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Invited Paper

THE TRANSPORTATION OF PuO_2 AND MOX FUEL AND MANAGEMENT OF IRRADIATED MOX FUEL

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Abstract

Information on the transportation of PuO_2 and mixed-oxide (MOX) fuel, the regulatory requirements for transportation, the packages used and the security provisions for transports are given. The experience with and management of irradiated MOX fuel and the reprocessing of MOX fuel are described. Information on the amount of MOX fuel irradiated are provided.

1. INTRODUCTION

Spent fuel management comprises the technical operations that begin with the discharge of spent fuel from a power reactor and end either with the reprocessing of spent fuel and recycling of plutonium and uranium in new mixed oxide fuel (closed cycle) or with the direct disposal of the spent fuel elements in a geological repository (open, once-through cycle).

A third approach is the deferral of a decision, the 'wait and see' strategy with interim storage, which provides the ability to monitor the storage continuously and to retrieve the spent fuel later for either reprocessing or direct disposal.

Countries like Canada, Sweden and USA retain their plutonium in the spent fuel and are planning to put their fuel in long-term storage followed by final disposal in deep geological formations. At least part of the fuel is reprocessed from countries like Belgium, France, Germany, Japan, Russia, Switzerland and UK. Countries with smaller nuclear programmes are currently deferring a decision on which of the strategies to select and are storing their fuel.

Plutonium from reprocessing is recycled in MOX fuel in Belgium, France, Germany, Japan, Russia and Switzerland.

Plutonium recycling and MOX fuel production are mature industries in Europe. PuO_2 powder and MOX fuel rods and assemblies are transported regularly. There is also wide experience in operating reactors with MOX fuel.

2. TRANSPORTATION OF PuO_2 AND MOX FUEL

Plutonium and MOX fuel have been safely transported for almost 40 years, mainly by road but also by the sea and air modes.

PuO_2 powder is filled in cans containing about 3 kg plutonium dioxide. According to the IAEA "Regulations for the Safe Transport of Radioactive Material" PuO_2 and MOX fuel must be packaged in accident resistant "Type B" containers which also take into consideration the fissile characteristics of the contents. BNFL, COGEMA and others have developed packages for PuO_2 powder transport. The BNFL 1680 and the COGEMA FS47 permit the shipment of large quantities of plutonium oxide in powder form. Similarly, packages designed for one or more MOX fuel assemblies have been produced and are currently in use.

2.1 Regulatory requirements

Shipments of plutonium and MOX have to fulfil the highest physical security requirements.

All packages and transport operations must comply with applicable national and international transport safety laws and regulations which are, in practically all cases, based on the transport safety regulations recommended by the IAEA. In addition to having been widely incorporated into national laws and regulations, the IAEA recommendations have also been introduced into international regulations including the:

- UN Committee of Experts on the Transport of Dangerous Goods "Recommendations on the Transport of Dangerous Goods - Model Regulations" (the "Orange Book")
- International Civil Aviation Organization (ICAO) - Technical Instructions for the Safe Transport of Dangerous Goods by Air
- International Maritime Organization (IMO) - International Maritime Dangerous Goods Code
- ADR - European Agreement concerning the International Carriage of Dangerous Goods by Road
- RID - European Agreement concerning the International Carriage of Dangerous Goods by Rail

Physical protection requirements are basically laid down in the IAEA document INFCIRC 225 , Rev. 3 and are further detailed in national regulations and guidelines which are classified “restricted”. For MOX shipments a large number of technical and administrative requirements have to be fulfilled.

In addition, for maritime transports, the “Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-Level-Wastes in Flasks on board of Ships” (the INF Code) is typically applied to all transports covered by this voluntary code. The IMO is currently taking the necessary steps to make the INF Code mandatory under the provisions of the Safety of Life at Sea Convention.

2.2 Packages

Plutonium transport packaging calls for diverse packaging types suitable for its many forms, ranging from powder to complete MOX fuel assemblies for LWRs and FBRs. Each type of package and design must satisfy the complete set of regulatory design and performance requirements. Although the material may be in very different forms the containment performance requirements for the packaging are the same. All packages for PuO_2 and MOX transport which contain “category I” quantities of plutonium must be designed to meet the Type B criteria. That means they are safe under both normal and accident conditions of transport. Additionally, their designs must be approved to account for the fissile nature of the contents.

For the transport of fresh fuel assemblies it is particularly important to ensure that the fuel is not subjected to any unacceptable shock loads or vibration. Continuous recording of vibration and shock loads are taken using special equipment such as recording accelerometers.

2.3 Transport

Type B(U) F packages are used for transportation of plutonium powder and fresh MOX fuel. Additionally, for road transport, special security trucks are typically used.

Irradiated MOX fuel moved from NPPs to reprocessing facilities is transported in Type B(U)F packages which are heavily shielded and which may be co-loaded with uranium fuel due to residual heat and neutron radiation considerations.

2.3. I Belgium

The transport of plutonium oxide and MOX fuel has been performed in Belgium for more than 30 years. The transport of PuO_2 has reached an industrial stage with the introduction of the French FS 47 packaging. Its handling at the reprocessing plant and at the fuel manufacturing plants, among those Belgonucleaire (Dessel), did not face any difficulty. So this system became standard. The safety margin offered by this packaging is largely in excess of the IAEA regulatory requirements. it has been demonstrated, for instance, that it can withstand extreme external pressures up to 1000 bar and that the seals of the containment envelope would not be affected by a 1000° C fire for a period of one and a half hour.

For smaller quantities of plutonium, TNB 145 packagings can be used too. This design was licensed in Belgium at the end of the 1979's and has been validated in several countries. It is used for the transportation of various types of materials including fissile material such as uranium and plutonium oxide. Various sizes of such drum like packagings are available, depending on the size and quantities of the material to be transported. The maximum allowed quantity of plutonium is 4.5 kg.

The transport of fresh MOX fuel assemblies is performed using packagings specially designed for such purpose. The TNB 176/FS 69 packagings are at present used for the transport of fuel assemblies in Belgium, France, and Switzerland.

In the same manner as for plutonium oxide, stringent security rules apply to the transport of MOX fuel assemblies. Depending on the type of security vehicle used for the transport, up to 8 MOX fuel assemblies can be transported at a time. Detailed procedures have been set up and approved by the Competent Authorities of the various European countries concerned.

Packagings for PuO_2 and MOX fuel assemblies

	Packaging	
	FS 47	**TNB 176/FS 69**
Content	**PUO_2**	**MOX fuel**
Capacity	**19 kg**	**2 assemblies**
Typical Activity (PBq)	**7.5**	**11**
Heat dissipation (max) (kW)	**0.3**	**1.2**
Weight (t)	**1.5**	**5 / 6.6**

2.3.2 *France*

The transport of plutonium and MOX fuel in France is performed in accordance with stringent requirements. France adopted the applicable international regulations which also take into account the IAEA regulations. To meet these regulations safety is usually provided by the package. Different packages have been developed and are used in France for the transport of material containing plutonium: FS-47 for PuO_2 powder, FS-67 for samples and FS-65 and FS-69 for fresh fuel elements.

Most of the plutonium powder is transported from the reprocessing plants to MOX fuel fabrication facilities for LWRs and FBRs (Belgonucleaire in Dessel, Cogema in Cadarache and Melox in Marcoule and in the past also Siemens in Hanau). More than 70 tons have been transported. The plutonium oxide powder separated at La Hague is loaded into stainless steal cans containing about 3 kg each. These cans are loaded into a leak-tight stainless steel canister. For transportation this container is placed in the FS 47 packaging with an overall weight of 1.5 tons and a capacity of about 19 kg of plutonium oxide. Ten FS 47 packagings are placed in a specially designed container providing additional security protection. A security truck is used for the transport of this type of packaging.

Since 1987, MOX fuel assemblies have been used in 900 MW type NPPs in France. MOX fuel rods are transported from the Cogema Cadarache facility to FBFC Dessel facility for assembling. MOX fuel assemblies are transported from the FBFC Dessel and Melox plants to the nuclear power plants. Two types of B(U)F packages are used which are transported in a security truck. The FS 69, designed for 2 PWR 900 MOX assemblies is equipped with neutron shielding and accommodates 1.2 kW thermal power resulting from the plutonium decay heat. Up to four FS 69 packages can be grouped in a protective container. Up to now 992 MOX fuel assemblies have been transported in the FS 69 container.

In 1994 COGEMA decided to develop a new container (FS 65) for MOX fuel serving both, 900 and 1300 MW PWR and BWR. The FS 65 can load 1 PWR 900 assembly, 2 BWR assemblies or 3 14 rods for PWR 1300 in the FS 65-1300 type. Up to now about 60 000 MOX fuel rods have been transported in the FS 65 and about 30 000 MOX fuel rods in the FS 65-1300.

As there will be up to 28 reactors at the end of the century loading MOX fuel a new packaging type, the MX 8, is under development to reduce the number of transports. This container and its basket are designed for 8 MOX assemblies.

2.3.3 *Germany*

2.3.3.1 Transport of fresh MOX fuel.

For road transport in Germany a combination of security systems is used. overview of equipment)

- an armoured transport vehicle
- an armoured escort vehicle
- an armoured control center
- communication lines between vehicles, control center and police
- vehicle tracking

Drivers, guards and control center operators have to undergo an extensive training and have to be licensed by the BfS.

The armoured transport vehicle "SIFA" is a tractor/trailer combination.

Class I shipments with this SIFA have been performed since 1982. More than 150 shipments from 3 manufacturers to 9 destinations have been carried out.

For shipments between UK and Germany an approach for sea transport has been developed which avoids loading/unloading procedures for container. The safety vehicle picks up the MOX fuel at the fabrication facility at Sellafield, brings it to the port, is loaded onto a Ro-Ro (roll on roll off) ship. and drives it from the German port to the final destination. For MOX scrap from Hanau it goes the other way around. The first transport of this kind took place in October 1996. 6 road/sea/road shipments have been performed since.

2.3.3.2 *Transport of irradiated MOX fuel:*

MOX fuel transported from German NPPs to reprocessing has been co-loaded with uanium fuel due to decay heat and neutron radiation considerations.

Specific transport systems for irradiated MOX fuel was licensed in Germany include:

Transport cask CASTOR-KRB-MOX

License:	D/4193/B(U)F, Rev. 0, 9.9.1986
Capacity:	16 MOX BWR FA
Max. burnup:	14 GWd/t HM
Decay time:	min. 5 years
Enrichment:	max. 2.5 % Pu in U_{nat}

This cask was used for the transport of MOX fuel from Germany to the CLAB facility in Sweden.

Transport cask CASTOR S1

This is a wet transport cask for the transport of spent fuel, including MOX fuel, from German NPPs to the reprocessing plant in Sellafield, UK.

License:	D/4229/B(U)F-85, Rev. 8 validation in France and UK
Capacity:	6 PWR fuel assemblies including 2 MOX fuel assemblies
Max. burnup:	50 GWd/t HM for MOX fuel
Decay time:	min. 2 years
Enrichment:	max. 4.1 % U-235 for Uranium fuel, max. 3.3 % Pu_{fiss} + max. 0.72 % U-235 for MOX fuel

120 transports were made with 4 casks including 15 transports with MOX fuel.

Transport and storage cask CASTOR V/19

License:	D/4323/B(U)F-85, Rev. 1 and D/4312/B(U)F-85, Rev. 2 storage license for Ahaus and Gorleben
Capacity:	19 PWR FA including 4 MOX FA
Max. burnup:	55 GWd/t HM for MOX fuel
Decay time:	min. 10 years
Enrichment:	max. 4.05 % U-235 for Uranium fuel, max. 3.95 % (Pu_{fiss} + U-235) for MOX fuel
Heat load:	max. 39 kW

3 casks are stored each in Ahaus and Gorleben with Uranium fuel only.

Transport and storage cask CASTOR V/52

License:	D/4319/B(U)F-85, Rev.1 storage license for Ahaus
Capacity:	52 BWR FA including 16 MOX FA
Max. burnup:	50 GWd/t HM for MOX fuel
Decay time:	min. 10 years
Enrichment:	max. 4.6 % U-235 for Uranium fuel, >4.2 % U-235 proof of min. 5 GWd/t HM burnup` max. 5.7 % (Pu_{fiss} + U-235) for MOX fuel or 4.9 % Pu_{fiss} and min. 0.2 % U-235.
Heat load:	max. 40 kW

3 casks are stored in Ahaus with uranium fuel only.

2.3.4 Japan

Fresh MOX fuel has been transported to the FBR reactors Monjyu and Joyo and the ATR reactor Fugen using type B(U)F and type B(M)F packages with a cylindrical design. The transports applied to the first core for Monjyu, about 450 MOX assemblies for Joyo and more than 500 MOX assemblies for Fugen.

Later this year it is planned to transport MOX fuel forthermal reactors from the UK to Japan. A modified ship will be used for the escorted shipment.

2.3.5 *Switzerland*

With the exception of small quantities of separated plutonium for research purposes, plutonium is shipped into Switzerland in the form of MOX assemblies only. A number of transport systems have been used over the last 20 years such as

- the French safety vehicle and FS 69 container
- the German safety vehicle "SIFA" with Siemens container.

2.3.6 UK

Plutonium has been safely transported by BNFL both nationally and internationally for the last 35 years. The transport operations have been carried out in accordance with national and international law which is based on regulations recommended by the IAEA.

The current practise in the UK is to use small MOX packages which fit into secure containers. A protection system is used to extend the time required to gain access to the cargo. With EUROMOX BNFL is designing a new system for secure transportation to cover a wide range of LWR fuel types and sizes within Europe.

MOX fuel shipped from the UK to Germany is transported by sea using a UK tractor unit and the German high security trailer. The MOX fuel is transported from Sellafield to the port and loaded on a German vessel as mentioned before.

For the transport to Japan late this year the fuel will be transported by rail from Sellafield to the port. A modified vessel will be used for the escorted shipment.

3. MOX FABRICATION

MOX fabrication is a mature technology in Europe. To better match the plutonium output from reprocessing and to reduce the present stockpile, MOX production capacity and utilization are in the stage to be increased.

Except for Germany (since termination in 1991) and Switzerland, the countries with reprocessing or plutonium recycling have their own MOX fabrication. In the 1950s plutonium from reprocessing was intended for feeding FBRs. In the 1960s, R&D activities started on the utilization of plutonium in MOX fuel for LWRs. The ALKEM facility in Germany for LWR MOX and FBR fuel, Belgonucleaire in Belgium, CEA facility in France, UKAEA in UK and PNC at Tokai Mura in Japan for FBR fuel started operation. The UK also demonstrated MOX utilization in the Windscale AGR.

Because of delays in the deployment of the FBR programme, the utilization of MOX fuel in LWRs became more and more important. Today MOX fuel fabrication and utilization reached a level of about 200 t HM/year and will further increase with the commissioning of BNFL's Sellafield MOX Plant (SMP). (Table I MOX fuel fabrication capacity)

While in France MELOX is a basic 17x17 PWR plant for EDF type fuel, Cadarache will cover PWR and BWR mainly for Germany and fast reactor fuel production. Belgonucleaire in Dessel, Belgium, fabricates MOX fuel for Belgium, France, Germany and Switzerland and SMP, UK is designed to make PWR, BWR and fast reactor fuel. Adequate capacity is provided in Japan to cope with the advanced breeder reactor and advanced thermal reactor requirements.

TABLE 1. MOX FUEL FABRICATION CAPACITY 1998

Country	Site	Plant	tHM/y
Belgium	Dessel	PO	35
France	Cadarache	CFC	35
	Marcoule	MELOX	120
India	Tarapur	AFFF	5
Japan	Tokai	PFPF	15
Russian Fed.	Chelyabinsk inside RT 1		
UK	Sellafield	MDF	8
Total			218

4. MANAGEMENT OF IRRADIATED MOX FUEL

Testing of MOX-fuel in reactors has taken place from the early days. In the last decade their performance approached that of conventional UO_2 fuel. Its use has increased enormously over recent years and will continue to do so. Many reactors will go up to 30 % of MOX-fuel in the core. At present European experience of MOX irradiation extends to 52 GWd/t rod average burn-up in commercial PWRs and up to 60 GWd/t in experimental assemblies. These irradiations show a good general behaviour of the MOX fuel.

Plutonium recycling in Germany started in the BWRs Kahl and KRB-A. The commercial MOX programme concentrated on PWRs starting with Obrigheim in Germany and Beznau-2 in Switzerland.

France started its MOX programme in 1987 with the 900 Mwe PWRs. Today MOX fuel is used in LWRs in Belgium, France, Germany and Switzerland. FBRs are in operation in France, India, Japan, Kazakhstan and Russia. (Table 2 Status of MOX fuel utilisation in thermal rectors)

TABLE 2. STATUS OF LARGE SCALE MOX FUEL UTILIZATION IN THERMAL REACTORS
Status end of 1998

	Number of Thermal Reactors			
	Operating [1]	**Licensed to use MOX FAs[a]**	**Loaded with MOX FAs[a]**	**Applied for MOX license[b]**
Belgium	7	2	2	
France	58	20	17	8
Germany	20	12	10	4
Japan	53	3	1	1
Switzerl and	5	3	3	
Total	133	40	33	13

[a] There are a number of reactors, notably in Europe and India, not included in this Table, which are
licensed to use MOX fuel and have MOX fuel loaded on an experimental basis;

[b] Technically capable reactors planned to be licensed.

4.1 Management of irradiated MOX-fuel in Belgium =

(Table 3 thermal reactors utilising MOX fuel)

Under experimental conditions MOX fuel from Belgonucleaire was inserted in the BR3 reactor in Belgium and Dodewaard in the Netherlands.

Doel-3 and Tihange-2 are licensed for MOX fuel reload. 56 MOX fuel assemblies have been loaded so far with 4.9% Pu_{fiss} in U_{tails}. The maximum FA burnup is 43,900 MWD/T HM (Table 4 experience with MOX reloads). Belgium also practices the recycling of the reprocessed uranium. As such, no stocks of usable fissile materials are built up.

Belgonucleaire evaluated for Eastern European countries the possibility of loading a WWER-1000 reactor with MOX-fuel. Calculations demonstrated the feasibility of the use of ex-weapon plutonium in MOX-fuel for this reactor type.

4.2 Management of irradiated MOX-fuel in France:

(Table 3 thermal reactors utilising MOX fuel)

France opted for the closed fuel cycle. After slowing down the FBR implementation, emphasis has been given on the plutonium recycling in PWRs. Every year, EDF unloads 1200 to 1300 tons of spent fuel. 850 tons are reprocessed by UP2 and 8 tons of plutonium are recovered. EDF's annual need of MOX fuel is about 120 tons.

EDF decided in 1985 to recycle plutonium in some of its PWR 900 units. A generic safety report was issued at the end of 1986 which demonstrated the feasibility of recycling MOX with a maximum ratio of 30 % MOX assemblies in each reload. This corresponds to 16 assemblies per reload. In 1987 the first MOX fuel was loaded into St. Laurent Bl and B2.

Today 17 of the 20 licensed reactors are loaded with MOX fuel. EDF applied for a license to load MOX fuel for another 8 reactors and in this year the number of plants loading MOX will increase to 19. Up to the end of 1998 992 MOX fuel assemblies were irradiated in France (Table 4 experience with MOX reloads). The licensed plutonium content is 7.08% to cope with the quality of Pu produced now by the reprocessing plant.

Every fuel loaded in a French PWR, including MOX fuel, is intended to be reprocessed and EDF has to demonstrate to the Safety Authority that reprocessing is feasible before loading any new type of fuel. After a cooling period of about 4 to 5 years in the power plant, MOX fuel is sent to La Hague reprocessing plant in the standard transport cask.. Four spent MOX fuel assemblies are loaded together with 8 spent U02 fuel assemblies. The MOX fuel assemblies are placed in the central positions of the cask internal basket and surrounded by the U02 fuel.

Some tons of used MOX assemblies have been reprocessed at La Hague (irradiated in German and Swiss reactors) to demonstrate the industrial feasibility of reprocessing and the possibility of recovering huge quantities of plutonium in the case of an eventual future fast reactor programme.

As used MOX fuel assemblies contain more plutonium (20 kg Pu) than used uranium assemblies (4 kg Pu), one could imagine it would be more beneficial to give them a priority in reprocessing. Nevertheless, second generation plutonium produced from reprocessing is rich in isotopes which make it less energetic in a LWR than first generation plutonium. As the MOX matrix is made with depleted uranium, reprocessed uranium separated from MOX assemblies cannot be recycled in LWRs.

The existing inventory of EDF's used UOz fuel (about 7000 fuel assemblies) permits it to choose for reprocessing those assemblies which contain the most easily handled plutonium in the MOX fuel fabrication plant. Therefore, in order to maximize the advantage of reducing the total inventory of used assemblies, it is not planned to reprocess MOX fuel in the near future.

TABLE 3. THERMAL REACTORS UTILIZATING MOXFUEL ON A LARGE SCALE

Status yearend 1998

	Licensed[a]	Loaded[a]	Applied for licence[b]
Belgium	Doel 3	Doel 3	
	Tihange 2	Tihange 2	
France	Blayais 1	Blayais 1	Blayais 3
	Blayais 2	Blayais 2	Blayais 4
	Dampierre 1	Dampierre 1	Cruas 1
	Dampierre 2	Dampierre 2	Cruas 2
	Dampierre 3	Dampierre 3	Cruas 3
	Dampierre 4	Dampierre 4	Cruas 4
	Gravelines 1	Gravelines 1	Gravelines C5
	Gravelines 2	Gravelines 2	Gravelines C6
	Gravelines 3	Gravelines 3	
	Gravelines 4	Gravelines 4	
	Tricastin 1	Tricastin 1	
	Tricastin 2	Tricastin 2	
	Tricastin 3	Tricastin 3	
	Tricastin 4	Tricastin 4	
	Saint-Laurent B 1	Saint-Laurent B1	
	Saint-Laurent B2	Saint-Laurent B2	
	Chinon B 1	Chinon B4	
	Chinon B2		
	Chinon B3		
	Chinon B4		
Germany	Brokdorf	Brokdorf	Biblis A
	Grafenrheinfeld	Grafenrheinfeld	Biblis B
	Grohnde	Grohnde	Brunsbiittel
	Gundremmingen B	Gundremmingen B	Krümmel
	Gundremmingen C	Gundremmingen C	
	Isar 2	Isar 2	
	Obrigheim	Obrigheim	
	Philippsburg 2	Philippsburg 2	
	Unterweser	Unterweser	
	Neckarwestheim 2	Neckarwestheim 2	
	Emsland		
	Neckarwestheim 1		
Japan	Fugen	Fugen	Fukushima-Daiichi-3
	Takahama 3		
	Takahama 4		
Switzerland	Benau 1	Beznau 1	
	Beznau 2	Beznau 2	
	Gösgen-Däniken	Gösgen-Däniken	

[a] There are a number of reactors, notably in Europe and India, not included in this Table, which are licensed to use MOX fuel and have loaded MOX fuel on an experimental basis;

[b] Technically capable reactors planned to be licensed.

4.3 Management of irradiated MOX fuel in Germany:

(Table 3 thermal reactors utilising MOX fuel)

The first MOX fuel was loaded in 1966 in VAK, a small BWR reactor with 6x6 fuel assemblies. In total **113** assemblies containing MOX fuel rods were irradiated in this plant. In 1970

TABLE 4. EXPERIENCE WITH MOX RELOADS IN BWR AND PWR FROM 1981 TO 1998

COUNTRY/ REACTOR -/ FA-TYPE	NO. OF REACTORS	NO. OF MOX FA RELOADED	MAX. AV. PU_{FISS} IN W/O / CARRIER MATERIAL	MAX. FA - EXPOSURE AT EOC IN MWD/TM
Belgium				
PWR (17x17-24)	**2**	**56**	**4.9** / U_{tails}	**43900**
France				
PWR (17x17-24)	17	992	7.08 / U_{tails}	40000
Germany				
PWR (18x18-24)	2	24	4.6 / U_{tails}	8000
PWR (16x16-20)	5	364	4.2 / U_{tails}	44900
PWR (15x15-20)	1	32	3 .o / U_{nat}	42000
PWR (14x14-16)	1	41	3.8 / U_{nat}	37000
BWR (9x9- 1)	2	116	3 .o / U_{tails}	32000
Switzerland				
PWR (15x15-20)	1	**28**	**4.8** / U_{tails}	**23000**
PWR (14x14-17)	2	152	4.1 / U_{tails}	51000

VAK was followed by the BWR KWL and in 1974 by KRB-A in using MOX fuel. In 1972 MOX fuel was inserted in the 2 PWR reactors MZFR and KWO. All this fuel is now stored in CLAB in Sweden in exchange of Swedish fuel sent to La Hague for reprocessing.

In 1981 commercial MOX irradiation started in Germany. Until now, almost 800 MOX fuel assemblies were inserted in German NPPs, including the test assemblies, with a maximum burnup of 45 GWD/t HM. (Table 5)

Some of the commercial MOX fuel was sent for reprocessing and part of it was reprocessed in La Hague in 1992. Most of the German utilities utilizing MOX like PreussenElektra plan to send their fuel for reprocessing. Quite a number of fuel assemblies are waiting for the lifting of the transport suspension order in Germany.

4.4 Management of irradiated MOX-fuel in India:

India has adopted the philosophy of a closed fuel cycle and recycling of plutonium essentially in the fast breeder programme. The 40 MW_{th} Fast Breeder Test Reactor at the Indira Gandhi Centre with the PuC-UC fuel is a forerunner of the fast breeder programme. Because of slow progress in the fast reactor programme, utilization of MOX fuel in thermal reactors has been considered. A study has been carried out by irradiating fuel assemblies consisting of 12 nat. UO_2 fuel rods in the outer periphery and 7 MOX fuel rods in the center in a PHWR reactor. Since the beginning of the 1980s irradiation experiments have been performed on short length MOX fuel rods in the pressurised water loop of the research reactor CIRRUS. After this MOX fuel development programme a few MOX assemblies have been loaded into one of the Tarapur reactors.

TABLE 5. COMMERCIAL MOX FUEL INSERTED IN GERMAN NPPs

Plant	**Fuel Type**	**First Insertion**	**Total Number of FA accumulated**	**Maximum FA Burnup [MWd/kgHM]**
KWO	14-16	1981	41	37
GKN-1	15-20	1982	32	42
KKU	16-20	1984	- 20	37
	16-20-4	1987	72	40
KKG	16-20	1985	16	40
	16-20-4	1987	44	45
KWG	16-20-4	1988	32	43
KKP-2	16-20-4	1988	32	45
KBR	16-20-4	1989	88	44
GKN-2	18-24-4	1998	8	15
GUN-B	9-1	1996	100	29
GUN-C	9-1	1995	16	34
Total			**501**	**45**

4.5 Management of irradiated MOX-fuel in Italy:

Some MOX fuel was irradiated in Italy before ending the nuclear programme.

Eight fuel assemblies were exposed in Trino until 1985 with a burnup of about 32 GWD/t HM and 63 FA in Garigliano with a maximum burnup of 28 GWD/t HM. There was one full MOX reload at the Garigliano plant.

These MOX assemblies were not sent for reprocessing. It is planned to store the MOX assemblies in the periphery of dry casks together with U assemblies.

4.6 Management of irradiated MOX-fuel in Japan:

(Table 3 thermal reactors utilising MOX fuel)

Japan has experience in burning MOX with two research reactors, Joyo and Fugen and the prototype fast breeder reactor Monju. Joyo used high enriched MOX fuel with 18% and 23%. About 380 irradiated fuel assemblies are in storage while 67 assemblies are still in the core. Fugen uses low enriched MOX fuel with 1.4% having 3 80 assemblies irradiated and 124 still in the core.

The LWR MOX fuel demonstration was started in 1986 at Tsuruga Unit-l for BWR and at Mihama Unit-l for PWR.

The 280 MW FBR Monju reached initial criticality in April 1994. Operation has **been** suspended because of a sodium leak accident in December 1995.

Japan will start plutonium utilization in LWRs this year by inserting MOX fuel fabricated by BNFL in the MOX demonstration facility.

4.7 Management of irradiated MOX-fuel in Russian Federation:

The information on the use of plutonium in Russia is very limited.

Work on integrating plutonium into the nuclear fuel cycle started in the mid 1970s. More than 300 MOX fuel assemblies have been irradiated in the BOR-60 reactor. The experience gained in this operation was the basis for the design of the MOX fuel inserted in the BN-350, which is now belonging to Kazakhstan and the BN-600. Some of this fuel was reprocessed in the RT-1 (Mayak) reprocessing plant.

The BOR-60 nuclear power plant was operated for 18 years with MOX and had a Pu consumption of 30 - 50 kg/year.

The WWER-1000 and BN-600 reactor designs are the main candidates to involve weapons grade plutonium in their fuel.

4.8 Management of irradiated MOX-fuel in Switzerland:

(Table 3 thermal reactors utilising MOX fuel)

In 1978 Beznau started its MOX recycling programme by loading 4 MOX assemblies into unit 1. Up to now, more than 150 MOX assemblies produced by Westinghouse, Belgonucleaire and Siemens have been loaded into both Beznau reactors. Due to slow build up of its own plutonium, NOK, the owner of Beznau, borrowed Pu from other parties. In this way it gained early experience in the use of MOX. The maximum assembly exposure is 43 GWD/t. Today's licensing allows 40% MOX or 48 MOX assemblies in the core. Lately, Goesgen also started to insert MOX fuel in their reactor. (Table 4 experience with MOX reloads).

The irradiated MOX fuel is stored in the reactor pools and it is not intended to send this fuel for reprocessing. In the case of dry interim storage the MOX fuel will be loaded into casks. Due to higher decay heat and neutron doses the number of MOX fuel assemblies per cask might be limited and a co-loading with uranium fuel might be necessary.

4.9 Management of irradiated MOX-fuel in the UK:

The UK has loaded some MOX fuel in the past. Experimental loadings of MOX fuel were made in the Windscale Advanced Gas Cooled Reactor in the 1960s. The fuel is being stored at Sellafield and is expected to be reprocessed at the Thorp facility. MOX fuel was also used in the Dounreay Fast Reactor (DFR) and the Prototype Fast Reactor (PFR). The fuel has been reprocessed in a mixed oxide reprocessing plant at Dounreay since 1979. The plutonium recovered was transferred to Sellafield for storage. Completion of the reprocessing is scheduled for around the year 2000. The UK government decided that the Dounreay facilities should close following completion of the existing reprocessing contracts.

5.0 Other MOX irradiation activities

The irradiation of the first Argentine prototypes of PHWR MOX fuel began in 1986. Four rods were irradiated in the HFR-Petten reactor in the Netherlands.

Canada fabricated about 150 CANDU MOX bundles from 1979 to 1987 containing more than 3 tons of MOX. Fabrication was suspended in 1987.

5. REPROCESSING OF MOX FUEL

In principle, reprocessing of MOX fuel is not much different from that of UO_2 spent fuel.

France started to gain reprocessing experience in 1967 with FBR fuel followed by Germany in the 1970s with LWR MOX fuel. Japan and UK also gained experience with the reprocessing of FBR fuel. Fuel from the Dounreay Fast Reactor (DFR) and the Prototype Fast Reactor (PFR) has been reprocessed in a mixed oxide reprocessing plant at Dounreay since 1979.

MOX fuel has been designed to be reprocessed. This leads to the monitoring of fresh pellet solubility during fabrication. France demonstrated in 1992 the feasibility of reprocessing MOX fuel in La Hague with a 4.7 ton campaign as mentioned before. The results were quite satisfactory.

6. CONCLUSIONS

There has been extensive experience in the transportation of plutonium powder and MOX fuel. Very rigorous transport safety requirements have been adopted by all participating countries and are based on the IAEA's "Regulations for the Safe Transport of Radioactive Material". MOX fuel is irradiated in a number of Member States and several have considerable experience in reprocessing irradiated MOX fuel. The storage of MOX fuel prior to reprocessing or final disposal requires longer periods due to higher decay heat and slower decrease of the decay heat compared with uranium fuel.

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