ADVANCED PLUTONIUM PWR FUEL ASSEMBLIES R&D IN FRANCE

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ABSTRACT

Management of the plutonium cycle associated with the fuel, and the fuel itself since it is continuously renewed so that improvements can be made to it in the short or medium term, play an important role in optimizing existing reactors and in achieving ambitious objectives for the use of natural resources, the management of ultimate waste and control of the plutonium inventory.

After it decided that the fast neutron reactor system was not going to expand as quickly as initially predicted, France committed itself towards recycling plutonium in pressurized water reactors as earlier as 1987.

A major R & D program was started in the mid 1970’s with critical mock-up experiments (EOLE, MINERVE) and irradiation experiments followed by post-irradiation examinations of experimental rods in test reactors and then in power reactors.

The first MOX assemblies were loaded into a 900 MWe PWR in 1987 to achieve a balanced cycle three years later.

Since then, the R & D program undertaken by the CEA in close relation with the industrialists concerned (EdF, Framatome-ANP, COGEMA) has been aimed at achieving identical management of MOX assemblies and standard UO$_2$ assemblies.

This first step has now been completed successfully, and the CEA is now committed to an R & D program intended to move on to plutonium management with multi-recycling in existing or future pressurized water reactor (EPR). Two systems are being examined in parallel.

The first system, CORAIL, maintains the 17x17 structure of the existing assembly, but due to a new layout of MOX rods in the assembly, will change to use cores in which all assemblies will be of the same type with plutonium. This new core management could be used in reactors by the middle of the next decade, due to its smoothly evolutionary nature.

The second system, APA, can be used to introduce plutonium fuels on an inert matrix. This could modify the mechanical structure of the assembly and the geometry of the rods themselves (annular or cross-pattern rod layout, etc.) while maintaining, as far as possible, external compatibility. The planned developments will require more validation work than the previous case, followed by a core management change in the 2020 – 2030 decade.

Scenario studies based on the different core cycle management systems studied show that multi-recycling of plutonium in pressurized water reactors is a means of stabilizing the plutonium inventory in French power stations (CORAIL), or even reducing it with more innovative core management systems (APA).

Keywords: advanced MOx fuel in PWR, R&D on MOx fuel in France, fuel cycle, plutonium management, waste management.

I. INTRODUCTION

Since 1987, the French policy concerning the plutonium has been to recycle it once in 900 MWe PWRs loaded with about 30% of MOX assemblies. That policy slows down the accumulation of plutonium, but does not balance the production and consumption. In the meantime, the CEA has been studying different options to stabilize France’s plutonium stockpile through multirecycling in reactors.

Some of these options involve only PWRs. The MIX fuel assembly (CORAIL assembly, ref. 1) is a standard 17x17 assembly in which the plutonium is blended with an enriched uranium support (U$_{enriched}$O$_2$-PuO$_2$). The APA assembly [2] is an evolutionary 17x17 assembly: it contains standard enriched UO$_2$ fuel rods together with large annular plutonium rods (PuO$_2$-CeO$_2$) providing a large local moderating ratio favorable to the burning of plutonium.

A large amount of results have already been accumulated and studies are still under way, investigating other options, in order to provide as soon as possible, a set of consistent solutions for short, medium or long term scenarios. In the framework of short term solutions, the
CORAiL concept, which will be presented in detail in this paper, is a standard 17×17 PWR fuel assembly made up of 180 standard enriched UO₂ fuel rods and 84 MOX fuel rods disposed at the periphery. The characteristics of the fuel assembly and of a 1300 MWe reactor loaded with such assemblies are described, together with a scenario of multirecycling.

Compared to the CORAIL concept, the aim of APA concepts is to still better improve the use of Pu in PWRs, while minimizing minor actinide production, with only slight modifications in the core design. The design, the initial neutronic and thermal hydraulic studies were published in [3,4]. In the “Charpin Dessus Pellat report”[5] and according to the National Evaluation Commission (CNE) in charge of evaluating these studies, APA concepts have been considered as scenarios allowing a stabilization of Pu inventory in medium term. This paper presents the wide range of APA concepts which may be considered in PWRs from a strictly physical point of view to quantify fuel characteristics and to guide preliminary feasibility assessments, while taking into account that the technological feasibility is currently premature. The potential of the innovative assemblies was investigated to determine the influence of the Pu and MA mass fluxes, by simulating multi-recycling scenarios supplying a 60 GWe power plant composed of current PWRs (1300MWe PWR) or of future PWRs (European Pressurized Reactor of 1450 MWe), loaded with such assemblies. If we want to drastically decrease the radiotoxicity of the spent fuel, the complete recycling of Pu is the preliminary condition followed by that of Am and Cm. Investigations have been carried out on Pu+(Am+Cm) multi-recycling with APA PWRs [6,7,8].

II. DESCRIPTION OF THE CORAIL ASSEMBLY AND CALCULATION SCHEME

When designing the CORAIL assembly, special care had to be given to the power distribution inside the assembly because of the presence of two fuel types having different neutronics properties. A compromise had to be found between the number of MOX fuel rods and their location, the amount of plutonium loaded in the MOX rods, and the enrichment of the UO₂ rods. The results of this first optimization phase, which are presented in Ref. [9], showed that in order to mitigate the hot-channel factor (ratio of the power released in the hottest channel of the core to that of the average channel), the MOX fuel rods should be located at the periphery of the assembly, where the thermal neutron flux level is the lowest. Furthermore, 84 MOX fuel rods seemed optimum. The reference CORAIL assembly geometry is displayed on Figure 1.

As in most nuclear reactor design studies, the CORAIL neutronics calculations are done in two steps. The first step, carried out with the collision probability code APOLLO2 [10], consists of a detailed description of the assembly in which each pin is taken into account individually, and the assembly is surrounded by an infinite array of similar assemblies. These calculations are performed with the 172-group CEA93,V4 library derived from JEF2.2 data. The assembly calculations provide the pin-by-pin power distribution ($P^{\text{micro}}$), as well as assembly-homogenized 2-group constants necessary for the second step.

The second step, carried out with the code CRONOS2 [11] together with the group constants created previously, consists in solving the neutron diffusion equation with the finite element technique, and taking into account the actual 3D core geometry of a 1300 MWe EDF (Electricité De France) reactor. In addition, CRONOS2 includes a simplified 1D thermal-hydraulics module to account for the feedback effects. The core calculations provide the assembly-by-assembly power distribution ($P^{\text{macro}}$), as well as the critical boron concentrations, the reactivity coefficients, and the shutdown margins.

An important design issue is the power distribution in the core and the minimization of the hot-channel factor. The latter should be close enough for both the CORAIL and the reference UO₂ cores, in order to ensure a proper cooling. With the adopted calculation model, the hot-channel factor is the product of the microscopic hot-channel factor obtained with APOLLO2 ($P^{\text{micro}}$,max), and the macroscopic hot-channel factor obtained with CRONOS2 ($P^{\text{macro}}$,max, also called $F_{\text{XY}}^{\text{assembly, max}}$). Hence, for a constant hot-channel factor, the higher the $P^{\text{micro}}$,max, the lower the $F_{\text{XY}}^{\text{assembly, max}}$ has to be.

III. CORAIL CORE CHARACTERISTICS AND PLUTONIUM BURNING CAPABILITIES

Three 1300 MWe cores at equilibrium were calculated: two different CORAIL cores (V1G1, V2G2) together with a reference UO₂ core representative of an actual plant operating on a 3×18 months fuel cycle length (all 1300 MWe reactors in France operate with this fuel cycle called GEMMES). The core is made up of 193 427-cm-high assemblies whose characteristics are presented in §4. In the reference UO₂ core, 20 assemblies, out of the 64 of the reload, contain 12 UO₂-Gd₃O₅ rods in order to limit both the soluble boron concentration and the hot-channel factor. On the other hand, the utilization of burnable poison in the CORAIL cores was not investigated, in this first round of calculations. The three loading patterns are based on “out-in” fuel management, i.e. the fresh fuel assemblies are located at the periphery.

A total of 65 reactivity control cluster assemblies (RCCA) are used to control the reactivity from full power to cold shutdown; 53 of these RCCA are made of 24 B4C rods with the lower part (102 cm) in AIC, whereas 12 RCCA are made of 8 AIC rods and 16 steel rods.

When all the RCCA are outside the core, the boron concentrations necessary to be just critical at BOC (Beginning Of Cycle), saturated xenon, are respectively 1631 ppm, 1516 ppm and 1400 ppm for V1G1, V2G2 and the reference UO₂. The $F_{\text{XY}}^{\text{assembly, max}}$ decreases between BOC and EOC (End Of Cycle) from 1.33 to 1.24 for V1G1 and from 1.30 to 1.26 for V2G2. For the reference UO₂ core, it goes from 1.27 to 1.26. Hence, the hot-channel factors ($F_{\text{XY}}^{\text{assembly, max}} \times P^{\text{micro}}\text{,max}$) are higher in the V1G1 (V2G2) than in the reference UO₂ core, by 17% (12%) at BOC and 5% (7%) at EOC. This is not considered too
much of a problem, since the utilization of burnable poison (not considered here) will improve the situation.

The calculated cycle lengths are somewhat shorter than expected: 14205 MWd/t instead of 15000 MWd/t for G1, and 12943 MWd/t instead of 13750 MWd/t for G2. The enrichments should be increased from 4.15% to 4.35% for G1 and from 4.91% to 5.25% for G2. Hence, with the enrichment limit of 5%, it seems difficult to go beyond about 52000 GWd/t for the second recycling of the Pu “2016”. The feasibility to extend the burnup by increasing both the U\(^{235}\) enrichment and the plutonium content, while still respecting the constraint on the hot-channel factor, is an important issue that will have to be examined carefully.

As far as the safety margins are concerned, the last point to be checked is the possibility of bringing the core subcritical by 1000 pcm without the RCCA, and with a soluble boron concentration below 2500 pcm. The calculated boron concentrations for V1G1 (V2G2) at BOC are, respectively, 2033 pcm (2009 pcm) and 2298 pcm (2435 pcm) at hot and cold shutdown. For the reference U\(_{2}\) core, the necessary boron concentrations are about 1700 ppm and 2000 ppm at hot and cold shutdown.

Finally, the margins calculated for the CORAIL cores are similar to those of the reference U\(_{2}\) cores, and the utilization of burnable poison necessary to limit the hot-channel factor will further improve the situation by decreasing the soluble boron concentrations at BOC.

The principle of the plutonium multirecycling is schematized on figure 1. It represents a 60 GWe PWR park loaded only with CORAIL assemblies, producing 400 TWhe per year, and recycling the totality of the plutonium. The U\(^{235}\) enrichments are calculated so as to reach a 3×15000 MWd/t cycle (3×18 months fuel cycle). Furthermore, a two-year aging time between reprocessing and BOC, and a five-year cooling time between EOC and reprocessing are taken into account. The plutonium losses at reprocessing amount to 0.1%.

With an average burnup at discharge of 45000 MWd/t, and an energy produced of 400 TWhe/year, the annual amount of fuel to be fabricated is 1089 tHM, whatever strategy is used (open cycle or reprocessing). In the case of a reference 100% U\(_{2}\) park, it is 1089 tHM of U\(_{2}\) fuel, whereas for a 100% CORAIL park it is 742.5 tHM of U\(_{2}\) fuel and 346.5 tHM of MOX fuel. As a remainder, the MELOX fabrication plant has a yearly MOX output capacity of 100 tHM that could be expanded to 250 tHM without any major modifications. The average burnup at discharge would have to be increased up to 62000 GWd/t (i.e. ~ 4 × 18 months) in order to need only 250 tHM of MOX fuel per year.

Averaged over the 7 recyclings, the CORAIL park necessitates about 15% less SWU (Separating Work Units) and 20% less natural uranium than an all-U\(_{2}\) park. On the other hand, the production of minor actinides is larger than for an all-U\(_{2}\) park. It is between 6.7 kg/TWhe (1\(^{st}\) recycling) and 8.8 kg/TWhe (7\(^{th}\) recycling) for the CORAIL park, compared with 3.6 kg/TWhe for the all-U\(_{2}\) park.

The overall annual amount of transuranics (plutonium + minor actinides) to the waste disposal is divided by almost a factor of 4 (from 13.6 tHM/year to 3.5 tHM/year) compared with the all-U\(_{2}\) park (Table 1). However, the amount of transuranics in the CORAIL cores stabilizes at about 130 tHM, whereas the amount immobilized at the fabrication and reprocessing plants are, respectively, about 55 tHM and 155 tHM. Hence, after, for example, 80 years of operation, the CORAIL and the all-U\(_{2}\) parks will have accumulated, respectively, about 620 tHM and 1100 tHM of transuranics, i.e. a decrease of 44% in favor of the CORAIL park.
IV. CONCLUSION

The recycling of plutonium has been a reality in France since 1987. However the present policy of monorecycling does not stop its accumulation, but only slows it down. Hence, studies are under way to demonstrate that it is possible to stabilize the plutonium inventory using only existing PWRs. Among the solutions which are proposed, some are very attractive from a neutronics point of view, but still necessitate development and testing (for example APA), while others, though less attractive, make only use of available technologies. The CORAIL assembly, which is in the latter category, is a standard 17×17 assembly containing 180 UO₂ rods and 84 MOX rods located at the periphery.

The results presented in this paper show that it is possible to stabilize the plutonium inventory in an all-CORAIL park operating on a 3×18 months fuel management. The plutonium content in the MOX rods reaches about 8% at equilibrium, whereas the enrichment of the UO₂ rods is about 4.8%. The MOX fabrication needs are about 345 tHM/year. Averaged over 7 recycles (i.e. about 80 years of operation) the gain on the SWU and natural uranium are, respectively, 15% and 20%. The mass of transuranics (plutonium + minor actinides) to the waste is divided by almost a factor of 4 : 13.6 tHM/year for the all-UO₂ park and 3.5 tHM/year for the all-CORAIL park.

The important characteristics of 1300 MWe PWRs loaded only with CORAIL assemblies, together with a reference 3×18 months UO₂ core, have been determined with 3D diffusion calculations. The reactivity coefficients and the shutdown margins of the CORAIL cores do not show any particular differences to those of the reference UO₂ core. Enriched boron will not be necessary either in the moderator or in the shutdown RCCA. However, the utilization of burnable poison will be imperative in order to limit the hot-channel factor which can otherwise be up to 17% larger than in the reference UO₂ core.

With the APA concepts, the results presented in the parametric study show that the stabilization of Pu inventory could be satisfied by a 100% APA-a-36 or a 100% APA-r-128 cores fraction around 31.8% and 36.2%, respectively. This study shows the interest of the over moderation for plutonium burning. The APA-a-36 concept with the highest moderator ratio exhibits the best performances. It is not possible to achieve the level of APA-a moderation with the APA-r concept for a technical reason. Averaged over 8 recycles (over 80 years of operation), the savings in natural uranium and SWU due to the introduction of APA PWRs in the nuclear park range from 25% to 15% depending the number of recycle and scenario used.

Pu management is the major problem. However, Pu management, both to stabilize inventories or decrease them, has to be viewed in connection with the minimization of the MA production. The incineration of Americium and Curium in the APA PWR by mixing (Am+Cm) with Pu (Np was not considered) was envisaged. The stabilization of Plutonium and (Am+Cm) inventories by multi-recycling requires less than 40% APA PWRs in a conventional PWRs park. The Pu and (Am+Cm) recycling involves an increase of the fraction APA PWRs lower than 8%.

Despite of the complexity of the operations, the multi-recycling of Plutonium and Minor Actinides in PWRs with APA concepts represents a real contribution to the solution of the major problem of long-lived waste in the future. Qualification of this design must be completed by neutronic core studies and accidents involving thermal-hydraulics, thermo-mechanics, and mechanics. Longer term research involves the use of APA reactors in order to multi-recycle Pu, and some long-lived waste for radiotoxicity reduction. It was thought to be a challenging technical task, and R&D must be undertaken to assess the technical feasibility of the APA concepts.

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