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Mixed Oxide (MOX) Fuel

(Updated March 2009)

Mixed oxide (MOX) fuel provides about 2% of the new nuclear fuel used today.

MOX fuel is manufactured from plutonium recovered from used reactor fuel.

MOX fuel also provides a means of burning weapons-grade plutonium (from military sources) to produce electricity.

In every nuclear reactor there is both fission of isotopes such as uranium-235, and the formation of new, heavier isotopes due to neutron capture, primarily by U-238. Most of the fuel mass in a reactor is U-238. This can become plutonium-239 and by successive neutron capture Pu-240, Pu-241 and Pu-242 as well as other transuranic isotopes (see page on Plutonium). Pu-239 and Pu-241 are fissile, like U-235. (Very small quantities of Pu-236 and Pu-238 are formed similarly from U-235.)

Normally, with the fuel being changed every three years or so, about half of the Pu-239 is 'burned' in the reactor, providing about one third of the total energy. It behaves like U-235 and its fission releases a similar amount of energy. The higher the burn-up, the less fissile plutonium remains in the used fuel. Typically about one percent of the used fuel discharged from a reactor is plutonium, and some two thirds of this is fissile (c. 50% Pu-239, 15% Pu-241). Worldwide, some 70 tonnes of plutonium contained in used fuel is removed when refuelling reactors each year.

The plutonium (and uranium) in used fuel can be recovered through reprocessing. The plutonium could then be used in the manufacture mixed oxide (MOX) nuclear fuel, to provide energy through electricity generation. A single recycle of plutonium in the form of MOX fuel increases the energy derived from the original uranium by some 12%, and if the uranium is also recycled this becomes about 22% (based on light water reactor fuel with burn-up of 45 GWd/tU).

Today there is a significant amount of separated uranium and plutonium which may be recycled, including from ex-military sources. It is equivalent to about three years' supply of natural uranium from world mines.

Inventory of separated recyclable materials1

Quantity (tonnes) Natural U equivalent (tonnes)

Plutonium from reprocessed fuel 320 60,000

Uranium from reprocessed fuel 45,000 50,000

Ex-military plutonium 70 15,000

Ex-military high-enriched uranium 230 70,000

In addition, there is about 1.6 million tonnes of enrichment tails, with recoverable fissile uranium.

MOX use

MOX fuel was first used in a thermal reactor in 1963, but did not come into commercial use until the 1980s. So far about 2000 tonnes of MOX fuel has been fabricated and loaded into power reactors. In 2006 about 180 tonnes of MOX fuel was loaded into over 30 reactors (mostly PWR) in Europe.

Today MOX is widely used in Europe and is planned to be used in Japan. Currently about 40 reactors in Europe (Belgium, Switzerland, Germany and France) are licensed to use MOX, and over 30 are doing so. These reactors generally use MOX fuel as about one third of their core, but some will accept up to 50% MOX assemblies. France aims to have all its 900 MWe series of reactors running with at least one third MOX. Japan also plans to use MOX in one third of its reactors in the near future and expects to start up a 1383 MWe (gross) reactor with a complete fuel loading of MOX at the Ohma plant in late 2014.2 Other advanced light water reactors such as the EPR or AP1000 will be able to accept complete fuel loadings of MOX if required.

The use of up to 50% of MOX does not change the operating characteristics of a reactor, though the plant must be designed or adapted slightly to take it. More control rods are needed. For more than 50% MOX loading, significant changes are necessary and a reactor needs to be designed accordingly.

An advantage of MOX is that the fissile concentration of the fuel can be increased easily by adding a bit more plutonium, whereas enriching uranium to higher levels of U-235 is relatively expensive. As reactor operators seek to burn fuel harder and longer, increasing burnup from around 30,000 MW days per tonne a few years ago to over 50,000 MWd/t now, MOX use becomes more attractive.

Reprocessing to separate plutonium for recycle as MOX becomes more economic as uranium prices rise. MOX use also becomes more attractive as the need to reduce the volume of spent fuel increase. Seven UO2 fuel assemblies give rise to one MOX assembly plus some vitrified high-level waste, resulting in only about 35% of the volume, mass and cost of disposal.

Recycling used fuel

If used fuel is to be recycled, the first step is separating the plutonium and the remaining uranium (about 96% of the spent fuel) from the fission products with other wastes (together about 3%). The plutonium then needs to be separated from most or all of the uranium. All this is undertaken at a reprocessing plant (see information page on Processing of Used Nuclear Fuel).

The plutonium, as an oxide, is then mixed with depleted uranium left over from an enrichment plant to form fresh mixed oxide fuel (MOX, which is UO2+PuO2). MOX fuel, consisting of about 7% plutonium mixed with depleted uranium, is equivalent to uranium oxide fuel enriched to about 4.5% U-235, assuming that the plutonium has about two thirds fissile isotopes. If weapons plutonium is used (>90% Pu-239), only about 5% plutonium is needed in the mix. Areva has stated that the plutonium content of commercial MOX fuel varies between 3 and 10% depending on the design of the fuel.

Plutonium from reprocessed fuel is usually fabricated into MOX as soon as possible to avoid problems with the decay of short-lived plutonium isotopes. In particular, Pu-241 (half-life 14 years) decays to Am-241 which is a strong gamma emitter, giving rise to a potential occupational health hazard if separated plutonium over five years old is used in a normal MOX plant. The Am-241 level in stored plutonium increases about 0.5% per year, with corresponding decrease in fissile value of the plutonium. Pu-238 (half-life 88 years), a strong alpha emitter and a source of spontaneous neutrons, is increased in high-burnup fuel. Pu-239, Pu-240 and Pu-242 are long-lived and hence little changed with prolonged storage. (See also information page on Plutonium).

Fast neutron reactors allow multiple recycling of plutonium, since all transuranic isotopes there are fissionable, but in thermal reactors isotopic degradation limits the plutonium recycle potential and most spent MOX fuel is stored pending the greater deployment of fast reactors. (The plutonium isotopic composition of used MOX fuel at 45 GWd/tU burnup is about 37% Pu-239, 32% Pu-240, 16% Pu-241, 12% Pu-242 and 4% Pu-238.)

Recovered uranium from a reprocessing plant may be re-enriched on its own for use as fresh fuel. Because it contains some neutron-absorbing U-234 and U-236, reprocessed uranium must be enriched significantly (e.g. one-tenth) more than is required for natural uranium. Thus reprocessed uranium from low-burn-up fuel is more likely to be suitable for re-enrichment, while that from high burn-up fuel is best used for blending or MOX fabrication.

Reprocessing of 850 tonnes of French used fuel per year (about 15 years after discharge) produces 8.5 tonnes of plutonium (immediately recycled as 100 tonnes of MOX) and 810 tonnes of reprocessed uranium (RepU). Of this about two-thirds is converted into stable oxide form for storage. One-third of the RepU is re-enriched and EdF has demonstrated its use in 900 MWe power reactors.

MOX production

Two plants currently produce commercial quantities of MOX fuel – in France and UK. In 2006 a 40 t/yr Belgian plant closed3 and in April 2007 the French Melox plant was licensed for an increase in production from 145 to 195 t/yr. Also the Sellafield MOX Plant in UK was downrated from 128 to 40 t/yr, although the plant has to date not been able to achieve anything close to its capacity. Japan is planning to start up a 130 t/yr J-MOX plant at Rokkasho in 2015. Meanwhile, construction on a MOX fabrication facility at the Savannah River Site in the USA is underway – see section below on MOX and disposition of weapons plutonium.

World mixed oxide fuel fabrication capacities (t/yr)

2009 2015

France, Melox 195 195

Japan, Tokai 10 10

Japan, Rokkasho 0 130

Russia, Mayak, Ozersk 5 5

UK, Sellafield 40 40

Total for LWR 250 380

MOX is also used in fast neutron reactors in several countries, particularly France and Russia. It was first developed for this purpose, with experimental work being done in USA, Russia, UK, France, Germany, Belgium and **Japan**. Today, Russia leads the way in fast reactor development and has long-term plans to build a new generation of fast reactors fuelled by MOX. The world's largest fast reactor – the 800 MWe BN-800 – is currently under construction at Beloyarsk in the Urals and due to start up in 2010.

At present the output of reprocessing plants exceeds the rate of plutonium usage in MOX, resulting in inventories of (civil) plutonium in several countries. These stocks are expected to exceed 250 tonnes before they start to decline after 2010 as MOX use increases, with MOX then expected to supply about 5% of world reactor fuel requirements.

MOX and disposition of weapons plutonium

Under the Plutonium Management and Disposition Agreement, Russia and the USA agreed in 2000 to each dispose of (or immobilise) 34 tonnes of weapons-grade plutonium deemed surplus to requirements (see page on Military Warheads as a Source of Nuclear Fuel). The Mixed Oxide Fuel Fabrication Facility (MFFF) at the Savannah River Site in the US state of South Carolina began construction in August 2007 and will convert the US plutonium to MOX fuel. Expected to begin operations in 2016, the MFFF is designed to turn 3.5 t/yr of weapons-grade plutonium into MOX fuel assemblies, which will be loaded at Duke Energy's Catawba and McGuire plants. The contract to design, build and operate the MFFF was awarded to the Shaw AREVA MOX Services consortium in 1999, with the $2.7 billion construction option being exercised in May 2008.4 Four MOX fuel lead test assemblies manufactured from US weapons plutonium and fabricated at the Melox plant in France are being burned on a trial basis at the Catawba plant.

Meanwhile, following several years of dispute, in November 2007 the USA and Russia agreed that Russia would dispose of its 34 t of weapons-grade plutonium by conversion to MOX fuel, which would be burned in the BN-600 reactor at the Beloyarsk nuclear plant, and in the BN-800 under construction at the same site.5 Under this plan, Russia would begin disposition in the BN-600 reactor in the 2012 timeframe. Disposition in the BN-800 would follow soon thereafter. Once disposition begins, the two reactors could dispose of approximately 1.5 t of Russian weapons plutonium per year. The USA agreed to contribute $400 million to the project. The MOX fuel will be manufactured at a plant that is planned to be built at Tomsk, Siberia – though no firm plans for its construction currently exist.

MOX reprocessing and further use

Used MOX fuel reprocessing has been demonstrated since 1992 in France, at the La Hague plant. In 2004 the first reprocessing of used MOX fuel was undertaken on a larger scale with continuous process. Ten tonnes of MOX irradiated to about 35,000 MWd/t and with Pu content of about 4% was involved. The main problem of fully dissolving PuO2 was overcome.

However, at present the general policy is not to reprocess used MOX fuel, but to store it and await the advent of fuel cycle developments related to Generation IV fast neutron reactor designs.

Plutonium-thorium fuel

Since the early 1990s Russia has had a programme to develop a thorium-uranium fuel, which more recently has moved to have a particular emphasis on utilisation of weapons-grade plutonium in a thorium-plutonium fuel. The programme is described in the information page on Thorium. With an estimated 150 tonnes of surplus weapons plutonium in Russia, the thorium-plutonium project would not necessarily cut across existing plans to make MOX fuel.

Further information

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Related information pages

The Nuclear Fuel Cycle

Plutonium

Processing of Used Nuclear Fuel

Military Warheads as a Source of Nuclear Fuel

Japanese Waste and MOX Shipments From Europe

Japanese Waste and MOX Shipments From Europe

(**Updated June 2010)**

http://www.world-nuclear.org/info/inf39.html

From 1969-90 there were more than 160 shipments of used nuclear reactor fuel from Japan to Europe.

Reprocessing of the Japanese used fuel has been undertaken in UK and France under contract with Japanese utilities.

Recovered fissile materials are returned to Japan as reactor fuel, notably as mixed oxide (MOX) fuel.

The first shipment to Japan of immobilised high-level waste from reprocessing took place in 1995 and the 12th and last one from France was in 2007.

Nuclear power provides about one third of Japan's electricity, and with the enhanced efficiency brought about by reprocessing used fuel to recycle the uranium and plutonium, it represents a major part of Japan's endeavours to achieve maximum self sufficiency in energy. Japan plans to have one third of its 53 reactors using some mixed uranium-plutonium oxide (MOX) fuel by 2010.

Reprocessing separates the waste, particularly the high-level waste containing nearly all of the radioactivity in spent fuel, from the uranium and plutonium which are recycled as fresh fuel. Separated high-level wastes – about 3% of the used fuel – remain.

A total of ten Japanese electric utilities had contracts with the French company Cogema (now Areva NC) to reprocess their used fuel. These Reprocessing Service Agreements date from 1977-78. Other contracts were with British Nuclear Fuels Limited (BNFL) in UK and are now held by the government's Nuclear Decommissioning Authority. About 40% of the used fuel involved was reprocessed by Cogema/Areva and the rest by BNFL.

From 1969-1990, some 2940 tonnes of used fuel in total was shipped (in over 160 shipments) by these utilities to France for reprocessing. Shipments of about 4100 tonnes were to the UK, and by mid 2007 more than 2600 tonnes of oxide fuel had been reprocessed there, plus a small amount of Japanese Magnox used fuel.

Reprocessing of Japanese used fuel in France finished in 2004 and all the high-level waste from reprocessing the used fuel in France has now been shipped back to Rokkasho in Japan for long-term (30-50 year) storage prior to ultimate disposal. Waste shipments from the UK should be completed by 2016.

Japan has a small (210 tonnes/yr) reprocessing plant already in operation at Tokai, associated with the Monju fast neutron reactor. A much larger (800 t/yr) reprocessing plant has been built at Rokkasho has been undergoing commissioning activities since March 2006. A 130 t/yr MOX Fuel Fabrication Plant at Rokkasho is under construction and due to enter operation in 2012.

Return of high-level wastes

In February 1995 the first of 12 shipments of vitrified high-level waste (HLW) departed from France for Japan. The last was in 2007. This waste belonged to the ten Japanese power utilities who are responsible for its safe storage and eventual disposal.

The 12 waste shipments over 12 years total 1310 canisters containing almost 700 tonnes of vitrified high-level wastes. These are packed in heavy steel shipping casks (see section on Marine transport below).

Year of shipment Number of HLW canisters from France

1995 28

1997 40

1998 60

1999 40 + 104

2000 192

2001 152

2003 144

2004 132

2005 124

2006 164

2007 130

Total 1310

Shipment of the vitrified high-level wastes from UK to Japan commenced early in 2010 and require about 11 shipments over 8-10 years to move about 1850 canisters. Under the Vitrified Residue Returns (VRR) program, some of this HLW will be substituting for a larger volume of intermediate-level wastes, on the basis that a radiologically-equivalent amount of HLW can be substituted in order to minimise the volume shipped. Both UK and Japan have legislation allowing this. The shipments are a continuation of the established waste return program from France.

Year of shipment Number of HLW canisters from UK

2010 28

Total 28

Return of plutonium and MOX

So far one shipment of separated reactor-grade plutonium recovered from used fuel reprocessing has been returned to Japan, in 1993. This was reactor-grade material, with about 30% Pu-240 in it and therefore useable only as a reactor fuel. It is not suitable for nuclear weapons.

Further plutonium is being returned as mixed oxide (MOX) fuel, in which the plutonium is mixed with depleted uranium and fabricated into fresh fuel elements ready for use in a power station reactor (see information page on Mixed Oxide (MOX) Fuel). Shipments of MOX fuel assemblies were sent in mid-1999, early 2001, early 2009 and mid-2010.

Part of the 1999 shipment, intended for Kansai's Takehama plant, was returned to the UK in 2002 due to doubts about quality control. In 1999 and 2001, the shipments contained 60 MOX fuel assemblies for use in

Tepco's Fukishima I-3 and Kashiwazaki-Kariwa 3 BWR units, respectively. The 2009 shipment contained 24 assemblies for Shikoku's Ikata 3, 28 for Chubu's Hamaoka 4, and 16 for Kyushu's Genkai 3. The 2010 shipment from France contained 12 assemblies for Kansai's Takahama 4 and 20 assemblies for the second load at Genkai 3.

Vitrification of separated waste

To enable safe storage and transport, the separated high-level waste arising from reprocessing is immobilised in a process known as vitrification. This involves mixing the waste with molten borosilicate glass and poured into 1.3 metre high stainless steel canisters. The waste becomes locked into the matrix of the glass as it cools, making it stable and resistant to leaching. Lids are then welded on to the canisters to seal them.

Each canister contains 150 litres of glass weighing 400 kilograms. Some 14% of the content is high-level waste derived from the reprocessing of about two tonnes of used fuel. After storage for several years, the thermal output of each canister as shipped is less than 1.5 kilowatts.

Marine transport

The 500 kg stainless steel canisters containing high-level waste are transported in specially-engineered, heavily shielded steel and resin containers called casks or flasks. Each cask holds up to 28 canisters of vitrified waste and weighs about 100 tonnes. Those used for the high-level waste are very similar to those for transporting the spent fuel from Japan to Europe in the first place, and the MOX fuel on the return voyage.

The ships involved are 104-metre, 5100 tonne, specially designed double-hulled vessels used only for the transport of nuclear material. The ships belonging to a British-based company Pacific Nuclear Transport Ltd (PNTL), have been approved for the transport of vitrified residues, and conform to all relevant international safety standards, notably one known as INF-3 (Irradiated Nuclear Fuel class 3) set by the International Maritime Organization. This allows them to carry highly radioactive materials such as high-level wastes, used nuclear fuel, MOX fuel, and plutonium.

They have completed more than 170 shipments and travelled over 8 million kilometres in the 30 years to 2007 without any incident involving a radioactive release. PNTL is now owned by International Nuclear Services Ltd (INS, 62.5%), Japanese utilities (25%) and Areva (12.5%). It is currently renewing its fleet. INS is 51% owned by Sellafield Ltd and 49% by the UK's Nuclear Decommissioning Authority, and managed by Sellafield Ltd.

Further information

General sources

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Related information pages

Processing of Used Nuclear Fuel

Plutonium

Mixed Oxide (MOX) Fuel

Waste Management in the Nuclear Fuel Cycle

Nuclear Power in Japan

Transport of Radioactive Materials

Plutonium Information

http://www.world-nuclear.org/info/inf15.html

Warheads as Nuclear Fuel

http://www.world-nuclear.org/info/inf13.html