PLUTONIUM RECYCLING THROUGH LWR MOX FUEL: TODAY AND TOMORROW

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Abstract

Recycling operations have been mastered for long in France, from the plutonium separation to the irradiation of MOX fuel, as France committed itself towards recycling plutonium in PWRs since 1987. Today, the French reactors using MOX are operated according to fuel management allowing equivalent performance of energy supplied with the same reliability as those using UO_2 fuels.

The paper first presents the experience feedback obtained up to 65 GWd/tHM (rod average). Fuel microstructural evolutions under operations as well as the behavior of fission products have been thoroughly examined. A somewhat higher fission gas release is observed compared to UO_2 fuel mainly due to the higher power levels of the MOX fuel and its more heterogeneous microstructure. To keep the parity with UO_2 in the future, MOX evolution based on advanced microstructures is considered to provide the required performance. In that respect, the CHROMOX microstructure obtained by Cr_2O_3 doping shows an enhanced homogeneity notably with smaller primary blend agglomerates and increased matrix grain size. With these evolutions, internal pressure margins are anticipated and better retention of gaseous fission products in accidental conditions by reduction of restructured areas.

To sustain the use of MOX fuel in the future, the second part of the paper presents the adaptations to be implemented at the MELOX production plant to face the inherent degradation of the Pu isotopic vector of MOX fuel and its higher Pu content from increased core management cycle length.

In addition, Pu multi-recycling strategies in LWRs are studied with new fuel technologies. In order to be able to use low quality Pu in a PWR spectrum, fissile uranium needs to be added. With the CORAIL-A option, developed by Framatome and Orano, the assembly contains about half of MOX fuel rods and the remaining as UO_2 rods. By contrast, the MIX fuel assembly contains only MOX rods with an enriched uranium matrix that compensates the Pu degradation. Development of those fuel technologies, that could be coupled with the most advanced Framatome fuel assembly design GAIA, will offer flexibility to switch to future technically and economically robust advanced cycles in current or future LWRs with a limited impact to the reactor design and its performance. These developments will allow implementing efficient solutions bridging the gap with the potential development of GEN IV reactors.

1. INTRODUCTION

Plutonium recycling through MOX fabrication and irradiation in Light Water Reactors (LWRs) is a proven industrial solution with both fuel design and supply chain well mastered. The R&D efforts have allowed enhancing the performance and meeting utilities requirements, i.e. MOX parity with UO_2 fuel in reactors in a complete safety approach, especially at high burnup.

Though the situation is highly satisfactory, especially in France, Framatome and Orano are both committed to improve the MOX fuel product technology. A special development effort was invested to change the MOX fuel pellet microstructure for enabling a better distribution of the plutonium rich-phases within the fuel matrix. This evolution is desired to account for plutonium isotopic quality in the future leading to increase the plutonium content of the MOX fuel for LWRs. In that case, margins to safety criteria will decrease, notably fuel rod internal pressure margins which may question the parity principle. To maintain that objective, doping MOX fuel with chromium oxide is considered with the so-called CHROMOX concept. Besides favoring the homogenization of uranium and plutonium, doping also activates the grain growth. The first results obtained after irradiation in an experimental reactor are on line with the expectations, namely enhanced fission gas retention in the fuel matrix, a beneficial feature for both normal operation and accidental conditions.

Mono-recycling in LWRs is an interesting strategy to reach a rapid decrease of the total used fuel inventory resulting in a reliable and safe solution. It also maximizes the energy that can be extracted from uranium resources. However, a plutonium multi-recycling strategy in LWRs can be also considered to go further in the use of energy potential contained in both UOX and MOX fuels. In this context, the CORAIL-A and MIX fuel assembly designs have been developed with special care to the minimization of power distributions inside the assembly and of interactions with the neighbors.

These different aspects are addressed in greater details hereafter, as well as the necessary adaptations to be implemented at the MELOX production plant to face the MOX fuel developments considered in the future.

2. MOX FUEL EXPERIENCE FEEDBACK AND MID-TERM EVOLUTION

2.1. MOX fuel performance in LWRs operation conditions

MOX fuel is used in Light Water Reactors (LWRs) since 1972 with no safety related issues. At mid-2018, Framatome had delivered about 8700 fuel assemblies in more than 40 reactors worldwide. Today in France, 'MOX Parity' is achieved with UO_2 fuel. The AFA 3GA MOX product has a reference assembly Pu content of 8.65% (9.77% for the high content zone) and is irradiated in an annual quarter core reload basis up to a maximum burnup of 52 GWd/tHM (corresponding to 59 GWd/tHM maximum fuel rod burnup).

The qualification of the so-called Parity MOX 52 product is based on a large scale R&D program carried out since the beginning of Pu recycling in LWRs. The database includes several surveillance and analytical programs, in and out of pile, performed within the French cooperation scope with CEA, EDF and Framatome or within international programs. In pile analytical experiments have been performed in normal and off-normal conditions up to high burnup with the aim of collecting relevant data to develop and validate behavior models. Currently, the experience feedback reached a maximum fuel rod average burnup of 65 GWd/tHM.

MOX fuel features and evolutions during irradiation have been thoroughly examined. It is concluded that most of the physical properties of MOX fuel for LWR applications do not differ significantly from those of UO_2 fuel because of the relatively low Pu content. However, noticeable exceptions exist which directly affect MOX fuel in-pile behaviour:

— Higher fuel temperatures are observed due to lower thermal conductivity and higher reactivity for MOX fuel [1];
— Higher rod internal pressure at end of life is observed as a consequence of Fission Gas Release (FGR) which is somewhat larger compared to UO_2. This behaviour results mainly from the linear heat rates experienced by MOX fuel during their last irradiation cycles **Error! Reference source not found.**. In current French MOX fuel managements, FGR is especially sensitive to power levels and fuel temperatures during the 3rd irradiation cycle at a stage where incubation of the insoluble fission gases in the fuel matrix has been long enough to reach a saturation threshold (so-called Vitanza threshold for FGR >1% **Error! Reference source not found.**).
  In addition, helium production during irradiation and its release contributes to the rod internal pressure increase especially at high burnup **Error! Reference source not found.**. The different sources of helium production in MOX fuel under irradiation are α decay from specific minor actinides, ternary fissions and $^{16}O(n,\alpha)$ reactions.
— Increase in MOX fuel creep rate and plasticity flow leading to a better pellet-clad-interaction resistance relatively to UO_2 fuel **Error! Reference source not found.**.

Beyond its properties, MOX fuel differentiates from UO_2 by its microstructure when manufactured with the MIMAS (MIcronized MASterblend) process as is the case at the Orano / MELOX facility. This process guaranties an homogeneous Pu distribution at the pellet scale but the MIMAS MOX pellets have a multi-phasic microstructure at the microscopic scale **Error! Reference source not found.**. The microstructure consists of three phases: Pu-rich agglomerates with the Pu content of the master blend, i.e. ~ 28 %, U-rich agglomerates with a very low Pu content, and a (U,Pu) matrix coating with an intermediate Pu content, i.e. 5 ~ 10 % (see *Fig. 1*). During normal operation, the larger Pu-rich agglomerates reach a much higher burnup than the average pellet and consequently an HBS (High Burnup Structure) restructuring can occur if the temperature of these Pu-rich

agglomerates remains low enough **Error! Reference source not found.**. Electron probe micro analyses highlight high concentration of fission gases in the restructured Pu-agglomerates. Fission gas (Xe, Kr) atoms are trapped within intergranular positions and formed into gas bubbles. The intergranular gas is considered to be potentially released during accident transients. This is notably the case following Reactivity-Initiated Accident (RIA) tests for which MOX fuel exhibit higher FGR compared to UO_2 for a similar burnup level **Error! Reference source not found.**. Considering the two phases of an RIA transient, the behaviour of fission products has a double impact:

— During the Pellet-Cladding Mechanical Interaction (PCMI) phase, the cladding remains at low temperature (< 400-500°C) and the power increase leads to pellet expansion and swelling. Here, the key parameter is the pellet swelling and so the effect of the gases during the short duration of the transient (>20s).
— The post-DNB (Departure from Nucleate Boiling) phase where the cladding temperature rises above 800 °C and the rod can burst if the rod inner pressure is above the system pressure. The key parameters in this phase are the initial rod inner pressure and the transient FGR.

The main improvements to gain margins would be to decrease rod inner pressure before and during the transient to limit the risk of rod ballooning and burst. These improvements are also desired for LOCA (Loss Of Coolant Accident).

2.2. The CHROMOX Concept

The analysis of the current MOX fuel experience feedback shows that the existing margins in internal pressure in normal and accident conditions could be enhanced. This objective is of peculiar importance to keep the parity principle with UO_2 in the future. Evolutions in fuel managements, including multi recycling (see Section 4) and the progressive increase of plutonium content in MOX fuel due to the Pu isotopic vector degradation will contribute to increase FGR and rod internal pressure. Therefore, MOX evolution based on advanced microstructures is considered to provide the required performance in a complete safety approach. In 1998, a MOX fuel development program was initiated between EDF, CEA, COGEMA and Framatome resulting in a new fuel microstructure, characterized by a near-complete homogenization of the Pu-rich phase and an increase of the average $(U,Pu)O_2$ grain size. This microstructure is obtained by doping with Cr_2O_3, giving the so-called CHROMOX microstructure (see *Fig.1*).

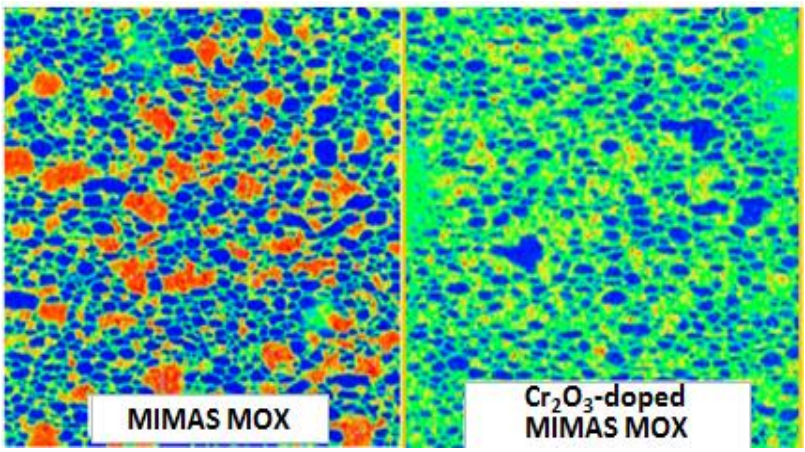

FIG. 1. Post-processes micrographs (1 mm²) of MIMAS MOX products highlighting the effect of Cr_2O_3-doping on the phase distribution [8] (Pu content in the different zones varies from red for primary blend agglomerates to blue for UO_2 agglomerates

The use of Cr_2O_3 as a dopant in MOX fuel is drawn from the Cr_2O_3-doped UO_2 fuel pellet development program **Error! Reference source not found.**. An example of CHROMOX microstructure obtained at MELOX and characterized at CEA is shown on the right-hand side post-processed EPMA mapping of *FIG. 1*. It is shown

that an ''inversed'' microstructure as compared to the standard MIMAS MOX product is obtained: a $(U,Pu)O_2$ solid solution containing small UO_2 agglomerates. Quantitative analyses of EPMA mappings obtained on standard and Cr_2O_3-doped MOX fuel pellets show that Cr_2O_3 doping in MOX fuel results in:

- An increase of the mean grain size in Pu-rich phases, as measured by linear intercept method, for the doped lot as compared to the standard fuel lot.
- An enhanced homogeneity characterized by smaller $(U,Pu)O_2$ primary blend agglomerates and increased Pu fraction in the coating phase. As a consequence of the decrease of the surface and Pu fraction in the $(U,Pu)O_2$ agglomerates, the coating phase is shown to be very large and containing most of the total Pu.

Additionally, the CHROMOX microstructure is expected to be beneficial regarding the extent of fuel restructuring during irradiation. The current understanding is that a MOX microstructure containing small UO_2 agglomerates for the dilution of fission products is preferred. The dilution effect is beneficial as long as the HBS formation threshold is not met. With a MOX microstructure characterized by a large coating phase, small UO_2 agglomerates and a better primary blend distribution, the CHROMOX product appears to be consistent with such a microstructural evolution.

Considering PCI, the favorable mechanical properties of MOX fuel are anticipated not to be modified because of Cr_2O_3 doping, even possibly enhanced as observed for UO_2 (due to the larger grain size) **Error! Reference source not found.**, **Error! Reference source not found.** . Moreover, power ramp tests performed on homogeneous SBR (Short Binderless Route) MOX fuel have shown a good behavior with regard to PCI as already observed for other heterogeneous MOX fuel types **Error! Reference source not found.**.

The first CHROMOX-type product has been irradiated in the HALDEN test reactor up to a burnup of ~55 GWd/tHM. At end of irradiation, rod puncturing results confirm the expected benefit with respect to FGR; benefit which can be expressed as a gain of about 20 bars (hot conditions) for the MOX fuel rod internal pressure. This behavior is considered as resulting from the increased mean grain size of the fuel matrix. Furthermore, post-irradiation thermal annealing tests highlighted an improvement by ~50% (in relative) regarding transient FGR underlining the prominent role of the homogenization of the Pu distribution **Error! Reference source not found.**. Following this first set of promising results and trends, the irradiation of lead fuel rods in a commercial PWR is now considered. Finally, it is to be noted that the analysis of the use of Cr_2O_3 dopant in nuclear fuel shows that it is compatible with recycling strategy.

3. MOX FUEL MANUFACTURING EVOLUTION

Orano has about 60 cumulated years of experience of $(U,Pu)O_2$ fuel manufacturing at industrial scale: about 30 years at the AtPu at Cadarache, with both fast neutron reactors and LWR designs based on a wide range of Pu enrichments and more than 30 years at MELOX plant for LWR designs. In both plants flexibility allowed to manufacture various designs for BWR and PWR with various Pu enrichments and pellet / cladding dimensions. During this period, about 350 tHM of MOX for LWRs have been produced at Cadarache and more than 2600 tHM at MELOX *(see FIG.2)*. All along, Orano has gathered a unique experience of MOX plant design and operation optimization, including the specificities and constrains linked to plutonium handling. In addition, a constant effort on R&D over the years, using both internal workshops, typically the pilot line and CDA at MELOX [11] and external means in collaboration with CEA and various universities and laboratories has allowed ensuring an in depth knowledge of the different fabrication steps and developing process parameters optimization. The use of plutonium makes MOX fuel a more complex product to manufacture compared to UO_2 fuel, requiring specific expertise. Efficient mastering of this expertise has been demonstrated by MELOX through the manufacturing of 30 million fuel pellets a year.

Regarding process optimization, since MELOX start in 1995, different evolutions of the production lines have been successfully implemented. Upon them, there was the optimization of primary blend preparation, with an improvement of pellet microstructure regarding Pu agglomerates size distribution. Another interesting step regarding fabrication is the qualification of an increase of scrap content in primary blend, which has been possible with the support of the pilot line and of the manufacturing feedback. Regarding fabrication controls,

improvement and technological developments of γ-scan allow a more efficient control of fuel rod final quality.

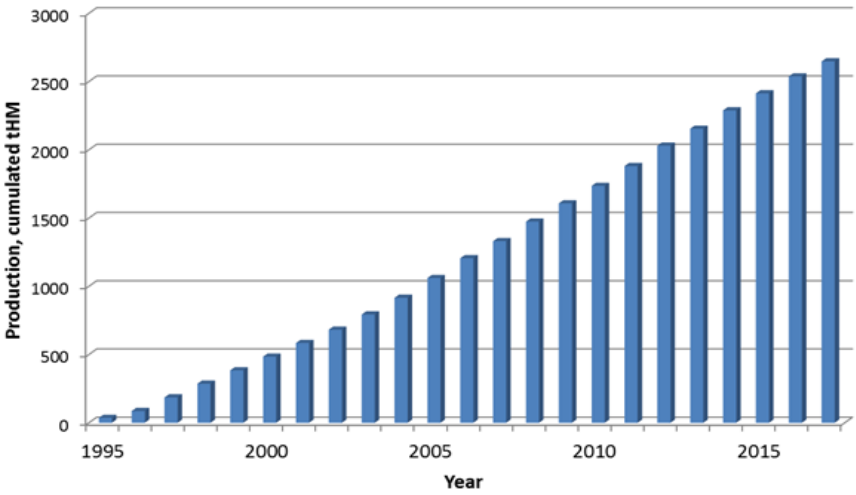

FIG. 2. Cumulated production of LWR MOX fuel at MELOX plant

MOX manufacturing facilities require developing and implementing a safety excellence culture based on the following pillars; management of plutonium confinement and worker radiation protection. Manufacturing MOX fuel in the coming years for EDF and other customers, will lead to handle plutonium with less ^{239}Pu and a higher total Pu content, this being the consequences of reactor fuel management evolution (higher burnup). This means an increase in thermal and radioprotection constrains during fuel fabrication, storage and transport stages.

In order to improve management of plutonium confinement, a significant work on human factors, including glovebox and tooling optimization, training using virtual reality have been successfully developed at MELOX. Regarding radiation protection, continuous improvement has been a major driver for innovation and R&D to minimise workers exposure. MELOX has developed and implemented new materials and tools in order to increase radioprotection efficiency. Individual protections and design of the facility improvements (glove box shielding, gloves material, individual shielded glasses, etc.) together with optimization of operational and maintenance procedures allow to significantly reduce the workers exposure. In addition, new technologies such as remote handling devices and robotics are developed. As a result, in a context of constant regulation requirements evolution, these efforts have led to continuous dose exposure reduction much below the regulatory dose limitations.

Meanwhile, developing together with Framatome optimized products like CHROMOX (see Section 2) or new concepts like MIX and CORAIL-A (see Section 4) is also a driver for new improvements regarding manufacturing. For CHROMOX, first tests performed at the pilot line at MELOX allowed demonstrating the compatibility of MOX process with Cr_2O_3 doping and to assess the benefits regarding microstructure evolution. Such tests are necessary to define the optimized process parameters before fabrication at industrial scale. For CORAIL-A, adaptations may be necessary regarding radioprotection shielding and venting systems but feasibility of fabrication of such assemblies at MELOX plant has been confirmed [12]. For MIX, additional modification for criticality aspects may be necessary and industrial fabrication simultaneously with MOX is not possible.

4. PU MULTI-RECYCLING STRATEGY FOR LWRS

The reuse in LWRs of fissile materials arising from reprocessing has reached maturity and allows going further in the recycling process. Actually, there is still a great energy potential in MOX fuel after irradiation in PWRs. While working on GEN IV solutions, investigations on a shorter term option have been launched for the reused MOX fuel to ensure a transition in current or future PWRs. The following issues need to be addressed when studying solutions of Pu multi-recycling:

— Plutonium management strategies should be consistent with maintaining high standards of safety. The requirements of nuclear safety in relation to the reactor physics properties of the various reactor

systems have to be considered, which includes guaranteeing sub-criticality in all stages of the closed fuel cycle;
— Plutonium management strategies should maintain flexibility in the fuel cycle, such that future options like fast reactors are not foreclosed;
— Plutonium management strategies should be consistent with maintaining adequate security standards and safeguards arrangements to meet non-proliferation requirements, too.

4.1. Two approaches to multi-recycle Pu in PWRs

Multi-recycling strategies i.e. Pu recycling from used MOX fuel are studied based on built experience and validated codes and methods. However, current MOX assembly design needs to evolve in order to maintain the energy equivalence when degrading the Pu isotopic quality.

Since the Pu content in fuel is limited mainly for safety reasons, the solution is then to increase the number of fissions in the uranium matrix by ^{235}U enrichment. Two fuel assembly designs and approaches have been developed in parallel, so the best solution, technically and economically, could be defined after a thorough comparison of the respective fuel assembly performance:

— The first concept, CORAIL-A, considers the use of UO_2 and MOX fuel rods in the same assembly like for the CORAIL fuel assembly [13]. However, the original concept has been upgraded with significant modifications to improve performances regarding the use of Pu and of the reactor;
— The second, MIX, is only composed of MOX fuel rods (mono-Pu content) with enriched uranium for the mixed oxide fuel matrix instead of depleted uranium as for current MOX fuel. The enrichment of the UO_2 matrix is adaptable depending on the Pu quality and the UO_2 fuel assembly equivalence to be reached.

The analyses have been performed in 2D in an infinite medium with the code APOLLO2-A. In this study, the fuel assembly concepts are irradiated in an EPR reactor. The reference cycle selected for this study is the UO_2 equilibrium cycle – 18 months – 4.2 ^{235}U%. The average core burnup is 34 GWd/tHM and the average fuel assembly discharge burnup is 46 GWd/tHM. .

The multi-recycling capacity of both fuel assembly designs has been analysed for up to five generations. One generation is considered for about 15 years and cover all the processes from fabrication, in-reactor irradiation, cooldown, transport, reprocessing, etc.

4.1.1. CORAIL-A fuel assembly concept

For the first concept, the purpose is to maximize the plutonium mass per assembly while respecting the energy equivalence to be reached. Different configurations of UO_2 and MOX rods have been tested in order to limit the peaking factors in the fuel assembly and interfaces with UO_2 fuel assemblies. The variants which were considered include the modification of the Pu content of the MOX rods depending on their location in the assembly. For example, around some guide tubes the Pu content is reduced and it is higher at the center of the assembly. However the number of Pu contents is limited to three in order to bound fuel assembly heterogeneity. The UO_2 rods are enriched at the maximum value allowed, that is to say ~5%, therefore the spectrum is a bit harder than for current UO_2 fuel assemblies.

After testing different configurations, the configuration displayed in *FIG.3* was deemed to be the optimum with:

— UO_2 rods at the periphery to facilitate the introduction of this new fuel assembly concept in an operating reactor. The interface between the UO_2 fuel and CORAIL-A assemblies is in this way smooth, taking into account also the benefit of reduced Pu content to get a flatter power distribution;
— The Pu content is limited to 11.5%: the maximum value compatible with existing industrial manufacturing installation and operational feedback could be valued. Other limitation to account for regarding Pu content is corium sub criticality that should be ensured for all the configurations;

— Three Pu contents for the MOX rods (see *FIG.3*) to reduce the impact of UO_2/MOX interface within the assembly: low content (purple) on interface with UO_2 rods nearby guide tubes, medium content (light blue) and high content at the centre (yellow).

The number of UO_2 and MOX rods may be adjusted depending on the fuel cycle strategy and performance. As an example, for a 4.2% enriched uranium fuel assembly equivalence, the configuration with 141 MOX rods and 124 UO_2 rods is used.

The average Pu content and quality define the fuel assembly energy equivalence as compared to a UO_2 one. To cope with Pu degradation from one cycle to another and to have a more efficient management of the used fuel inventory, mixing of Pu contained in the various used fuels (UO_2, MOX or CORAIL-A) is considered. This mixing allows also limiting as much as possible the creation of ^{241}Am from decay of fissile ^{241}Pu. After two generations the fissile Pu isotopic composition could be considered as stabilized, only the ^{242}Pu inventory increases slowly.

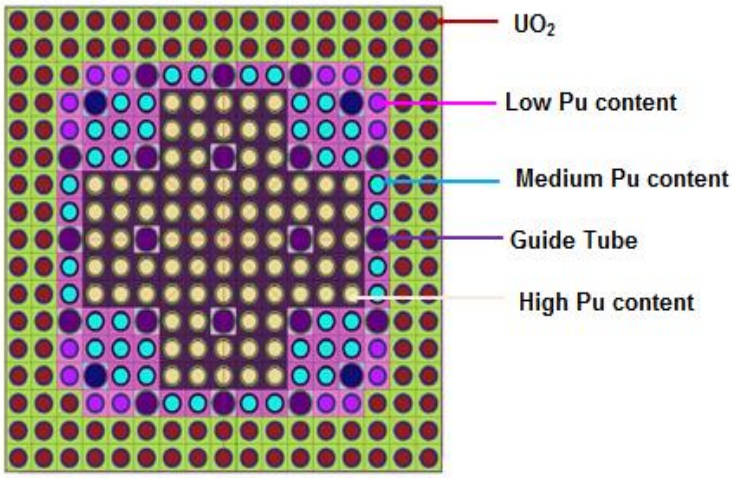

FIG. 3. CORAIL-A fuel assembly design.

4.1.2. MIX fuel assembly concept

Regarding the MIX fuel concept, Pu content and quality is determined so the economy is robust and the safety demonstration may benefit from the available feedback from MOX fuel cycles. The following parameters have been identified in order to develop a MIX fuel assembly:

— The assembly is only made of MOX fuel rods but with an enriched ^{235}U matrix. The uranium enrichment can be adjusted depending on the energetic and isotopic characteristics of the fuel assembly.
— The ^{235}U enrichment is adjusted to compensate for degradation of the Pu vector due to multi-recycling. Nonetheless, the ^{235}U enrichment value is limited for two particular reasons:
  - The economy of the multi-recycling depends on the ^{235}U enrichment associated cost;
  - The used MIX fuel should not contain too large amount of ^{235}U so current reprocessed uranium recycling supply chain could be used (about 1.2 % max).
— The Pu content is limited to overcome any safety issues, mainly related to void coefficient and corium criticality.
— In order to be able to use as much Pu as possible per fuel assembly, therefore reducing the reactor fleet mobilized for multi-recycling, the Pu quality is controlled by mixing Pu from used MIX or MOX fuel and used UO_2 fuel.
— After two generations the Pu isotopic composition could be considered as stabilized, meaning that the ^{235}U enrichment of the UO_2 matrix is also constant; only the ^{242}Pu inventory increases slowly.

As an example of MIX assembly, fuel assembly studies were done on the basis of an equivalent 4.2% enriched UO_2 fuel assembly for EPR. The characteristics obtained for this MIX fuel assembly are the following: 9.5% Pu content for all the rods - 2% ^{235}U enrichment - 50% Pu from used MOX or MIX and 50% used UO_2

4.1.3. Comparison of the reactor performance of the two fuel designs

Main reactor parameters for both concepts were compared:

— Void coefficient: Both concepts respect this important safety criterion. A sensitivity study to the boron concentration was performed (2000 to 3000 ppm). For the MIX assembly the improvement of the Pu quality thanks to the use of Pu from used UO_2 fuel allows to upload rods with 9.5% Pu. Otherwise the Pu content should have been reduced and uranium enrichment increased for the sake of offset. Regarding the CORAIL-A concept, no difficulty is encountered because of the use of UO_2 rods;
— RCCA efficiency for both concepts is comparable but slightly better for the CORAIL-A concept which again benefits of the presence of UO_2 rods;
— The interface between UO_2 and MOX rods may create high peaking factors especially in case of the CORAIL-A design. The proposed Pu zoning allows to overcome that and to fulfil the design criterion imposed (peak factor ≤ 1.15). For the MIX fuel assembly there is not such an interface for equilibrium fuel management. However, the fuel assembly zoning may be required for the transition fuel management;
— Moderator temperature coefficient has been determined using current validated methodology. In all configurations and for both designs, the results show that the moderator temperature coefficient is always negative. Sensitivity analysis to the boron concentration with enveloped values confirmed the results.

The studies reported above highlight that for both concepts high performance regarding fuel cycle length or burnup could be reached by controlling the Pu content and/or the isotopic composition depending on the defined cycle strategy. The feasibility for multi-recycling up to 4-5 fuel generations of about 15 years each has been demonstrated. The stabilization of the Pu isotopic composition is reached after about 2 generations when mixing CORAIL-A or MIX used fuel and UOX used fuel. The analyses performed are based on an EPR reactor and 100% MIX or CORAIL-A fuel management. However, the results obtained and our significant experience with 30% MOX fuel management emphasize the possibility to proceed also with a 30% multi-recycling CORAIL-A or MIX fuel management. The fuel assembly choice will depend on the available reactor fleet and its performances, the manufacturing capabilities and the used fuel management strategy.

Both concepts contribute to reduce the available Pu stock because they burn Pu during the cycle. The downloaded U enrichment is lower than the limit accepted by the fuel cycle facilities, about 1% max. As an example here below the figures for consumed Pu based on fuel assembly calculations for an EPR standard fuel cycle:

— CORAIL-A: about 18 kg of Pu per TWh(e) for all generations;
— MIX: about 48 kg of Pu per TWh(e) for all generations

5. CONCLUSION

In more than 60 years of Framatome and Orano experience, Pu recycling through fabrication and irradiation of MOX fuel in LWRs has demonstrated the reliability of this process allowing managing at best uranium resources. The operational performance of MOX fuel rods and assemblies has been assessed by numerous pool-site inspection and hot-cell measurement campaigns. This unique feedback experience points out that MOX fuel behaviour is as good as UO_2 fuel. However, the high linear heat generation rates seen by the MOX fuel rods induce a somewhat higher fission gas release and subsequent reduction of rod internal pressure margins to safety criterion. To maintain in a sustain way the energy parity principle between MOX and UO_2 fuel, product development is considered based on advanced microstructures. In that respect, the CHROMOX product which involves Cr_2O_3 doping is characterized by an enhanced homogeneity of the Pu distribution in the

fuel and an increased matrix grain size. With these evolutions, larger internal pressure margins are anticipated as well as some enhancement in the retention of gaseous fission products in accidental conditions by reduction of restructured areas.

The design and operation of the MELOX MOX production plant takes account for the most recent and stringent safety requirements regarding confinement of high radioactive materials, protection of workers and environment from exposure, safety criticality, etc. To support the MOX fuel development in the future and maintain energetic equivalence with UO_2 fuel in more demanding core managements, some adaptations are already considered. The objectives are to be able to manufacture the CHROMOX product and also to face the inherent degradation of the Pu isotopic vector of MOX fuel and its higher Pu content from increased core management cycle length.

On this last point, Pu multi-recycling strategies in LWRs are studied with new fuel technologies. In order to be able to use low quality Pu in a PWR spectrum, fissile uranium needs to be added. With the CORAIL-A option, developed by Framatome and Orano, the assembly contains about half of MOX fuel rods and the remaining as UO_2 rods. By contrast, the MIX fuel assembly contains only MOX rods with an enriched uranium matrix that compensates the Pu degradation. Development of those fuel technologies, that could be coupled with the most advanced Framatome fuel assembly design GAIA for PWRs, will offer flexibility to switch to future technically and economically robust advanced cycles in current or future LWRs with a limited impact to the reactor design and its performance. Thus, these developments will allow implementing efficient solutions bridging the gap with the potential development of GEN IV reactors. Any solution of advanced fuel developed within the closed cycle strategy integrates aspects of the whole fuel cycle, including the recycling of such fuel.

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