

3. MOX FUEL FABRICATION

Overviews of the historical evolution of MOX fuel fabrication and the resulting achievements have been adequately covered in an OECD NEA publication [7], in a presentation at TOPFUEL'97 [28] and at an International Symposium on MOX Fuel Cycle Technologies [29]. These are complemented by several, more limited scope, presentations at various conferences, see for example Refs [30–37]. Relevant parts of these publications are summarized here. (The important safeguards aspects of fuel fabrication are discussed in Section 9.)

This section deals with the fabrication of MOX fuels for LWRs (including the closely related ATR fuel) as well as for FBRs. It is recognized that the two types of fuel have quite different characteristics, which have an impact on both the fabrication processes and the quality requirements [29]. Most industrial fabrication plants are therefore devoted exclusively to either LWR or FBR fuel. Dual purpose facilities have, nevertheless, operated successfully in the past (Belgonucleaire/Dessel, Siemens/Hanau and Cogema/Cadarache) and are still under consideration for future plants (Russian Federation).

3.1. PRESENT STATUS

3.1.1. Fabrication capacities

Significant MOX fuel fabrication activities, in advance of industrial deployments, have been conducted since the 1950s in Belgium and the USA, since the 1960s in France, Germany, Japan, the Russian Federation and the UK, and since the 1970s in India.

In the USA, five pilot facilities, with a combined fabrication capacity of 50–70 t HM/a, were in operation up to 1976 when President Carter took the political decision to defer reprocessing indefinitely. As a result, the facilities were shut down and decommissioned. Most of this valuable experience is now considered out of date.

In Germany, the Siemens/Hanau plant, which started operation in 1972 as a dual purpose (FBR and LWR) facility, reached an effective capacity of 20–25 t HM/a of LWR fuel in the 1987–1991 period. It was shut down by order of the Hesse Ministry of Environment at the time of a contamination incident on 19 June 1991. This plant is now being decommissioned. Since the operating experience is recent enough still to have some relevance today, further mention of this plant is included here. A larger plant (120 t HM/a), constructed on the same site and which was almost ready to start operation, never received a licence to operate and is now abandoned.

The Belgonucleaire plant started operation in 1973 on the basis of R&D conducted over the previous fourteen years in successive facilities from laboratory to

pilot scale and also pursued during the first few years of operation of the plant. During the initial period of operation (10 years), the plant was equipped to fabricate both FBR and LWR fuel and did indeed fabricate both types of fuel. On the basis of lessons learned during that period, the plant was temporarily shut down for refurbishment in 1984 and the capacity upgraded to 35 t HM/a for LWR fuel, the only fuel to be manufactured thereafter. Since the mid-1990s, the plant has been backfitted, without interrupting fabrication, to incorporate improvements resulting from accumulated experience and deemed necessary to meet more challenging future requirements.

During the first ten years of operation, the end product of the plant was LWR and FBR fuel assemblies (FAs). Since the mid-1980s, the end product has been fuel rods (FRs), with assembly being performed in the adjacent Franco-Belge de fabrication de combustible (FBFC) international (Dessel) uranium fuel manufacturing plant, to benefit from their large scale production capacity (800–900 FAs/a). The FBFC international plant is equipped with a dedicated MOX fuel assembly, control and storage facility devoted to the LWR FRs produced by Belgonucleaire and Centre de fabrication de Cadarache (CFCa). Their experience dates back to 1963, with the manufacture of the first PWR MOX FA incorporating FRs fabricated by Belgonucleaire.

The CFCa plant, now renamed Cogema/Cadarache, the ultimate achievement of a facility that started operation on a pilot scale in 1962, is devoted to FBR fuels. In the mid-1980s, with Electricité de France's (EDF) decision to utilize MOX fuel in their PWRs, one of the FBR lines was converted to LWR fuel fabrication and started operation on PWR fuel in 1990. More recently, the second fabrication line, up to then still devoted to FBR fuel, has been modified into a dual purpose facility, capable of fabricating either FBR or LWR fuel. The resulting capacity is 40 t HM/a for LWR fuel if no FBR fuel is being fabricated. The manufacturing is performed within CFCa up to finished FAs for FBR fuel but only up to FRs for LWR fuel, the assembly being performed at FBFC International or the Melange Oxides (MELOX) fabrication plant at Marcoule.

A decision to construct the MELOX/Marcoule plant was made in 1985, as a consequence of EDF's decision to load MOX fuel in their 900 MWe PWRs. The plant was originally planned for this purpose only. MOX operation started in 1995 and took over the fabrications for EDF that had been conducted at Belgonucleaire and CFCa during the interim period of construction of MELOX. From this perspective, the plant was licensed for a production of 100 t HM/a. MELOX benefits from a very high level of automation allowing large scale fabrication while minimizing personnel dose uptake. As planned, Cogema recently fitted out the MELOX plant for the fabrication of both BWR and foreign PWR fuel and enhanced the capacity to potentially 250 t HM/a. Details of these developments are provided in Refs [32, 35].

The UKAEA produced 13 t HM FBR fuel between 1970 and 1988 in a now decommissioned plant at Sellafield. In the early 1990s, UKAEA, acting for BNFL,

equipped the MOX Demonstration Facility (MDF) in a building at Sellafield that housed MOX fuel development facilities. Both MDF and the UKAEA team were soon thereafter incorporated into BNFL. The purpose of MDF was to gain commercial experience on manufacturing and inspecting thermal MOX fuel in preparation for the large scale Sellafield MOX Plant (SMP) project. It operated in this framework until 1999 when it was shut down because of quality related issues. In the future, when MDF reopens, it will be used as a support facility to SMP, an automated 120 t HM/a book capacity plant described further in Section 3.3. BNFL has proceeded since 1999 with uranium commissioning of SMP but, at the December 2000 status date of this report, was still awaiting the required licence to introduce plutonium into the facility.

In India, a pilot scale fabrication plant, Bhabha Atomic Research Center (BARC), is in operation at Tarapur, producing only BWR fuel at present, but foreseen to be adapted later to produce CANDU and FBR fuel [38].

After conducting development for some years on a laboratory scale in the Plutonium Fuel Development Facility (PFDF) (which is still in operation), JNC started the Plutonium Fuel Fabrication Facility (PFFF) with two completely separate lines — one for Advanced Thermal Reactor (ATR) fuel (1972), still in operation, and one for FBR fuel (1973), which was shut down in 1987. The latter was replaced in 1988 by the Plutonium Fuel Production Facility (PFPF), a fully automated plant with a fabrication capacity sufficient to fuel the Joyo and Monju FBRs. After a few years of operation, PFPF production was temporarily suspended in 1998 (due to a sodium leak in the secondary heat transport system of Monju in 1995). This provided the opportunity to perform planned maintenance and refitting of the facility on the basis of lessons learned, including adapting or replacing equipment which had malfunctioned and reducing the accumulation of plutonium hold-up in the fabrication line. The plan to expand PFPF by adding a production line for ATR fuel has been abandoned with the decision to cancel the intended Ohma demonstration ATR NPP.

In the Russian Federation, three small scale facilities started operation in the 1970s for FBR fuel: the Granat/Chelyabinsk laboratory scale facility and the Paket/Chelyabinsk small scale facility, both fabricating pellet fuels, and the Research Institute of Atomic Reactors (RIAR)/Dimitrovgrad integrated reprocessing–refabrication facility, producing Vipac fuel [39].

Table I summarizes the main characteristics of the MOX manufacturing facilities functioning today. The seven operators of these facilities have an aggregate experience of some 160 years of MOX fuel fabrication. To this should be added the valuable technology background of the now defunct Siemens MOX operations and of the laboratory scale and pilot scale facility predecessors to the facilities listed in Table I. The available capacity for LWR (+ATR) fuel is approximately 210 t HM/a, which is insufficient to serve the short and medium term demand from customers for return of their separated plutonium as MOX fuel; this is one cause of the increasing

TABLE I. CURRENT CHARACTERISTICS OF OPERATING MOX FUEL FABRICATION FACILITIES

Country	Facility	Operator	Start of operation	Capacity (t HM/a)	Feed	Product	Process
Belgium	BN/Dessel	Belgonucleaire	1973	40 ^a	PuO ₂	LWR FRs	MIMAS
	FBFC Int'l	FBFC	1987 ^b	120-200 ^c	FRs	LWR FAs	Assembly
France	CFCa	Cogema	1962	10	PuO ₂	FBR FAs	COCA
	MELOX	Cogema	1989	40 ^d	PuO ₂	PWR FRs	MIMAS
			1995	100 ^a	PuO ₂	PWR FAs	MIMAS
India	Tarapur	BARC	1994	18	PuO ₂	BWR FAs	Conventional ^e
Japan	PFFF	JNC	1972	10 ^f	(U-50%Pu)O ₂	ATR FAs	Conventional
	PFPF	JNC	1988	5 ^g	(U-50%Pu)O ₂	FBR FAs	Conventional
Russian Federation	Paket	Mayak	1986	0.3	PuO ₂	FBR FAs	Conventional
	ERC	RIAR	1981	1	Spent fuel	FBR FAs	Vipac
UK	MDF ^h	BNFL	1994	8	PuO ₂	PWR FAs	SBR

^a Capacity restricted by licensing.

^b New part of a uranium fuel fabrication plant in operation since 1963.

^c 120 t HM/a (700 FAs/a) (BWR only); 200 t HM/a (440 FAs/a) (PWR only).

^d Capacity if no FBR fuel is being fabricated.

^e 'Conventional' means pellet fabrication processes based on compaction granulation of the feed powders, as is used in most uranium fuel fabrication plants.

^f The licence is based on plutonium processed annually, i.e. 850 kg Pu/a.

^g The licence is based on plutonium processed annually, i.e. 2.5 t Pu/a.

^h The facility ceased commercial operation in 1999 and, in the future, it is intended that it will be used as a technical support facility to the Sellafeld MOX plant [40].

plutonium stockpile over the past decade. The available fabrication capacity for FBR fuel is over 20 t HM/a, which significantly exceeds demand [29].

3.1.2. Fabrication processes

The various fabrication processes developed historically and applied currently, well described in some detail in Refs [7, 29], will only be summarized here.

3.1.2.1. Powder processing routes

In enriched uranium, the fissile material is inherently present in the fuel. In MOX fuel, the fissile material, plutonium, has to be added to the carrier material, uranium. This blending of two fissile/fertile materials is the most specific difference between uranium and MOX fuel manufacturing.

The conventional fabrication route is a direct application of the most common industrial fabrication process for uranium fuel, the enrichment of uranium being replaced by a mechanical blending of the feed powders: UO_2 and PuO_2 , or $(\text{U-Pu})\text{O}_2$ for the plutonium delivered by the JNC reprocessing plant. As the blended powder is not free flowing, and is therefore unsuitable for feeding to a pellet press, the powder is preconditioned by precompaction in a slugging press, followed by granulation, the granules being obtained by crushing the slugs. The challenge in this process is to obtain a uniform distribution of the plutonium in the product [29]. Optimizing the ball (or attritor) mill is of paramount importance for achieving uniformity of the plutonium distribution, as well as a good dispersion of the lubricant and of the pore former, if the use of a pore former is required.

Figure 5 illustrates a schematic flow sheet of such a conventional fuel fabrication process. It represents the process applied by JNC in PFFF and PFPF and, approximately, by Mayak in Paket. While JNC most commonly starts from co-denitrated $(\text{U-50\% Pu})\text{O}_2$, Paket is fed by PuO_2 , as are all other current MOX fuel manufacturing plants.

The elaborate process currently applied by JNC in PFPF (Fig. 6) provides a particular example of a conventional powder production process. The additives utilized include a binder, to improve granulation, a pore former, to achieve the low density specified for FBR fuel, and a lubricant, as universally used to optimize pelletizing. In such processes, de-waxing of the green pellets is required prior to sintering. Excellent quality fuel can be fabricated by such a process.

The BARC plant also utilizes the conventional process, with the specific feature that the blending and ball milling operations are conducted in a single attritor mill, as initiated by BNFL.

A simplification of the conventional feed powder processing route (which is to MOX fuel what the enrichment operation is to uranium fuel) was developed in the

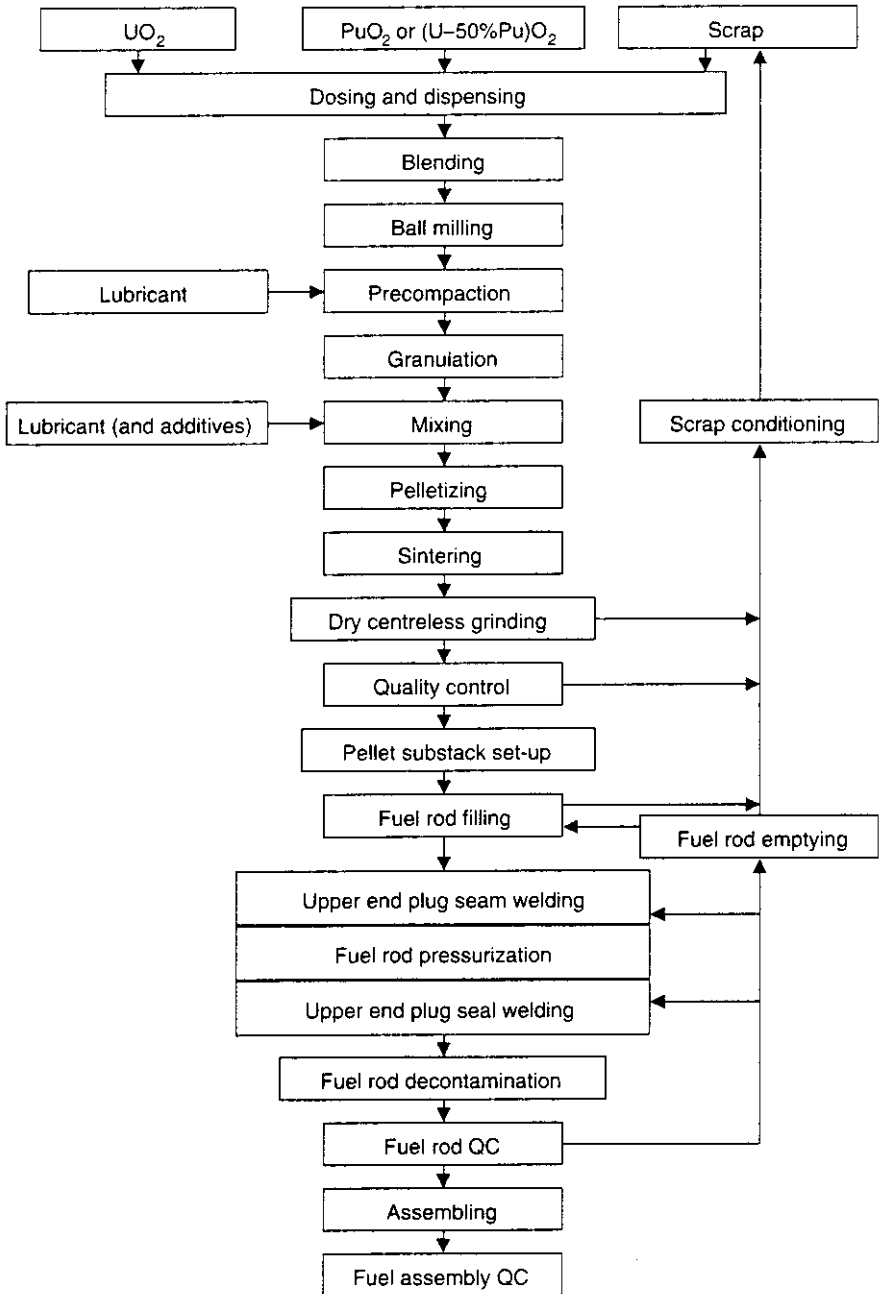


FIG. 5. Flow sheet of a conventional fabrication process.

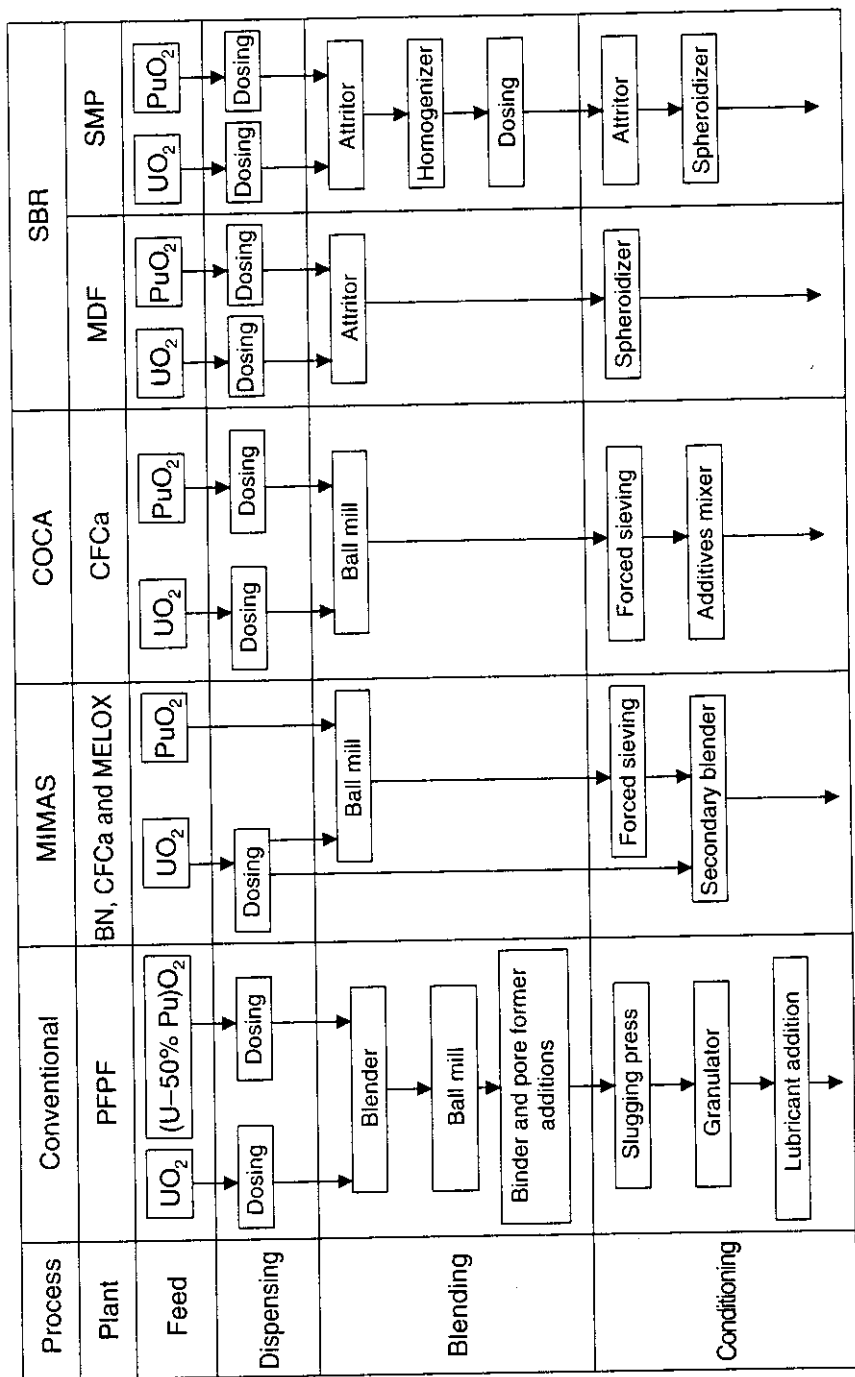


FIG. 6. Schematic flow sheets of the powder processing routes (incorporation of additives and scrap recycling not represented).

1970s by CEA and applied in the Cadarache fabrication plant under the name COCA, an acronym for Cobroyage (co-milling) Cadarache. It is based on the use of an optimized ball mill acting as a blender and of a forced extrusion of the lubricated micronized powder through a sieve, resulting in free flowing granules adequate for feeding the pellet press (Fig. 6). This process, originally developed for FBR fuel, has been adapted for LWR fuel and used from 1989 to 1994 for manufacturing MOX fuel for EDF's PWRs. However, this adaptation has proved to be difficult to master [41] and, as a result, the micronized master blend (MIMAS) process has been preferred for LWR fuels and is now applied in this plant [29].

An original development was conducted in the 1980s by BNFL and resulted in the short binderless route (SBR), based on the application of alternative process equipment for the blending and granulation functions (Fig. 6). The traditional ball mill is replaced by an attritor, an off-the-shelf mill widely used in the pharmaceutical industry and adapted for providing good blends of constituents in a short processing time. The precompaction granulation equipment is replaced by a spheroidizer, working on a powder agglomeration principle [29].

The MIMAS process, invented by Belgonucleaire in the early 1980s, is an adaptation of the reference fabrication process developed earlier and applied commercially in the 1970s at the Dessel plant. The reference process consisted of a single blending of PuO_2 powder with free flowing UO_2 powder, resulting in a blend of adequate flowability to feed the pellet press. However, when the reprocessors decided that even unirradiated MOX fuel had to be almost completely soluble in a pure nitric acid solution, the reference fuel was deemed to be no longer acceptable [29]. To meet this new specification, the earlier single blending step was replaced by a two step blending approach: in the first step, the pure PuO_2 feed and some UO_2 are co-micronized resulting in a master mix of UO_2 -(typically)30% PuO_2 , which is the fundamental principle of the MIMAS process (Fig. 6); in the second step, the master mix is blended down with free flowing AUC or ADU UO_2 to the specified plutonium content of the MOX fuel. The very close contact between the micronized UO_2 and PuO_2 particles provides for adequate interdiffusion during sintering and therefore the required solubility. In parallel, Alkem (subsequently part of Siemens) had developed and applied commercially the sibling optimized co-milling (OCOM) process [7], with a similar success in fabricability and improved fuel behaviour. The main differences between MIMAS and OCOM were in the ball milling and powder conditioning steps.

While Paket uses a conventional process for manufacturing most of its FBR fuel, one third of the production has used ammonia co-precipitated MOX powder and a further 5% of the production was by a sol-gel process, i.e. two alternative processes developed at Mayak. The facility uses a high energy mixer for milling and blending feed oxides and scrap.

The process being developed at the Experimental Research Complex by the radiochemistry department (ERC/RIAR) there starts with spent fuel and produces

Vipac fuel. It is based on molten salt dissolution in a 'chlorator-electrolyzer' made of pyrolytic graphite; the electrorefined UO_2 and/or MOX is deposited on the cathode as a loose crust that is crushed and sized to produce the required size fractions which are fed into the fuel rod by vibro-compaction. More details on the process can be found elsewhere, for example Ref. [36]. Although further development is being pursued, the facility has already produced fuel [37].

3.1.2.2. *Fabrication technology*

Following preparation of the MOX powder, all the subsequent processes are similar with some minor variations. Pelletizing is carried out in hydraulic presses; only Siemens/Hanau has installed rotary presses in their large plant. Sintering is most commonly conducted in continuous furnaces, except in PFFF, which is equipped with batch furnaces, and in PFPF, currently equipped with both types of furnace. Centreless grinding is now performed dry, which, in principle, does not require subsequent drying of the ground pellets. However, the JNC operation includes a degassing step after sintering for the low density Monju fuel pellets. Tungsten inert gas (TIG) welding is commonly adopted, for both the seam and the seal welds of the end plug. Only Siemens/Hanau used resistance welding, as for their uranium fuel.

For FBR FAs, the assembling operation starts, in most cases, with fitting a helical spacing wire to the rods and involves the introduction of a bundle of FRs into the FA wrapper tube (hexcan). For LWR FAs, the FRs are positioned in magazines and drawn from the magazines through the FA skeleton. For ATR FAs and most of the UK FBR fuel (up to 1988), individual FRs are directly loaded into the gridded FA skeleton.

As for the powder preparation routes described above, each fabrication plant is characterized by specific processing approaches, influenced by their design bases and licensing limits. In this respect it is worth noting, amongst other factors, the minimum ^{240}Pu content of the plutonium to be processed, its maximum americium content, the maximum percentage of plutonium in the MOX fuel and the maximum allowed personnel exposure. These are provided, as illustrations, in Ref. [29] and influence the equipment adopted and the plant layout.

The Belgonucleaire plant has fitted the original MIMAS process to the requirements of their 40 t HM/a industrial operation. An almost uniform isotopic composition throughout a fabrication campaign is achieved by computerized selection of the feeding sequence of PuO_2 supply cans to the process, guaranteeing thereby the energetic equivalence of all the FAs throughout their utilization. The automated operation of a sophisticated ball mill provides for homogeneous and uniform distribution of the PuO_2 in the 60 kg MIMAS master blends. Developments have broadened the types and proportions of scrap that can routinely be dry recycled in the process (Section 3.1.5). The 80 kg capacity of the secondary blender, optimized

to obtain a uniform distribution of the master blend in the free flowing UO_2 , is a compromise between simplification of product traceability and minimization of the scrap and waste arisings, taking due consideration of the required plant flexibility. In general, all the items of equipment and their sizes have been conceived in line with the objectives of the plant: producing fuel to a large variety of specifications in rather small fabrication campaigns (typically 4–29 t HM, each comprising three to eight different fuel compositions and/or FR types). The FR filling and welding unit is designed with minimum intrusion of the cladding into the glovebox, to minimize FR surface contamination, decontamination and contamination monitoring.

CFCa, later renamed Cogema/Cadarache, which has historically been the largest FBR fuel plant with two dedicated fabrication lines, has acquired and implemented the Belgonucleaire LWR fuel technology to launch industrial LWR operations while, at the same time, testing automated transfer and quality control (QC) devices for MELOX [15]. The adjacent Commissariat à l'énergie atomique (CEA) plutonium facilities provide for scientific research into the process parameters, resulting in an opportunity to improve fabrication continuously, complementing the large database acquired by the past industrial operation of the MIMAS process.

The MELOX plant [32] is the first large scale LWR MOX fuel facility. The MIMAS process was adapted ('A-MIMAS') to achieve the main objective of the plant, namely to fabricate fuel in large fabrication campaigns (typically 90 t HM, each consisting of only three discrete plutonium contents). In this context:

- (a) Complete automation has been implemented from the selection and opening of the PuO_2 canisters to the emptying of individually chosen PuO_2 cans.
- (b) The ball mill has been maintained at 60 kg capacity, providing the possibility to use up to 70% pellet scraps as input and resulting in the same excellent homogeneity and uniformity of PuO_2 distribution in the A-MIMAS master blend as from the original ball mills.
- (c) A high capacity (640 kg) secondary blender, consisting of a conical screw mixer with a double envelope air cooling system, has been adopted.
- (d) An automatic video inspection of the pellets with rejection of out-of-specification pellets has been incorporated in the fabrication line.
- (e) The filling, welding and decontamination of FRs has been enclosed in one single glovebox, containing essentially the same industrial equipment as used for uranium fuel in the FBFC plants.
- (f) The FA manufacture, QC and handling have been fully automated.
- (g) The waste is minimized through sorting and treating it and irrecoverable scrap in a dedicated building on the MELOX site, in the liquid effluent treatment unit of Cogema Marcoule and in the centralized UCD and URP facilities at Cogema La Hague.

As its name indicates, MDF was conceived as a test facility for the SBR concept and not as an industrial fabrication facility: the emphasis was to put it rapidly into operation and gain irradiation experience of SBR fuel, rather than to optimize the equipment layout. Attention was mainly exercised on the demonstration of four specific features:

- (1) The vertically integrated attritor–spheroidizer system.
- (2) The transport system of pellets: picking and placement of the green pellets in the sintering boats and cushion transfer.
- (3) The loading system of pellets into the FRs.
- (4) The development of all the QC procedures and techniques required for commercial fuel.

The BARC facility, devoted to the development and demonstration of an industrial fabrication technology, is described in Ref. [38].

Similarly, the PFFF and PFPF plants are described respectively in Refs [33, 42]. PFPF has raised the fabrication technology to a very high degree of automation. The experience resulting from the problems encountered (e.g. the historical high level of plutonium hold-up and the jamming of the sintering furnace) has resulted in innovations and is invaluable for progressing towards a proper selection of MOX fabrication equipment and appropriate technology.

The facilities in the Russian Federation are developing technology for future industrial fabrication plants and, in this context, are producing demonstration quantities of MOX fuel [43]. This will define the technologies and equipment appropriate for future deployment [44, 45].

3.1.3. Fabrication records

Tables II and III provide, for LWR and FBR fuels, respectively, the production quantities from all facilities since the start of their operation until 31 December 2000. Although definitively shut down, the Siemens/Hanau plant, the Sellafield FBR facility and the FBR line of PFFF have been included in recognition of their significant contribution to MOX fuel industrialization. In these tables, and throughout this section, only deliveries accepted by the customers are included; additional quantities either rejected or still to be accepted by the customer have, of course, been fabricated. Operators of the current fabrication plants have also fabricated small additional quantities of fuel in the 1960s in earlier laboratory (and sometimes demonstration) facilities: Belgonucleaire SCK/CEN (at Mol), Siemens (at Karlsruhe) and the United Kingdom Atomic Energy Authority (UKAEA).

While the fabrication experiences for both types of fuel are equivalent in terms of numbers of FRs and FAs, the tonnage of fuel produced and of plutonium processed

TABLE II. LWR FUEL FABRICATION RECORDS AS OF 31 DECEMBER 2000
(rounded figures)

Facility	Since facility startup				1999 (t HM)	2000 (t HM)
	t HM	t Pu ^a	FRs	FAs		
Belgonucleaire	467	26	246 000	1420 ^b	38	38
Siemens/Hanau	158	6.4	77 000	380	—	—
CFCa	248	16	126 000	480 ^b	40	41
MELOX	455	24	254 000	1050 ^c	104	102
MDF ^d	14 ^e	1 ^e	7 300 ^e	36 ^e	Nil	Nil
BARC	3	0.1	800	23	1	1
PFFF (ATR fuel)	120	1.9	22 500	750	Nil	Nil
Total	1500	80	700 000	4100	180	180

^a Contained in the delivered fuel.

^b Mainly manufactured at FBFC.

^c Includes 92 FAs incorporating pellets and FRs fabricated at CFCa.

^d The philosophy was to make different fuel designs (Table IV) to support business in SMP.

^e Out of which, respectively 3.9 t HM, 0.3 t Pu, 2112 FRs and 8 FAs were later not accepted by the customer [46].

TABLE III. FBR FUEL FABRICATION RECORDS AS OF 31 DECEMBER 2000
(rounded figures)

Facility	Since facility startup				1999 (t HM)	2000 (t HM)
	t HM	t Pu	FRs	FAs		
Belgonucleaire	4.2	1.3	14 000	70	—	—
Siemens/Hanau ^a	5.9	1.9	26 000	100	—	—
CFCa	110	22	430 000	2300	Nil	Nil
Sellafield ^b	13	2.6	98 000	300	—	—
PFFF	4	1.1	44 000	375	—	—
PFPF	10	2.5	63 000	401	Nil	Nil
Paket	1.4	0.5	6 700	53	Nil	Nil
RIAR	4.3	0.5	26 000	436	Negl. ^c	Negl. ^c
Total	150	33	710 000	4000	Negl. ^c	Negl. ^c

^a Now being decommissioned.

^b Decommissioned.

^c Less than 1 t HM.

is larger for LWR fuel than for FBR fuel and the LWR experience is more contemporary.

The fuels mentioned in Tables II and III are for a large variety of NPPs in thirteen countries (Table IV).

The experience over the past decade encompasses a broad range of characteristics [29], covering the full range of industrial MOX fuel of current design. It is particularly important to notice that personnel exposure has been generally decreasing or stabilizing over the years, notwithstanding the increasing radioactivity of the plutonium being processed and the increasing plutonium contents of the fuel being fabricated. Indeed, while plutonium derived from reprocessing of gas cooled reactor (GCR) fuel was a common feed in the 1980s, almost all the feed is now plutonium derived from reprocessing of LWR fuel, with consequentially higher specific gamma and neutron activities.

3.1.4. Fuel quality

As is evidenced in a large number of publications by fabricators as well as customers, the fuel produced today meets the specification requirements and is of a quality equivalent to top grade uranium fuels. A good illustration is the burnup achieved by commercial MOX fuels in NPPs (Section 5).

The difficulties of working in gloveboxes without adequate space in facilities not originally designed for industrial production can lead to short-cuts in the manner in which procedures are actually applied [46]. Owing to the importance of MOX fuel quality to the customers' licensing authority and the public, any malfunction in the QC and/or QA related systems has serious consequences for the fuel manufacturer [46, 47].

It is beyond the scope of this report to overview all the quality attributes of MOX fuels, FRs and FAs. Various publications have dealt with this topic or have been devoted to it, for example Refs [31, 48]. Only two characteristics, approached and achieved differently by each specific fabrication route, will be reviewed: the homogeneity of the plutonium distribution in the MOX fuel and the uniformity of the plutonium isotopic composition within a fabrication campaign.

3.1.4.1. Homogeneity of plutonium distribution

A homogeneous distribution of the plutonium within the fuel serves four purposes:

- (1) It imparts to MOX fuel the same resistance to reactivity initiated accident (RIA) failures as that for uranium fuel. This (historically first) requirement resulted from the Special Power Excursion Reactor Test (SPERT) power burst

TABLE IV. NPPs FOR WHICH THE FUEL HAS BEEN FABRICATED
(status as of 31 December 2000)

Plant	Type ^a	Belgo-nucleaire	Siemens	CFCa	MELOX	Others ^b
Belgium	BR 3	P	x ^c			
	Doel 3	P	+ ^d			
	Tihange 2	P	+			
Canada	NPD	H	x			
Czech Republic	Beznau 1	P	+			M
	Beznau 2	P	+	+		M
	Gösgen	P	+			
France	Blayais 1	P				+
	Blayais 2	P	+		+	+
	Chinon B 1	P				+
	CNA	P	x	x		
	Chinon B 2	P				+
	Chinon B 3	P				+
	Chinon B 4	P				+
	Dampierre 1	P	+		+	+
	Dampierre 2	P	+		+	+
	Dampierre 3	P				+
	Dampierre 4	P				+
	Gravelines 1	P				+
	Gravelines 2	P				+
	Gravelines 3	P	+		+	+
	Gravelines 4	P	+		+	+
	Phenix	F	+		+	
	St. Laurent B1	P	+		+	+
	St. Laurent B2	P	+		+	+
	Superphenix	F			x	
	Tricastin 1	P			+	+
Tricastin 2	P			+	+	
Tricastin 3	P			+	+	
Tricastin 4	P				+	

TABLE IV. (cont.)

Plant	Type ^a	Belgo-nucleaire	Siemens	CFCa	MELOX	Others ^b	
Germany	Grafenrheinfeld	P	+	+	+		
	Isar 2	P			+		
	Philippsburg 2	P	+	+	+		
	Obrigheim	P		+	+		
	Neckarwestheim 1	P		+			
	Neckarwestheim 2	P			+		
	MZFR	H		×			
	KNK	F	×	×			
	Lingen	B		×			
	Brokdorf	P	+	+			
	Unterweser	P	+	+	+	M	
	Grohnde	P		+	+		
	Gundremmingen A	B		+			
	Gundremmingen B	B	+	+			
	Gundremmingen C	B	+				
	SNR	F	×	×			
	VAK	B		×			
	India	Tarapur 1	B				T
		Tarapur 2	B				T
Italy	Garigliano	B	×				
Japan	Fugen	A				J	
	Joyo	F				J	
	Monju	F				J	
	Takahama ^c	P				M	
	Fukushima 1-3	B	+				
	Kashiwazaki Kariwa 3	B	+				
Kazakhstan	BN-350	F				P + R	
Netherlands	Dodewaard	B	×				

TABLE IV. (cont.)

Plant		Type ^a	Belgo-nucleaire	Siemens	CFCa	MELOX	Others ^b
Russian Federation	BOR-60 BN-600	F F					R P + R
Sweden	Oskarshamn 1	B	+				
United Kingdom	DFR ^f PFR ^f	F F	× ×		×		
Totals	PWR + PHWR BWR + ATR FBR	38 13 11	19 7 4	9 4 2	17 — 3	20 — —	3(M) 2(T) + 1(J) 2(P) + 3 (R) + 2(J)

^a A = ATR; B = BWR; F = FBR; H = PHWR; P = PWR.

^b M = MDF; P = Paket; R = ERC/RIAR; T = BARC; J = PFFF/PFPF.

^c ×, Reactor now shut down.

^d +, Reactor still operating (not necessarily with MOX fuel).

^e Fuel delivered to the NPP, but not loaded [40].

^f Most of the fuel was fabricated in a BNFL facility now shut down.

experiments [49] conducted in the late 1960s. The conclusion drawn from these experiments was that a fissile particle of some threshold size could potentially pierce the cladding below the fuel failure limit of homogeneous fuel (170 cal/g radially averaged fuel enthalpy). In view of this, the pellet specifications define a maximum plutonium-rich agglomerate size (e.g. corresponding to a pure PuO₂ particle of 400 μm diameter) and a plutonium dispersion criterion (e.g. less than 5% of the plutonium to be present in agglomerates larger than 100 μm). Although more recent Nuclear Safety Research Reactor (NSRR) tests conducted by JAERI have failed to reveal any influence of plutonium-rich particles on the power excursion failure threshold, the MOX specifications continue to include plutonium-rich particle size limits. Modern fuel fabrication technologies can easily meet this specification item.

- (2) It minimizes power peaks resulting from plutonium maldistribution. While the pellet-to-pellet enrichment is practically constant in uranium fuel, the plutonium

- content of pellets varies in MOX fuel, as a result of mechanical blending of the constituents. The power peaks resulting therefrom penalize the admissible power ratings of MOX fuel. Therefore the pellet-to-pellet homogeneity of the plutonium distribution is included in the specifications. The term 'macrohomogeneity' can be used to distinguish it from 'microhomogeneity'.
- (3) It ensures solubility in pure nitric acid solutions. As indicated previously, this requirement was raised in the early 1980s by the industrial reprocessors. As MOX crystallographic lattices containing less than 40–50% plutonium are soluble, the solubility criterion requires that the plutonium content be below the solubility threshold in the individual grains. This plutonium distribution attribute can be called 'microhomogeneity'.
 - (4) It minimizes fission gas release (FGR) and the resulting rod internal pressure. This aspect will be elaborated in Section 5.

The degree of macrohomogeneity depends on the sophistication of the blending technology. Great efforts at optimizing the blending equipment and procedure have been made at each fabricator. All other factors being equal, the fabrication routes involving a progressive dilution of PuO_2 into UO_2 can more easily achieve macrohomogeneity than the processes that directly mix PuO_2 and UO_2 to the final required composition. Examples of such progressive blending processes are the MIMAS process, with the intermediate master blend, and the JNC process, with the co-denitrated (U–50% Pu) O_2 feed. Rod scanners are utilized for QC of the macrohomogeneity. In their most sophisticated version, they combine passive and active gamma and neutron scanning and provide for the QC of a large number of other FR attributes.

The degree of microhomogeneity depends on the blending and sintering technologies. In this respect, single step blending fabrication routes are better suited. The achievement of the SBR process is a good example. Through proper optimization of the powder processing and sintering steps, the MIMAS process, which produces generically microheterogeneous fuel, has been improved. As a result, a negligible amount of the plutonium is in agglomerates of a size sufficient to enhance FGR. Various publications have provided examples of plutonium particle size distribution and of their analytical determination, see for example, Refs [50–54].

3.1.4.2. Uniformity of plutonium isotopic composition

Plutonium dioxide is produced by European reprocessing plants in batches of typically 90–100 kg plutonium and conditioned in cans with around 3 kg (Cogema) or 7 kg (BNFL) plutonium for delivery to fabrication plants. While PuO_2 precipitation and finishing is a batch operation at La Hague, resulting in strictly identical isotopic composition of the plutonium throughout the batch, it is a continuous process at

Sellafield, resulting in a 'rainbow' transition affecting the first and the last cans of each PuO₂ batch. Depending on the average plutonium content of the MOX fuel, from 3 to 11 PuO₂ batches are involved in the fabrication campaigns typical for most plants but more than 50 PuO₂ batches for MELOX (90 t HM fabrication campaign).

The variability of the plutonium isotopic compositions amongst the PuO₂ batches to be incorporated in a fabrication campaign depends on the variation in types (PWR, BWR, advanced gas cooled reactor (AGR), Magnox) and burnups (from first cores to extended burnup reloads) of fuel that have been reprocessed. With a dwindling number of first cores being reprocessed, the variability of plutonium isotopic compositions is progressively diminishing. However it is still much too large to be neglected, since it critically affects MOX fuel design and performance. To compensate for the variability of the plutonium isotopic composition, Belgonucleaire initiated a plutonium equivalence formulation enabling the plutonium contents of each fabrication campaign, and of each MOX fuel batch within a fabrication campaign, to be corrected relative to the design basis plutonium contents. A similar approach has been adopted by all fuel designers and is now universally applied, except when NPP licence limits also require a consideration of the fissile plutonium content. For FBR fuel, the variability of the plutonium isotopic composition corrected by application of an adequate equivalence formula does not result in deterioration of the fuel quality. For LWR fuel, however sophisticated the equivalence formula, fuel performance is still affected by non-uniformity of the plutonium isotopic composition within a MOX fuel fabrication campaign. For instance, in a PWR, a power peak up to 6% can result from a variability of only 2% ²³⁹Pu in the plutonium isotopic composition, even when the plutonium contents are adjusted through a sophisticated equivalence formulation [55]. This illustrates the importance of achieving a uniformity in the plutonium isotopic compositions within a fabrication campaign of LWR fuel.

In the Belgonucleaire plant, uniformity is achieved by computerized selection of the four or five La Hague cans being incorporated in the ball mill to produce one 60 kg master blend. The computer programme takes into account, three months prior to starting up the campaign, the actual characteristics of each PuO₂ can provided (at the reprocessing plant) by the customer, of the PuO₂ cans in the fabrication plant buffer store and of the scrap cans available for incorporation in the primary and/or secondary blend. On the basis of the optimized feeding sequence defined by the computer programme, the PuO₂ transport sequence is organized from the reprocessing to the fabrication plant, the PuO₂ transport canisters are opened at the fabrication plant, and the PuO₂ and scrap cans are withdrawn from the store. This results in good uniformity of the plutonium isotopic composition amongst all the master blends within a fabrication campaign (for which the customer provides 3–15 PuO₂ batches). If this single homogenization step were to be insufficient, the

MIMAS process intrinsically offers the possibility of feeding the secondary blender with different master blends, providing an additional homogenization opportunity. Uniformity of the isotopic composition is likewise achieved in the LWR fuel fabricated at CFCa, since the same MIMAS process and the same ball mill are utilized.

The MELOX plant utilizes the same 60 kg ball mills and a similarly powerful computer programme for the selection of suitable PuO_2 cans. However, the homogenization is enhanced by a buffer store of 30 PuO_2 cans before ball milling and by the incorporation of at least two (and potentially up to eight) different master blends in the 640 kg secondary blender. While all the primary blends already meet the specified tolerances for isotopic uniformity, the variability achieved on the pellets is even smaller.

The other MOX fabrication facilities do not provide for a specific opportunity to cross-blend the PuO_2 , or co-denitrated (U-50% Pu) O_2 , feed batches within the MOX manufacturing process, except for the relatively large scale fuel fabrication at PFPP.

3.1.5. Scraps and wastes

For their plutonium management, all MOX fabrication plants have incorporated sophisticated systems for real time accountancy (see, e.g., Ref. [56]) and for minimization of the plutonium hold-ups within the equipment and gloveboxes.

Scraps are generated by the process itself (e.g. centreless grinding fines or sludge), by the rejects (e.g. non-conforming pellets) and by the surpluses fabricated within a fabrication campaign before switching to the next fabrication campaign. The latter in-line contingency inventories of MOX powder, pellets and FRs are relatively large whenever the campaign size is small. Adequate management of the scraps is an important consideration having economic (fabrication cost) and environmental (personnel exposure and waste generation) impacts. From this perspective, all the MOX fuel manufacturers have developed and/or are examining technologies (including scrap conditioning) to recycle scraps into the process without prejudicing MOX fuel quality. Belgonucleaire can now operate with up to 76% of primary blend consisting of scrap. Their current experience extends to scrap feed being 23% of the final product. In CFCa, the transition from the COCA to the MIMAS process has resulted in the possibility of incorporating up to 50% scrap in the primary blend. Similarly, the A-MIMAS process in MELOX can accommodate 70% rejected pellets (clean scrap) in the master blend. This corresponds, respectively, to approximately 15 and 20% of the total feed. Trials made by BNFL with UO_2 at Springfields and with MOX at Sellafield have supported the development of an SBR flow sheet with recycle of sintered scrap.

Waste arisings originating from plant operation and maintenance, as well as waste due to originate from plant backfitting and ultimate decommissioning, have also received proper attention. Indeed, waste management influences fabrication costs, personnel exposure, licensability and public acceptance. At the Belgonucleaire plant, by identifying and optimizing the waste generating operations and by educating the personnel, plutonium contained in the waste has been reduced to less than 0.1% of the plutonium contained in the delivered MOX fuel [7], notwithstanding the policy of not stripping plutonium from the waste. This illustrates the accomplishments achievable by feedback from lessons learned. At MELOX, licensing authorizations impose a reduction in the radioactivity releases and the plutonium wastage to almost zero: as mentioned in Section 3.1.2, dedicated facilities have been commissioned at the MELOX/Marcoule site and at La Hague to achieve this target. In addition to this effort by all the manufacturing plants to minimize plutonium in the waste streams, improvement programmes are also being pursued to reduce the volumes of each radioactive waste category.

3.2. ISSUES AND CHALLENGES

In line with the evolution observed over the past few years, MOX fuel fabrication will be confronted with increasingly demanding and difficult targets and conditions.

The evolution to more radioactive plutonium feeds will continue, with the processing of aged plutonium stockpiles and the separation of plutonium from higher burnup uranium fuels. It can be assumed that the incentive to reduce personnel exposure will also persist.

With the increased likelihood of degraded plutonium isotopic compositions and the move to higher design burnups of MOX fuels, the plutonium contents will continue to increase (Section 4.4.2), potentially having an impact on personnel exposure and the quality of MOX fuel. The fuel itself may have to be fabricated to tighter specifications to account for the more severe irradiation duties.

On the other hand, weapons grade plutonium (WPu) will have to be manufactured into MOX fuel in the Russian Federation and the USA. The very high ^{239}Pu content of this plutonium simplifies the handling and processing it has undergone, but imposes criticality precautions and may consequently require adaptation of the equipment. The waste minimization objective will continue to be pursued.

In spite of this context, fabrication costs will have to be controlled, as the continuing decline of uranium prices and the fierce competition amongst uranium fuel fabricators affect the competitiveness of MOX fuel.

3.3. FUTURE DEVELOPMENTS

On the basis of lessons learned, the SBR process tested in MDF has been further developed for SMP [57, 58]. This optimized SBR process reduces the number of QC samples required and results in a larger quantity of fuel with an almost uniform plutonium isotopic composition. The following improvements are noted:

- (a) In the feed powder receipt and dispensing units installed on top of each of the two identical powder processing columns, a dual PuO_2 feed has been provided: it allows metered aliquots of plutonium of two different isotopic compositions to be incorporated in a MOX powder lot, to homogenize to some extent the isotopic composition within a fabrication campaign.
- (b) A homogenizer and a second stage attritor mill have been added (Fig. 6) to bulk together three 50 kg sub-lots from the first stage mill, with the advantage of constituting 150 kg powder lots.
- (c) The four continuous furnaces are capable of operating at up to 1750°C.
- (d) Each of the two identical FR fabrication and inspection lines is suitable for both PWR and BWR fuel.
- (e) The FA facilities consist of one automatic PWR assembly and inspection line and one automatic BWR assembly and inspection line.
- (f) The plant, which is fully automatic, is operated from a central control room which has been designed using virtual reality techniques to ensure that it is ergonomically correct.
- (g) An export facility has been built adjacent to SMP, to provide facilities for loading FAs into transport containers for shipment to customers.

From the perspective of preparing for the future, JNC has begun the development of a short process that omits the homogeneous blending and granulation steps, in a further cost reduction initiative [59].

The construction of the Japanese MOX plant (J-MOX), to be sited near the Rokkasho-mura reprocessing plant, is scheduled [60] to start in 2004 and to be completed in 2008. The design capacity has been selected to be 130 t/a of MOX fuel, predominantly for BWRs. The MIMAS process has been selected as the basis for the fabrication technology to be implemented.

As a result of its good performance for the fabrication of FBR fuel, the joint French–German–Russian team has selected the COCA process for disposition of Russian WPU into FBR fuel [61] in the planned DEMOX fabrication plant. The MIMAS process has been retained for the WPU to be dispositioned into WWER fuel [61, 62]. The MIMAS process has also been selected by the USA for fabricating their WPU into PWR fuel.

3.4. CONCLUSIONS

The MOX fuel manufacturing industry has reached maturity as a result of the long operating experience of current fabrication plants. Statistically significant evidence demonstrates that industrially produced MOX fuel achieves the same quality level as uranium fuel and meets customer requirements.

The large scale MELOX, PFPP and SMP plants are examples of extending technologies tried out in smaller plants to building and commissioning more advanced and larger facilities. The lessons learned from experience have been instrumental not only in designing and starting up the new facilities but also in backfitting smaller plants which have operated for many years.

In the next few decades, the industry will be confronted by additional challenges, which will again require similar progressive improvements dictated by experience.

4. LWR FUEL ASSEMBLY DESIGN, IN-CORE FUEL MANAGEMENT AND LICENSING

4.1. STATUS OF EXPERIENCE

MOX fuel assemblies are licensed today for a substantial number of commercially operated PWRs and BWRs in Belgium, France, Germany, India and Switzerland. Additionally, Japan, after performing an LWR MOX demonstration programme, now has four reactors currently licensed for MOX usage. The variety of reactors involved in commercial plutonium recycling and the fuel assembly types in use are shown by Table V. It also summarizes the status of experience with neutronic fuel assembly and core design using commercial MOX fuel. The number of MOX fuel assemblies reloaded demonstrates that plutonium recycling in LWRs has reached industrial maturity [63-66].

4.2. QUALIFICATION OF NEUTRONIC FUEL ASSEMBLY AND CORE DESIGN METHODS

Modern low leakage core designs together with the higher enrichments of uranium and MOX fuel assemblies places increasing demands, with respect to accuracy and reliability, on the design codes. For normal applications, qualified design codes prove to be adequate, accurate and efficient. Current nuclear design