ISOTOPIC COMPOSITION CONSIDERED IN THE STUDY

Pu^{238}	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}
2.7	56.0	25.9	8.1	7.3

3. ASSEMBLY CHARACTERISTICS

3.1. The MIX assembly

The main interest of the MIX concept is that no modifications of neither the assembly nor the vessel are necessary. Thus, the data concerning the geometry of the MIX assembly come from the standard 1300 MWe EdF (Electricité de France) reactors, i.e. a 17x17 lattice with a 1.26 cm pitch and 25 water holes. Each assembly contains 535 kg of heavy metal (HM), and the specific power is 36.8 W/g. The U^{235} enrichment necessary to meet the fuel cycle length requirement is calculated for different Pu contents. It is found to be an almost linear function of the Pu content, going from 4.0% U^{235} for 0% Pu (i.e. UOX fuel) to 0.25% U^{235} (i.e. tail uranium) for 9.5% Pu.

As shown on Fig. la and b, the reactivity coefficients (fuel and moderator temperature coefficients and boron efficiency) deteriorate up to 4% Pu, and then stabilize, except for the boron efficiency which keeps decreasing. In order to keep some control margin, the boron efficiency should not be lower (in absolute value) than -4 pcm/ppm which sets the limit on the Pu content at 4%. The uranium support must be enriched up to 2.5% U^{235} in order to fullfill the fuel cycle requirement (3x18 months).

3.2. The HMR assembly

A parametric study carried out to assess the effect of the moderation ratio demonstrates the strong impact on the reactivity coefficients. For example, in a 100% MOX core, the increase of the moderation ratio from 2 (standard PWR) to 4, brings about an increase of the boron efficiency by a factor 2.5, and a 20% decrease on the doppler coefficient. The moderator temperature coefficient becomes less negative as well. The main cause is the difference in the Pu inventories: increasing the moderation ratio provokes a 60% decrease of the Pu mass in the assembly (for a similar fuel management). Furthermore, the moderation ratio must be as high as possible in order to improve plutonium consumption and reduce minor actinide production

However the safety criterion concerning the nucleated boiling crisis sets limits on the surface heat flux released by the fuel rods. Thus at constant power, a geometry of the 17x 17 type cannot be retained for moderation ratios higher than 3.1. But in turning to geometries of the 19 x 19 type (while retaining the external dimensions of the fuel assemblies), a moderation ratio of 4 can be reached. The latter configuration was chosen; it is characterized by a fuel pellet diameter of 6.12 mm and a 1.13 cm pitch. In this situation the neutron spectrum is thermalized but it remains characteristic of a MOX fuel. The specific power is high (56.6 W/g) and the Pu content necessary to meet the fuel cycle length is 9.7% (tail uranium is used, i.e. 0.25% U^{235}). Compared with a 17x17 assembly with a moderation ratio of 2, the 19x19 assembly chosen contains 40% less HM, i.e. 3 12 kg per assembly. Among the various solutions studied, the lattice containing 81 guide tubes (Fig. 2) presents the best power flattening within the assembly owing to the regularity of the lattice.

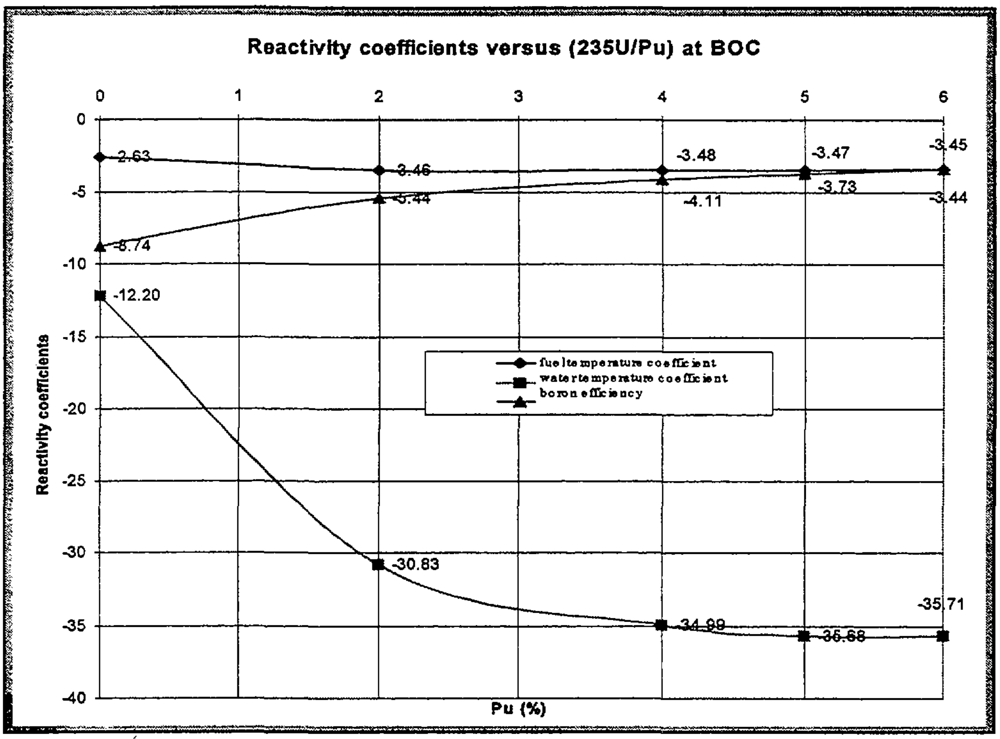

FIG.1A. Reactivity coefficients (at 150 MWd/t) vs. the Pu content

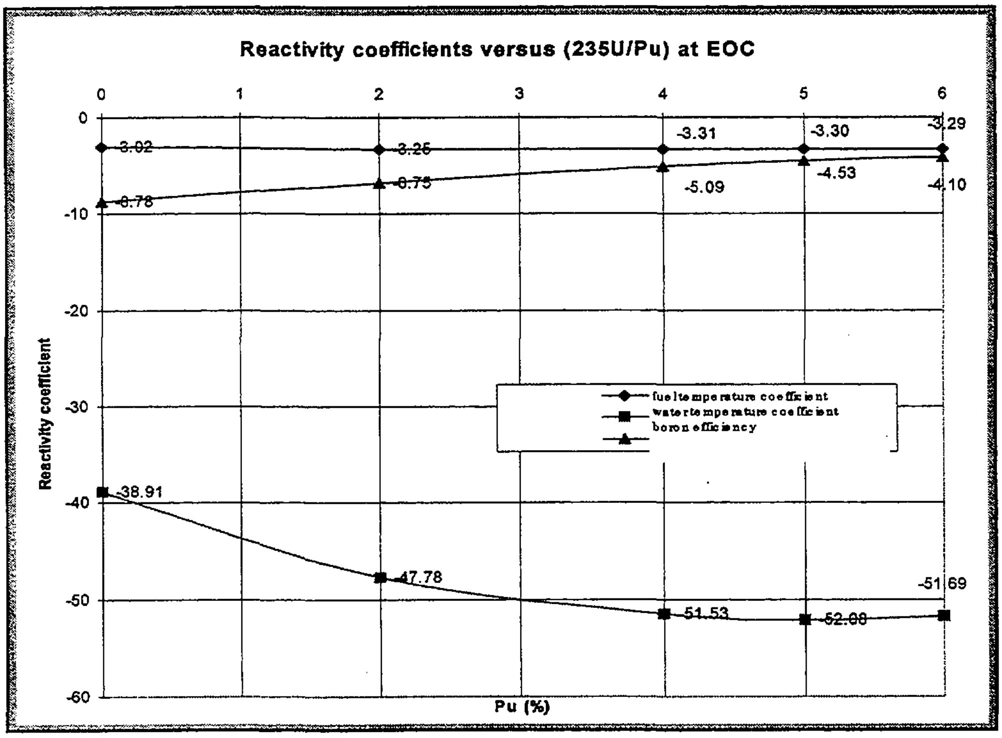

FIG.1B. Reactivity coefficients (at 45000 MWd/t) vs. the Pu content

4. MASS BALANCES

The Table II gives the Pu and MA (Minor Actinides) consumption for the two concepts. Furthermore, for the MIX, the needs in natural uranium as well as SWU (Separation Work Units) are compared to those of a reference 1300 MWe UOX core (3x18 months).

In the MIX, the gain in terms of SWU is important compared to the UOX (factor of 2). Furthermore, the U^{235} residual enrichment is not negligible, i.e. 1.14%; only 55% of the U^{235} is actually fissionned compared to 80% in the UOX. The MIX Pu burning rate is 25 kg/TWhe, however 41% is transmuted into MA (10.3 kg/TWhe). The HMR uses tail uranium, thus the needs in natural uranium and SWU are moot points. The interest of the HMR is highlighted by its capability to fission Pu. Of the 80.3 kg/TWhe of Pu destroyed, only 12.8% is transmuted into MA (10.3 kg/TWhe). The parametric study showed that the higher the moderation ratio, the smaller the MA quantity produced. At each cycle (i.e. 18 months), one third of the assemblies are changed, which means that 34.2 tons and 24.9 tons of HM are reloaded, respectively, in the MIX and in the HMR.

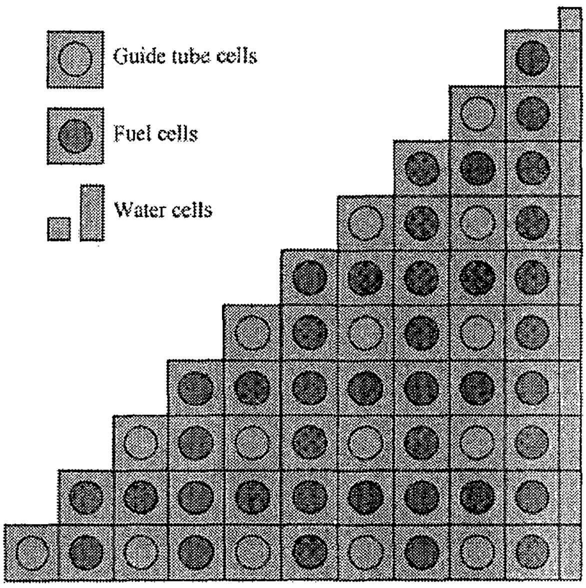

FIG. 2. 19×19 assembly, 81 guide tubes, $V_{mod} / V_{fuel} = 4$

TABLE II. MASS BALANCES FOR THE MIX, HMR AND A REFERENCE UOX WITH 3X18 MONTHS FUEL MANAGEMENT

Reactor Type	*Teneur Pu (%)*	*U^{235} enri. (%)*	*U^{235} resi. (%)*	*Δ Pu (kg/TWhe)*	*Δ A.M. (kg/TWhe)*	*U_{nat} (kg/tHM)*	*SWU (kg/tHM)*
UOX	0	4.0	0.85	+ 30.1	+ 3.6	8152	5839
MIX	4.0	2.53	1.14	- 25.0	+ 10.3	4956	2903
HMR	9.7	0.25	-	- 80.3	+ 10.3	-	-

5. CORE CHARACTERISTICS

The MIX and HMR cores contain, respectively, 193 and 241 of the assemblies described above. The soluble boron (B_{nat}) concentrations, the reactivity coefficients and the control rods' efficiency (from full power to hot shutdown) are given in Table III.

In a UOX core some of the control rods are weakly absorbant ('grey' clusters) whereas some are strongly absorbant ('black' clusters). This is designed in order to limit the perturbation on the flux, and limit the probability of any unstabilizing xenon-induced oscillations. Since the xenon capture rate is significantly smaller in a Pu loaded core than in a UOX core, we consider that all the clusters are made of strongly absorbant materials. For the

MIX the control and shutdown rods (65 clusters) are made of $B_{nat}4C$[1]. For the HMR the 33 control rod clusters are made of Hafnium whereas the 72 shutdown rod clusters are made of $B_{nat}4C$.

When the reactor is brought from its hot shutdown state to its cold shutdown state, characterized, respectively, by isothermal core temperatures of 296°C and 20°C, the reactivity increases. The safety authorities require that the reactor must be at least subcritical by 5000 pcm when it is in its cold shutdown state; as a consequence boron must be added to the moderator but should not, however, exceed the limit of 2500 ppm because recrystallization might then occur in auxilliary circuits. The calculations performed for the most penalizing situation, i.e. BOC, showed that 1470 ppm are sufficient to meet the safety criteria in the HMR, whereas the MIX needs 2645 ppm. Slightly enriched soluble boron or burnable poison should then be used in the MIX.

TABLE III. CORE REACTIVITY COEFFICIENTS AND CONTROL RODS' EFFICIENCIES

	MIX		HMR	
	BOC	EOC	BOC	EOC
C_{boron} (ppm)	1820	0	1500	0
α_{Tfuel} (pcm/°C)	-3.3	-3.4	-2.2	-2.1
α_{Tmod} (pcm/°C)	-24.9	-55.0	-15.1	-57.6
α_{Cboron} (pcm/ppm)	-3.8	-4.6	-5.8	-8.0
Reactivity at hot shutdown (pcm)*	-6210	-5780	-9685	-11070
Most effective cluster (pcm)	970	1210	3910	4620

* calculated as $(k_{eff}-1)/k_{eff}$ - all clusters inserted

6. ACCIDENTAL SITUATIONS

6.1. Control rod ejection

This accident has been analyzed at full power and zero power (critical reactor in both cases). For both the MIX and the HMR, the reactivity inserted is larger at zero power than at full power. The reactivity inserted is not very large, 380 pcm (0.7$) for the MIX and 320 pcm (0.9$) for the HMR. The same calculations performed with a UOX core (control clusters in Silver-Indium-Cadmium, shutdown clusters in B4C) results in a reactivity insertion of 280 pcm (0.5$).

6.2. Cooling transient

An unexpected valve opening leads to an overcooling of the core and to an increase of the reactivity. The reactor initially in its hot shutdown state, with the most effective cluster supposedly blocked out of the core, should not go critical during the 15 minutes necessary to the operator to stop the cooling. The calculations were performed at EOC since the moderator temperature coefficient is more negative. The analysis showed that this accident leads to an approximately 2500 pcm reactivity increase for the two concepts; neither cores go critical. However, if penalties of 10% are taken into account for all the parameters involved (reactivity

[1] Because of the swelling occuring in B4C rods, the control clusters should be changed every 3 years

coefficients, temperature, and moderator density) then the cores can go critical. For comparison, the reactivity increase calculated for a UOX core is about 1200 pcm.

7. MULTIRECYCLING CAPABILITIES

7.1. Multirecycling Pu in the HMR

The HMR is initialy loaded with Pu coming from UOX reactors (Fig. 3), i.e. containing about 64% fissile Pu. The Pu degrades very rapidly and at the end of the first cycle it contains already only about 39% fissile Pu. As a consequence, the Pu content must be increased as well; It goes from 10.1% for the first cycle to 13.7% and 16.1% for the second and third cycles. After 10 cycles, 25% Pu are needed, which is not realistic vis-à-vis the void coefficient; hence the number of recycling might be limited to two. Furthermore, the proportion of the Pu transmuted into MA, instead of fissionning, increases: 15% for the first cycle, 21% and 24% for the second and third cycles. The fraction of HMR necessary to balance the Pu production from UOX remains about constant: between 15 and 20%. The gain in terms of SWU is about 20% compared to a 100% UOX park.

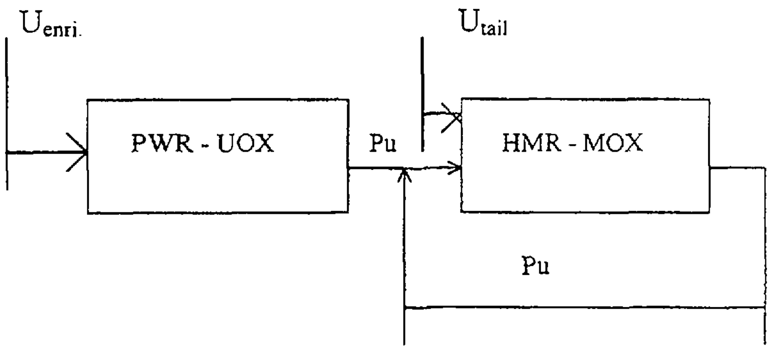

FIG. 3. Pu multirecycling scheme with the HMR

7.2. Multirecycling Pu in the MIX

As said in the introduction, the Pu management with the MIX implies the dilution of this Pu in all the reactors of the park (Fig. 4), i.e each reactor takes care of its own Pu. The Pu content corresponding to a zero Pu mass balance is about 2%; above this value the reactor burns Pu, whereas below this value it produces Pu. At equilibrium, the U^{235} enrichment needed to meet the fuel cycle length requirement (3x18 months - 45 Gwj/t) is about 3.4% compared to 4% for a UOX 3 x18 months. The gain in terms of SWU is about 20% compared to a similar park made up of only UOX cores. Hence, from a physics point of view, Pu management in MIX cores is an attractive solution for the short term.

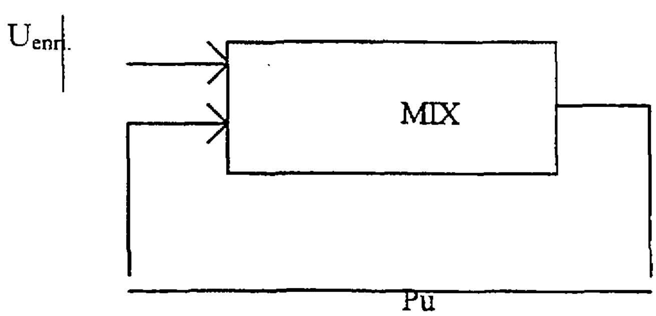

FIG. 4. Pu multirecycling scheme with the MIX

8. CONCLUSIONS

Introducing large amounts of Pu in a standard PWR core brings about penalties, especially on the control mean efficiency. Two solutions allowing to recycle Pu in a PWR and in the same time limit the consequences on the core control are presented. The first one (HMR) uses a high moderation ratio together with a tail uranium matrice and the second (MIX) uses a standard 17x17 assembly and an enriched uranium matrice. The two cores are characterized, and no major problems forbidding their realizations show up. In the MIX strategy, the Pu is diluted in all the reactors of the park, whereas the HMR must fed by Pu coming from UOX. The Pu multirecycling capabilities are assessed and show that the Pu content must be increased rapidly in the HMR because of its degradation; only two recycling might be allowed. In the MIX, the multirecycling is feasible: the Pu content stabilizes at about 2% and the U^{235} enrichment is 15% lower than in the corresponding UOX core.

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