Invited Paper

MOX FUEL FABRICATION AND UTILISATION IN LWRs WORLDWIDE

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Abstract

Early in the development of the nuclear programme, a large part of the countries using nuclear energy has studied the reprocessing and recycling option in order to develop a safe conditioning of fission products and to recycle fissile materials in reactors. In the sixties, the feasibility of recycling plutonium in LWRs has been successfully demonstrated by several experimentations of MOX rod irradiations in different countries.

Based on the background of the MOX behaviour collected during the seventies and on the results of the important MOX experimentation program implemented during this period, a large part of the European utilities decided at the beginning of the eighties to use MOX fuel in LWRs on an industrial scale. The main goals of the utilities were to use as a fuel an available fissile material and to control the stockpile of separated plutonium.

Today, the understanding of the behaviour of plutonium fuel has grown significantly since the launch of the first R&D programmes on LWR and FR MOX fuels. Plutonium oxide physical and neutron behaviour is well known, its modelling is now available as well as experimentally validated. Up to now, more than 750 tHM MOX fuel (more than 2000 FAs) have been loaded in 29 PWRs and in 2 BWRs in Europe, corresponding to the recycling of about 35 t of plutonium.

Reprocessing/recycling technology has reached maturity in the main nuclear industry countries. Spent fuel reprocessing and recycling of the separated fissile materials remains the main option for the back-end cycle. Today, the operation of MOX-recycling LWRs is considered satisfactory. Experience feedback shows that, in global terms, MOX cores behaviour is equivalent to that of U02 cores in terms of operation and safety.

1. THE ORIGINS OF PLUTONIUM RECYCLING IN LWRS

Early in the development of the nuclear programme, a large part of the countries using nuclear energy has studied the reprocessing and recycling option in order to develop a safe conditioning of fission products and to recycle fissile materials in reactors.

In the sixties, the feasibility of recycling plutonium in LWRs has been successfully demonstrated by several experimentations of MOX rod irradiations in different countries like :

⇨ in 1963, in BR3 reactor (PWR), at Mol (Belgium),
⇨ in 1964, in Saxton reactor (PWR) in USA,
⇨ in 1966, in VAK reactor (BWR) at Kahl (Germany),
⇨ in 1968, in Garigliano reactor (BWR) in Italy.

From the beginning of the sixties, an important development programme has also been implemented regarding MOX fuel for the FBRs in different European countries (France, Germany, UK, Belgium) but also in the USA and in Japan.

During the seventies, MOX recycling was implemented on a larger scale in several LWRs by the loading of batches of MOX FAs. The main experience of MOX recycling during this period has been obtained in Europe, in industrial scale nuclear power plants :

⇨ inBWR
  - VAK (Germany),
  - Gundremmingen A (Germany),
⇨ inPWR
  - Obrigheim (Germany)?
  - Chooz A (France).

At the beginning of the eighties, the development of FRs was delayed, and later stopped in France, and in Germany. Important stocks of plutonium, separated in the seventies for the FRs were available for the LWRs.

Based on the background of the MOX behaviour collected during the seventies and on the results of the important MOX experimentation program implemented during this period, a large part of the European utilities decided to use MOX fuel in LWRs on an industrial scale. The main goals of the utilities were to use as a fuel an available fissile material and to control the stockpile of separated plutonium.

Experience feedback of the seventies, based on reactor irradiations and R&D programmes in hot cells on the initial MOX design leaded the fuel manufacturers to improve the fuel design particularly to enhance the solubility of the MOX fuel for the reprocessing. The fuel manufacturing procedures had to be changed accordingly.

Today, the understanding of the behaviour of plutonium fuel has grown significantly since the launch of the first R&D programmes on LWR and FR MOX fuels. Plutonium oxide physical and neutron behaviour is well known, its modelling is now available as well as experimentally validated.

2. MOX FUEL FABRICATION

2.1. Fabrication Process

Today, only two processes of LWRs MOX fuel fabrication are used world-wide : the MIMAS process (Micronized MASter blend) developed by Belgonucléaire and the SBR process (Short Binderless Route) introduced by BNFL. These current processes satisfy the requirements of the fuel designers and the utilities regarding pellet specifications, fuel quality and fuel dissolution properties.

The MIMAS powder is obtained through two successive blending steps : the primary blend at high plutonium content obtained by ball milling so-called micronization step and the secondary blend

to reach the required plutonium content. The main advantages of this process is the reduced powder volume implemented during the micronization step, and the flexibility due to the possible intermediate storage of the master blend which can be used for isotopic homogenisation.

The SBR powder is obtained by only one blending step to prepare a granular feed suitable for pressing. The main advantages of this process is the homogeneity of the pellet and the lack of large Pu-rich areas.

The Siemens process used during the eighties was mainly the OCOM process (Optimised CO-Milling), quite similar to the MTMAS process with two steps : a master blending obtained by co-milling and a secondary blending to adjust the plutonium content.

2.2. Fabrication Plants (table 1)

The MIMAS process is implemented in 3 MOX fabrication plants : the PO plant (35tHlvVy) at Dessel (Belgium) operated by BN, the CFCa plant (30tHM/y) at Cadarache (France) operated by Cogema and the MELOX plant (lOOtHM/y) at Marcoule (France) also operated by Cogema.

The SBR process is used by BNFL in 2 MOX fabrication plants at Sellafield (UK) : the MDF plant (StHM/y for demonstration purpose) in operation and the SMP plant (120tHIWy) to be started in 1999.

Germany had MOX fabrication capabilities since the early seventies. The Siemens MOX fabrication plant at Hanau had a capacity of 30 tHIWyear (so called "old plant"). After a contamination event the plant was stopped in 1991 and Siemens decided in 1994 to close it because of the blockage of the local government. At that time the "new plant" (120 tHM/y) was about 95 % completed. For the same political reasons this new plant never went into operation and in 1995 Siemens decided to close down the total Hanau fabrication plant.

In Japan MOX fuels for core physics and irradiation testing have been manufactured in PNC plant since 1967. PNC MOX manufacturing plant (10 tMOX/y) produced nearly 135 ton of MOX fuel for thermal reactor utilisation, equivalent to about 1.6tHM of plutonium by 1998. Most of MOX fuel was for advanced thermal reactor Fugen. Micro-wave heating technique was developed by PNC to obtain a homogeneous plutonium-uranium powder directly from a reprocessed product of Tokai Reprocessing Plant. In the near future, when Rolckasho reprocessing facilities will go in operation, a commercial MOX fuel fabrication plant will be built in Japan with a capacity of about 100tHWy.

3. THE CURRENT SITUATION OF MOX UTILISATION

Today, 40 LWRs are licensed for MOX recycling world-wide, in 5 countries (20 in France, 12 in Germany, 4 in Switzerland, 2 in Belgium and 2 in Japan). In these countries, the main option for the back-end of the fuel cycle is currently reprocessing and plutonium recycling (table 3).
By the beginning of 1999, four European countries burn MOX fuel in LWRs (Germany, France, Belgium and Switzerland), and before the end of 1999, a fifth country : Japan will start using MOX in two LWRs (1 BWR and 1 PWR).

The main part of the NPP using MOX are 29 PWRs (17 in France, 7 in Germany, 2 in Belgium and 3 in Switzerland), but 2 BWRs use also MOX (in Germany).

3.1. Reactor Adaptation

The larger amount of plutonium in the core shifts the neutron spectrum towards higher energy levels, thereby reducing the efficiency of the reactivity control systems. The reduced neutron absorber worth needed in some cases to improve the control rod pattern, to increase boron concentration of the

boron make-up storage tank and to increase boron concentration of the refuelling water storage tank. In some specific cases, use of enriched boron is needed.

Taking into account these neutronic considerations, the number of MOX assemblies is limited on each reactor (MOX recycling rate), the limit depending upon the reactor initial design and its capability of evolution.

In Belgium the low recycling rate of 20% used by the utility is compatible with the reactor operation without any modification of the reactivity control systems.

In France, some light modifications of the reactor (4 RCCA added, increased boron concentration in the refuelling storage tank) have enabled to increase the recycling rate to 30%.
In Germany and in Switzerland, the recycling rate depends upon the type of reactor and is limited by each plant licence between 10% to 50% and yield normally no problems complying with the allowed limits for core-wide parameters as reactivity coefficients or shutdown margins without any changes of the plants. For high Pu-content, corresponding to high uranium enrichment, it could be necessary for PWRs to switch over to enriched B 10 to yield enough margins for a flexible operation.

3.2. Fuel Design and Core Management

MOX rods, together with all components of the MOX assembly, are designed to meet the same mechanical and thermohydraulic specifications as those set for uranium assemblies. The MOX skeleton is generally identical to the skeleton of a typical uranium assembly.
A MOX assembly contains only mixed oxide rods. The plutonium oxide is mixed with natural or depleted uranium oxide (tails from 0.15% to 0.3% U235) to maximise the quantity of plutonium per assembly.

To achieve better balanced rod power distribution in the assemblies, several plutonium contents (three for PWRs) are used in the MOX assembly (zoning). The low plutonium content zone is located at the periphery of the MOX assembly in order to compensate for local power peak in the interface with the uranium assemblies induced by the large increase of the fission and absoption cross-sections of the MOX compared to the U02. In Germany, a specific MOX assembly design uses also four water rods near the assembly centre to flatten the power distribution. Due to the relatively flat reactivity shape versus burn-up there is no urgent need for Gd rods in the PWR MOX FAs.

The BWR MOX fuel assemblies are even more complex with up to 6 MOX fuel rod types to compensate the spectrum changes between the fuel channels. As for all BWR fuel assemblies also the MOX FAs usually have some Gd poisoned rods. These Gd rods don't have any plutonium in the uranium matrix.

In order to meet the energy equivalence with enriched uranium fuel, the average plutonium content is adjusted using an equivalence formula that takes account of the isotopic composition of the plutonium. As the main part of the reprocessed fuel originates from the PWR reactors, the total plutonium contains between 60% and 70% of fissile isotopes of plutonium : 239 and 241 (table 2).

Regarding core management, the goal of each utility is to obtain the equivalence between MOX and U02 in terms of fuel performance and reactor operation.
In France, the MOX FAs are managed in annual cycles but with 3 cycles for MOX (equivalent to U02 3.25%) and 4 cycles for U02 3.7%. MOX limited irradiation performance is due to the physical behaviour of MOX pellets with respect to that of U02 pellets (higher temperature and greater fission gas release induced by higher power histories).

French utility target is to lift MOX fuel at the level of the uranium in four-batch core management by the beginning of the next century. MOX fuel will be equivalent to uranium fuel enriched to 3.70% and will reach 50 GWd/t.

In Germany, Switzerland and Belgium, the MOX FAs are used in short and long cycles and there is no special MOX measures in the normal fuel management. MOX and U02 FAs are still equivalent in terms of energy.

4. USING MOX : THE GLOBAL EXPERIENCE

4.1. Usable Feedback (table 4)

Up to now, more than 750 tHM MOX fuel (more than 2000 FAs) have been loaded in 29 PWRs and in 2 BWRs in Europe, corresponding to the recycling of about 35 t of plutonium.
In France, since 1987 about 1000 MOX assemblies have been loaded and 24 t of plutonium recycled in 17 PWRs (900 MWe - 17x17).

In Germany, since 1985, about 800 MOX FAs have been loaded in 9 PWRs (16x16 and 18x18) and 2 BWRs : Gundremmingen B and C (1344 MWe-9x9).
In Switzerland, about 160 MOX FAs have been loaded in PWRs : since 1978 in Benau 1 and 2 (PWR 350MWe - 14x14) and recently in Gosgen (PWR 1000MWe - 15x15).

In Belgium, since 1995 about 70 MOX FAs have been loaded in Doel 3 and Tihange 2 (PWR 1000MWe - 17x17).

In Japan, KEPCO is scheduled to load 9 MOX fuel assemblies in Takahama Unit-4 in 1999 and 9 MOX assemblies in Unit-3 in 2000 and an increased number during the following cycles in order to reach the maximum MOX recycling rate of a quarter of the core. TEPCO also expects to start reloading BWR Fukushima I Unit-3 (784 MWe) in 1999 and Kashiwazaki-Kariwa Unit-3 (1100 MWe) in 2000 with MOX fuel up to a third of the core after around four successive refuelling campaigns.

In terms of performance, the MOX discharge exposures are currently lower but close to those of uo2.

In Germany, mean MOX FA discharge exposure is about 40 GWd/t, maximum MOX FA exposure is about 48 GWd/t in commercial operation. The trend in this field is increasing and now many of the MOX FAs under irradiation will reach mean discharge exposure around 48 GWd/t.

In France, the average burn-up rate per MOX reload is maintained at around 37 GWd/t and the maximum assembly burn-up rate at 41 GWd/t, compared with the 50 GWd/t reached by UO2 assemblies obtained in annual cycle (3 cycles for MOX and 4 cycles for U02). By the beginning of the next century, the implementation of an optimised core management will increase MOX burn-up rate close to 50 GWdlt.

4.2. Reactor Operation

Reactor operation in base load and load follow mode has not raised any problems to operators. The main effect to be taken into account by operators is the improved axial neutronic stability due to the hardness of the neutron spectrum. One benefit observed was a cut in the volume of liquid waste due to the weaker influence of xenon : the volume of liquid waste generated during load follow decreases by about 30%. In France, where more than 75% of electricity is nuclear generated, load follow has been authorised and applied to all reactors recycling plutonium since 1994.

The loading patterns take account of the recommendations concerning MOX fuel induced by the physical properties of plutonium. One example is the limited number of MOX assemblies at the core periphery to prevent, if necessary, a build up of fluence in the reactor vessel, or under the RCCA to prevent the decrease of their efficiency. Loading pattern optimisation with these constraints is achieved without any difficulty.

Improvements of computer programmes relating to core behaviour supervision have resulted in greater consistency between predicted values and measurements taken during start-up tests and operation (neutronic flux maps). Computer models to predict the behaviour of MOX rods have also been validated by physical measurements taken during operation as well as by post-irradiation inspection.

Regarding the behaviour of MOX rods during transients, power ramp tests have been implemented at different burn-up rates, they have shown that MOX fuel behaves equal or better than UO2 fuel in terms of pellet/cladding interaction.
To justify the acceptable behaviour of the MOX during RCCA ejection transient (RIA), 3 MOX rod tests have been carried out in the Cabri reactor (Cadarache - France), the results show sufficient safety margins between the maximum values of stored enthalpy observed during the transient and the physical limit.

Globally, the operation of MOX-recycling LWRs is considered as satisfactory as the operation of pure uranium cores.

4.3. In-core fuel behaviour

Today, some 2000 MOX FAs have been loaded into LWRs, and more than 500 of them have been unloaded with an average discharge exposure reaching 35 to 40 GWd/t. So far, the behaviour of these MOX assemblies has been satisfactory.

The MOX rod failure statistics are within the range of the uranium rod failure statistics and the small failure frequency is not dependent on burn-up. As expected no MOX specific failure type appeared up to now. The MOX fuel in the LWRs has the same good reliability as the corresponding uranium fuel.

As an example, in France, after eleven years of reactor operation with MOX assemblies, corresponding to more than 70 reactor-cycles, only 2 MOX rod failures have been detected (due to debris), constituting an adequate demonstration of the outstanding performance of this fuel, which compares with UO2 for reliability.

5. MOX R&D

A number of experiments (irradiated materials, physical properties) and studies (core management, safety analysis) are under way with a view to achieve higher MOX discharge burn-up rates (50-60 GWd/t) and more economical core management, to reach the parity between MOX and **uo2.**

In France, out of pile studies, analytical experiments in test reactors and hot cell examinations of power reactor fuel rods have been conducted on the current MIMAS product up to 55GWj/t. The results confirm the good behaviour of this fuel in nominal operating conditions as well as in off-normal situations (cladding failure, class 2 incident transients, RIA).The main difference between U02 and MOX is a larger gas release enhanced by a higher linear heat rate at high burn-up : comprehensive investigation and modelling of the related phenomena are under way. Irradiation of lead fuel rods for a fifth cycle in a power reactor is in progress to reach a 60GWd/t target burn-up. In a more long term perspective (2010), an extensive RetD programme has been launched to support a 70GWd/t target burn-up, based on improving fission gas retention by developing optimized fuel microstructure.

In Germany, to cover the next burn-up step for MOX assemblies with average burnups over 60 GWd/t, utilities participate in the ARIANE program (also supported by Belgian, Swiss and Japanese utilities) to verify the data basis of actinides for depletion codes. Further on, Germany plans to participate in new RIA experiments to cover high enthalpy input conditions beside the operational experience. even if such conditions are extremely imurobable in German LWRs. The German

In Japan, the effect of plutonium spot, helium accumulation, and fuel failure were investigated up to high burn-up for MOX fuel rod. MOX fuel manufactured with MOX powder obtained by microwave heating technique tends to include a small size of plutonium spot. Its plutonium content in the spot, which is controlled with Pu-U ratio in a conversion process, is much lower than in MOX fuel manufactured by a direct mechanical mixing of PuO2 and U02 powders. Irradiation tests shows that above properties of PNC MOX fuel suppress a FP gas release, almost comparable to U02 fuel rod. Amount of helium released seems larger than in a U02 rod. This effect is included in the MOX fuel design to calculate an internal pressure.
PIE results of 60 GWd/t irradiated rod showed that there is still no significant difference between MOX fuel behaviour and U02 fuel. Power transient in BR-2 tests up to 600 W/cm demonstrated no breach of MOX fuel rod. Maximum linear heat of 440 W/cm in the present BWR is guaranteed by this results.

In order to verify the MOX fuel integrity which provides enhanced operational flexibility and the fuel safety tolerance, fuel segments pre-irradiated in Fugen since March 1987 were supplied for RIA tests to JAERI. Failure limit of MOX fuel under off-normal condition is currently investigated.

6. CONCLUSIONS

Reprocessing/recycling technology has reached maturity in the main nuclear industry countries. Spent fuel reprocessing and recycling of the separated fissile materials remains the main option for the back-end cycle.

Today, the operation of MOX-recycling LWRs is considered satisfactory. Experience feedback shows that, in global terms, MOX cores behaviour is equivalent to that of U02 cores in terms of operation and safety. The reliability of MOX fuel in LWRs has been confirmed by the experimental results as well as the operating experience to be equivalent to U02 fuel.

MOX fuel developments are in progress so as to achieve higher burn-up in order to manage MOX and U02 fuel with similar performances in terms of safety, reliability, flexibility. All R&D results show no unexpected behavior up to now and we have faith in further equivalent U02 and MOX operation under operating conditions of the future.

Table 1 : LWRs MOX fuel fabrication plants currently in operation

Manufacturing process	plant	capacity (tHM/Y)	location country	operator
MIMAS	P0	35	Dessel-Belgium	BN
MIMAS	CFCa	30	Cadarache-France	COGEMA
MIMAS	MELOX	100	Marcoule-France	COGEMA
SBR	MDF	8	Sellafield-UK	BNFL
SBR	SMP start-up	120	Sellafield-UK	BNFL

Table 2 : Plutonium in MOX fuel isotopic composition

Plutonium origin	Fissile P u (%)	Pu238 (%)	Pu 239 (%)	Pu240 (%)	Pu 241 (%)	Pu 242 (%)	Am 241 %	Pu content (%)	U02 enrichment equivalent (%)
U02 3,25 % 33GWd/t 5 years cooling 2 years storage	69,0	1,8	57,9	22,5	11,1	5,6	1,1	5,3	3,25
U02 3,7 % 45 GWd/t 9 years cooling 3 yearsstorage	63,1	2,5	54,5	25,2	8,6	7,9	1,3	7,1	3,25
U02 3,7 % 45 GWd/t 9 years cooling 3 years storage	63,1	2,5	54,5	25,2	8,6	7,9	1,3	8,6	3,7

Table 3 : MOX utilisation world-wide
the current situation

Countries	Reactors in operation		Reactors licensed for MOX use		Reactors loaded with MOX	
Reactor type	PWR	BWR	PWR	BWR	PWR	BWR
France	57	0	20	0	17	0
Germany	14	6	10	2	9	2
Belgium	7	0	2	0	2	0
Switzerland	3	2	3	1	3	0
Japan	23	2s	1	1	0	0
Total	104	36	36	4	31	2
LWRs totai	140		40		33	

Table 4 : Using MOX in LWRs
the global experience

Country	MOX loaded		Plutonium loaded in tHM (estimated)	reactors number
	in tHM (estimated)	in FAs number		
FRANCE	450	1000	23	17 PWR
GERMANY	210	800	12	9PWR 2BWR
SWITZERLAND	60	160	3	3PWR
BELGIUM	30	70	2	2 PWR
TOTAL	750	2030	40	33

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