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MIXED OXIDE (MOX) NUCLEAR FUEL
A UK PERSPECTIVE

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MIXED OXIDE NUCLEAR FUEL (MOX) - UNITED KINGDOM PERSPECTIVE

SUMMARY

In terms of its application to commercial nuclear power plants, mixed oxide fuel (MOX) is a relatively recent innovation.

The nuclear industry's enthusiasm to incorporate MOX fuel in light water reactors is driven by the mounting stockpiles of the fissile plutonium that is extracted from the chemical separation or reprocessing irradiated or spent nuclear reactor fuel. The original intention was that this plutonium would be used to fuel the first generation of fast breeder reactors, but this reactor technology has proved to be unachievable on a commercial scale. In addition to the growing stockpiles of plutonium from reprocessing the spent fuel of the domestic reactor programmes, plutonium from the reducing nuclear weapons arsenals of the United States and the former Soviet Union is also available for incorporation into MOX.

In the United Kingdom the domestic nuclear power reactor programme is mostly unsuited to burning MOX and the power utility that operates the single PWR at Sizewell has shown no enthusiasm for MOX. Unlike the French reprocessing company COGEMA that supports a large domestic nuclear power reactor programme, most of which can be adapted to receive MOX, the UK's BNFL has to seek overseas markets if it is to deplete its domestic stockpiles of plutonium.

In Europe, apart from France, nuclear power seems to be on the decline, with Sweden and more recently Germany announcing the phased closing down of their civil power generating reactors. Accordingly, even following the recent data falsification set-back, BNFL is likely to aggressively market its MOX product in the South East Asia region if it is to salvage its new MOX manufacturing facility at Sellafield and, indeed some would argue, justify the mainstay of its business, the thermal oxide fuel reprocessing plant THORP.

JOHN H LARGE

MIXED OXIDE NUCLEAR FUEL (MOX) - UNITED KINGDOM PERSPECTIVE

MOX is a mixture of uranium and plutonium oxides used in some nuclear power stations.

British Nuclear Fuels plc (BNFL) produced MOX for export at a small-scale demonstration plant at Sellafield. A full-scale commercial plant has been built but is awaiting government approval for operation.

Nuclear Power and Reprocessing

A nuclear power plant converts the energy generated by the fission of uranium 235 (U-235) and plutonium 239 (Pu-239) into electricity.[1] After about 3 years in the reactor, fuel is depleted and removed for interim storage. At this point it contains about 0.8% U-235 and 1% plutonium, depending on the type fuel used. Plutonium does not occur naturally and can only be produced, at any meaningful scale of production, by irradiating depleted uranium in a large, moderated reactor.

Although spent fuel can be stored safely for years, if not indefinitely, storage under water at the generating power station is not a permanent solution. Options for dealing with the fuel include dry storage, deep underground disposal, conversion into a less harmful substance (transmutation) and reprocessing (chemical separation). At this time, reprocessing is the only immediately available option in the UK, although wet pond storage of irradiated fuel could be maintained until dry storage facilities are developed and commissioned (about 10 years).

Reprocessing is the chemical separation of plutonium and uranium from the residue of the fission reactions. Separated uranium and plutonium can potentially be 'recycled' into useable nuclear fuel - this is known as 'closing the fuel cycle'.

The plutonium can also be used as the fissile core of a nuclear weapon. The parallel development of reprocessing and a series of heavily moderated reactors operating as civil nuclear power stations is the characteristic pattern of those countries wishing to leap-frog into a nuclear weapons programme.

This pattern of military-civil nuclear development was adopted by both the United Kingdom and France to acquire fissile plutonium for their respective nuclear weapons arsenals. Larger countries, the United State and the former Soviet Union, had reactor-reprocessing programmes totally dedicated to the military use of plutonium. This self-sufficiency means that the United States does not reprocess irradiated fuel from civil nuclear power reactors.

Mixed Oxide Fuel

MOX fuel is made from uranium *and* plutonium oxides, rather than just the uranium oxide that is used in conventional nuclear fuel. MOX fuel used in light water reactors (LWRs) typically contains between 3 and 10% plutonium, depending on the specific design of the reactor for which it is destined.

Uranium and plutonium oxide powders are mixed together by milling. The mixed powders, together with a small quantity of dry lubricant, are pressed into cylindrical pellets about 1cm in diameter. They are sintered (or 'fired') in a high temperature furnace, to make hard, dense pellets that are then ground to size. These are loaded into zirconium alloy tubes, which are sealed and welded to make fuel rods. The fuel rods are located in a grillage frame to forma lattice like fuel-assembly.

Since the mid-1980s, MOX development has been mainly aimed at overseas LWRs that are designed to use uranium oxide fuel. At present, up to a third of the fuel in a LWR core can be MOX without substantial redesign of the reactor, although work is underway to increase this proportion.[2]

World Trade In MOX

Four plants in Europe manufacture MOX fuel: one in Belgium run by Belgonucleaire; two in France run by COGEMA; and the MOX Demonstration Facility at Sellafield in the UK.

The Japan Nuclear Cycle Development Institute has also operated MOX manufacturing pilot plants for research purposes at Tokai, and Japan has a plan to build a commercial MOX fabrication facility as part of its policy to close its own nuclear fuel cycle.

German utilities had planned to produce MOX commercially, but a small MOX plant at Hanau was closed and the start-up of a larger plant stopped in the mid-90s, at least in part due to political opposition. In 1996 worldwide MOX production capacity was 188 tonnes per year. MOX is used regularly in France, Germany, Switzerland and Belgium. Now, the Japanese utilities also intend to utilize MOX in commercial power reactors.

MOX contains plutonium separated by reprocessing. Thus the fuel is inextricably linked to reprocessing, which began fifty years ago as a means of obtaining plutonium for nuclear weapons and research. Plutonium was also identified to fuel the planned generation of fast breeder reactors (FBRs) under development from the 1960s.

The nuclear industry now claims that the use of MOX fuel has two potential justifications: To extract energy from plutonium; and for plutonium management. In the United Kingdom there are no reactors licensed for MOX fuel so the UK's manufacturer of MOX, BNFL, justifies its manufacturer of MOX solely from an economic standpoint.

Technical difficulties have contributed to the slowing of work on FBRs in most nuclear power manufacturing states. The United States abandoned its FBR programme in the 1970s, the UK Government announced in 1990 that no further public funds would go towards

FBR development; while the French Superphénix reactor last operated in 1996, and was closed permanently in 1997 for 'economic reasons'; and similar FBR development difficulties have been experienced in Japan.

Since the FBR programmes ended, the nuclear reprocessing companies have examined other means of dealing with the products of reprocessing. For some countries with limited natural fuel resources, such as France, the MOX route of closing of the fuel cycle is seen as important in maintaining independent energy production capabilities, although the economics of MOX itself are not clear-cut.

Proliferation risks and radiotoxicity mean that separated plutonium needs to be carefully managed. Managing increasing plutonium stockpiles produced by reprocessing is argued to be a key reason for MOX use.[3]

Countries that have sent spent fuel to Sellafield for reprocessing are required to receive their plutonium back. However, the transport of plutonium is politically sensitive and MOX transport has proved controversial.

UK Production of MOX

MOX Demonstration Facility

The UK Atomic Energy Authority and BNFL have produced MOX at Sellafield for more than 30 years. Initial development was in support of the UK FBR programme and more than 20 tonnes of MOX was produced.

After the FBR programme was abandoned, BNFL developed a two-stage strategy to manufacture MOX for LWRs. This involved construction of a small MOX Demonstration Facility (MDF), and then a larger plant for bulk supply of commercial fuel (the Sellafield MOX Plant).

Construction of the Sellafield MDF began in 1991, and uranium and plutonium commissioning took place in 1993. It is a small pilot plant for commercial fuel with an annual capacity of 8 tonnes. By the time the BNFL data falsification[4] became apparent (September 1999), it had produced MOX for Swiss, German and Japanese fuel utilities. MOX for the Japanese Kansai Electric Power Company was en route to Japan, but had not yet been loaded into reactors – this fuel is awaiting return to the United Kingdom unused.

Sellafield MOX Plant

Conceived in the late 1980s, planning permission for the full-scale Sellafield MOX Plant (SMP) was granted in March 1994, and construction began in April of that year. The plant was completed in 1998, at a cost of £300m. It is intended to fabricate MOX for foreign customers from plutonium and depleted, natural or recycled uranium, with a production capacity of up to 120 tonnes per year (containing 7.2 tonnes of plutonium). However, before the SMP can start production, it will need consent to operate from the NII and a variation in its authorisation from the Environment Agency (EA) for discharges into the marine and atmospheric environments

A decision has not yet been given. However, it is likely that, given the implications of recent events at Sellafield for relations with BNFL's main customers, the economic case for MOX may have altered and hence further justification may be sought.

MOX Economics

An initial justification for reprocessing was that uranium costs would be high, so utilising the energy in plutonium and uranium from spent fuel would be economic. However, at present the price of natural uranium is low. Recent research suggests that it is likely to remain so for some time. This is partly due to surplus military uranium from the former USSR and the USA being allowed onto the world market, alongside improvements in segregating the highly enriched fraction of uranium.

The cost of uranium enrichment is also low, so the economic incentive for the use of MOX over uranium fuel is currently questionable. Research at Harvard University has suggested that MOX costs around $1,500 per kilogram of heavy metal that is about $450 more than uranium fuel. A power station using MOX will also incur further additional costs, such as security and in reactor safety system modifications. Taking reprocessing and MOX production together, the research concluded that costs are considerably higher than 'once-through' use of uranium fuel followed by direct disposal of spent fuel.

PREDICTED MOX FUEL REQUIREMENTS IN 2005

COUNTRY	REQUIREMENT (TONNES/YEAR)
Belgium	14 (year 2000 requirement)
France	118
Germany	100
Japan	95
Switzerland	18 (year 2000 requirement)
UK	7
Total	**352**

Key customers for BNFL MOX are Japan, Germany and Switzerland. The above table shows estimated demand for the countries assumed to be in the commercial market for MOX in 2005. This can be compared with the 1996-estimated MOX production capacity of 188 tonnes and SMP capacity of 120 tonnes. The French manufacturer COGEMA has plans to increase the output of one of its plants to 180 tonnes (from its present 120 tonnes). However, the market for MOX is not totally free; it is tied to nuclear policy in the customer countries, and may therefore not be stable.

To justify operation of SMP, BNFL needs to secure 30-40% of Japanese, German and Swiss sales within the reference case market. In June 1999 it had 6.7% of the reference case contracted, with 11% covered by a letter of intent and 25.7% "*under offer*". This equates to a cost of £2,052/kg for MOX to break-even if it won 40% of the reference case. This compares with a reported price of around £1,850/kg which COGEMA has charged German utilities, and around £750/kg which COGEMA charged the French utility EdF.

Such assessments are critically dependent on assumptions regarding the future market for MOX and the operating costs for the SMP. Incidents such as the data falsification can bring about a loss of confidence in MOX, applied to all manufacturers and, indeed, in a rapidly changing nuclear fuel economic climate the data falsification incident might provide excuse for some nuclear power utilities to withdraw from existing commitments. Given subsequent effects on relations with BNFL's customer countries, previous analysis may need to be substantially revised.

Reprocessing and Waste Management

Because the plutonium used in MOX comes from reprocessed spent fuel, MOX is closely linked to reprocessing. The decision to reprocess spent fuel has implications for the amount and type of waste produced. The exact implications depend on a number of factors, including what is done with the separated uranium and plutonium, ie whether they are made into MOX fuel, reused in some other form, disposed of, or stored. In this cost equation, the use of uranium recovered from reprocessing is of little or no significance.

As MOX production is seen (by BNFL) to be an inherent part of reprocessing, its justification is linked to continuing operation of reprocessing at the thermal oxide reprocessing plant (THORP). THORP has contracts for 100% of its capacity up to 2004, and about 50% of its capacity for the following 10 years. Nevertheless, commentators have suggested **that** the utilities and BNFL would be financially better off renegotiating the THORP reprocessing contracts into storage contracts. If so, the long-term storage of overseas waste would require a change in UK Government policy.

Were the route of reprocessing at THORP not available, policy issues about the long-term management of nuclear waste may be seen as more pressing, both in the UK and overseas. Marine discharges from reprocessing at Sellafield have been ***the*** subject of some international concern, particularly from Ireland and Nordic countries. Ireland and Denmark have tabled proposals which would end reprocessing at Sellafield, under the OSPAR convention - the international protocol on marine pollution to which the UK is a signatory.

Plutonium Disposition

The SMP is to make MOX for overseas customers in which it utilizes the equivalent amount of plutonium recovered from reprocessing that customer's irradiated fuel. Therefore, overseas sales of MOX will not necessarily reduce the UK's domestic plutonium stockpile.

The UK currently has a separated civil plutonium stockpile of around 60 tonnes stored at Sellafield. This mainly belongs to BNFL, and comes from reprocessing Magnox fuel. British Energy **has** contracts with BNFL for reprocessing 4,700 tonnes of spent fuel at THORP. Only 1,200 tonnes have so far been reprocessed, and British Energy has said that it is "*a* *matter of indifference"* whether the fuel is reprocessed or stored, although it would prefer more flexibility to move towards storage.

The UK separated plutonium stockpile is predicted to reach 100 tonnes, around two thirds of the world's total, by 2010. Of the UK reactors, only Sizewell B could be practicably modified to take MOX fuel, and this power station alone would take 35 to 50 years to use up 25 tonnes of separated plutonium. British Energy has stated that it considers MOX use uneconomic at present, while the Government is in the early stages of reviewing its policy for the management of UK plutonium. One option for dealing with plutonium is not to reprocess, leaving the plutonium in spent fuel form. This avoids the circular difficulty of reprocessing and then trying to find a method of disposition, which meets the 'spent fuel standard'. However, the plutonium that has already been separated would still need to be managed.[5]

Transport

The International Atomic Energy Agency, principally concerning the package design for the radioactive materials, regulates the transport of nuclear materials. Transport by sea is also governed by regulations, conventions and codes from the International Maritime Organisation. Intercontinental transports are by sea.

Some plutonium from the reprocessed Japanese spent fuel originates from uranium enriched in the USA. The USA therefore has rights of prior consent over the transport of Japanese nuclear materials, under the 1988 US-Japan Agreement for Peaceful Nuclear Co-operation. US consent was received for the transfer of reprocessed plutonium back to Japan, in the form of plutonium powder or MOX. However, this transfer had to take place by ship (not by air) and stringent security requirements were put in place. For example, requiring:

- a dedicated transport ship
- no scheduled port of call during the journey
- an armed escort vessel to accompany the transport ship

The two ships taking MOX fuel to Japan were both armed, and were acting as each other's escort. Armed officers of the UK Atomic Energy Authority Constabulary were on board each ship. The transport proved internationally controversial, although the cargo was delivered without major incident. The fate of the fuel in Japan is still to be settled, but similar arrangements would be necessary if the BNFL MOX shipment is to be returned to the UK.

International Issues

The existence of the international market for MOX is determined by the nuclear policies of the customer countries, so is not a 'normal' commercial market. It is therefore worth examining briefly the current situations in the three main customer countries for BNFL MOX – Japan, Germany and Switzerland.[6]

Japan: In 1997 the Federation of Electric Power Companies gave details of plans to load MOX into 16-18 LWRs by 2010. Japan has also been working towards the use of plutonium in FBRs, although this was delayed by a leakage incident at a prototype reactor in 1995. Confidence in the nuclear industry in Japan was damaged by the 1999 accident at the Tokaimura nuclear fuel plant. Japan has a policy not to store any surplus plutonium that it is not planned for future use. This may have implications for the final destination of the recent pellet shipment.

Germany: The German Government has now resolved to phase out the use of nuclear power. BNFL stated in June 1999 that the German Government and utilities planned to fulfill their THORP base load contracts. However, it is not yet clear what effect the recent NII reports and data falsification incident has had on this view. It is also now uncertain whether any new German contracts for MOX will be signed, which may have implications for the profitability of SMP.

Switzerland: Switzerland is a much smaller market for MOX fuel than Japan or Germany, and so less central to the case for SMP. Three reactors in Switzerland are using MOX fuel and until the recent intervention by the Swiss regulator the relationship with BNFL had been good. There will be two referenda this year about use of nuclear power in Switzerland, adding to the uncertainty over the longer-term market for MOX.

In summary: The production and economics of MOX fuel is intimately tied to reprocessing and, it might be argued, that the future of reprocessing is likewise dependent upon a successful MOX sales strategy.

Other than France, the recent withdrawal of support of the nuclear power industry, first in Sweden, more recently in Germany and, perhaps, shortly in Spain, means that BNFL, and the other MOX manufacturers COGEMA and Belgonucleaire, are likely to double their efforts to market MOX fuel in Japan and South East Asia, thus potentially increasing the propose seas voyages verging on New Zealand's Economic Zone.

1 Naturally occurring uranium comes in several forms (isotopes), the principal ones being: U-235, which has 235 particles in its nucleus (92 protons and 143 neutrons), and U-238, with 238 particles (92 protons and 146 neutrons). Naturally occurring uranium consists of 99.3% U-238 and 0.7% U-235. Uranium for use as fuel in a nuclear reactor is normally either natural uranium in metallic form, or enriched oxide, with about 4% U-235 present. The U-235 isotope is the 'active' ingredient in the fuel. In a nuclear reactor, a U-235 nucleus can absorb a further neutron, which makes it unstable. It splits ('fissions') into fission fragments, converting mass into energy as it does so. The U-238 nucleus can also absorb a neutron, turning into plutonium (Pu-239). If Pu-239 absorbs a neutron, it may fission, giving off energy. In a Light Water Reactor, 40% of the energy produced is from Pu. If a Pu-239 atom escapes fission and absorbs a further neutron, it forms Pu-240. The plutonium in spent fuel normally consists of 60% Pu-239. It is not well suited for use in nuclear weapons, since military grade plutonium typically has at least 93% Pu-239. MOX fuel releases energy from the fission of Pu-239, as well as the U-235 found in uranium

fuel. Using MOX also creates Pu-239 from U-238 in the fuel. The balance between consumption and creation of Pu-239 depends on reactor and fuel types.

2 The first MOX element was loaded into a Belgian LWR in 1963. Large-scale use started in Germany in 1981 and France in 1985. By 1999, 34 operating LWRs, 6 fast breeder reactors and one advanced thermal reactor had used MOX.[2] The fuel has been used in reactors in Belgium, France, Germany, Switzerland, Japan, USA, UK and Russia and over 750 tonnes of MOX have been used in LWRs. No reactors in the UK currently use MOX. Spent MOX fuel can theoretically be reprocessed and used again, although plans for this are currently at a trial stage. The build-up of contaminants means that MOX can be reprocessed only up to four times. Because it contains plutonium, which is toxic and radioactive, people cannot directly handle MOX outside sealed containment and contamination is a risk. Therefore it is more difficult and expensive to make and use than conventional uranium fuel, although BNFL assert that savings on uranium enrichment and mining offsets this. Due to the plutonium content of MOX, there are additional security issues that do not arise with conventional uranium fuel.

3 Plutonium is a "fissile" material, which under certain circumstances can undergo a chain reaction. Plutonium management is internationally regulated by the International Atomic Energy Agency and in Europe by the European Atomic Energy Community. Plutonium is one of the most radiologically toxic materials known. In particular, it can cause damage if inhaled. It is radioactive, but the main type of radiation it emits (alpha particles) does not penetrate thin layers of material. In 1997 it was estimated that there were about 1,240 tonnes of plutonium in the world, the majority in the form of spent fuel.[3] Russia and the US have declared almost half their weapons plutonium as excess: about 100 tonnes in total. There were around 140 tonnes of separated civil plutonium, mostly held at three reprocessing plants: Sellafield in the UK, La Hague in France and Chelyabinsk in Russia. Civil reprocessing programmes in France and Britain are separating about 20 tonnes of plutonium each year. The civil separated plutonium stockpile stored in the UK was about 67 tonnes in December 1998, mainly stored at Sellafield. This is estimated to be more than one-third of the world total.

These stockpiles of plutonium raise proliferation concerns and are thus stored to international security standards. 'Weapons grade' plutonium contains more Pu-239 than reactor grade plutonium, but it would still be possible (although difficult) to make nuclear weapons from the latter. Plutonium in spent fuel is extremely difficult to extract. One approach, therefore, would be to store already separated plutonium in a form that is as secure as spent fuel. This 'spent fuel standard' was suggested in 1994 by the US National Academy of Sciences. Unused MOX does not meet the spent fuel standard. Plutonium from overseas spent fuel sent to Sellafield for reprocessing must be returned to its country of origin. This is governed by reprocessing contracts, international agreements and exchange of letters. In 1997 there were 5 tonnes of overseas separated civil plutonium at Sellafield, with a further 35 tonnes due to be separated from spent fuel awaiting reprocessing. At present, this is seen as an energy source, and it is planned that some will be returned to its countries of origin in the form of MOX. The US and Russia have recently classed 100 tonnes of military plutonium as waste. Were reprocessed plutonium to be classed as waste, there are a number of possibilities for disposition, including:

- immobilisation in a waste matrix, either by mixing the plutonium with waste or by placing a small amount of plutonium oxide in the centre of a canister containing waste ('can-in-canister'), which can be disposed of or stored
- less immediately feasible concepts, such as firing the plutonium into space; disposing of it directly in a deep borehole; or transmutation [4] of the plutonium.

Although some of the immobilisation options are technically possible, none is yet available commercially. Immobilisation would require purpose-built facilities and one option would be for BNFL to provide plutonium management services to its customers. Plutonium could also be stored, as it is now at Sellafield, but further storage capacity would have to be built. The plutonium would remain a security risk and costs could be high.

CIVIL PLUTONIUM STORED IN UK - DECEMBER 98

	In spent fuel	Separated or in MOX	
	UK & Overseas Owned	UK owned	Overseas Owned
tonnes	46	59	10

4 In September 1999, BNFL reported to the United Kingdom's nuclear regulator, the Nuclear Installations Inspectorate (NII), that quality control data concerning secondary checks on the diameter of MOX fuel pellets manufactured in the Sellafield MOX Demonstration Facility (MDF) appeared to have been falsified.

The NII investigated the incident and reported in February 2000. BNFL also published a report on the falsification on the same day. The MDF is currently shut awaiting the NII's approval to reopen.

As a result of the falsification, four process workers at the MDF were dismissed and BNFL's Chief Executive left the company.

5 The 1998 Royal Society Report *"Management of Separated Plutonium"* highlighted four options for disposition of UK plutonium:

- Immobilisation and deep disposal in geological structures
- Using MOX in existing or specially built UK thermal reactors
- Sending MOX to other countries for use as fuel in their reactors
- Possible future alternative fuel cycles and reactor designs to use plutonium. They also proposed that steps be taken to reduce the amount being added to the plutonium stockpile, primarily by reducing the amount of reprocessing.

They suggested the Government *"commission a comprehensive review by independent experts of the options"* for plutonium management. The 1999 House of Lords Science and Technology Committee Report on *"Management of Nuclear Waste"* concluded that:

- There is a large and growing stock of plutonium. The excess over foreseeable need should be declared as waste
- Phased disposal of nuclear waste in a deep repository is feasible and desirable
- There is a need for widespread public consultation
- A Radioactive Waste Management Commission should be established to develop a comprehensive strategy.

6 **Japan:** Nuclear power makes up about one third of Japan's power supply. Its nuclear policy includes the use of reprocessing and the manufacture of MOX, aiming to close the nuclear fuel cycle. A reprocessing plant is being built in Japan, but at present Japanese utilities send fuel to the UK and France for reprocessing; all the Japanese spent fuel contracted up to 2004 has been delivered to Sellafield. Negotiations on reprocessing contracts beyond this period are likely to have been affected by the falsification and safety issues. **Germany:** Nuclear power produces about a third of Germany' s energy. Until recently, Germany had reprocessed around 30% of its spent fuel, split between BNFL and COGEMA. Its plutonium is made into MOX in France, Belgium or the UK, since the closure of the sole German plant. At present, 12 reactors are licensed to use MOX; to date approximately 250 tonnes have been used in German reactors.