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Note on MOX Fuel

Summary
A number of factors militate against the use of MOX (mixed U oxide and Pu oxide) fuel. There are many questions concerning the alleged rationales for MOX fuel. In addition, considerable technical, economic, proliferation and radiological disadvantages are associated with MOX production, use, and recycle. Volumes of MOX fuel production and use are insignificant compared to those for uranium fuel. In global terms, MOX fuel use will remain restricted to countries or utilities retaining the view that separated Pu should be a resource rather than a waste.

1. Queries of Alleged Rationales

MOX proponents argue MOX fuel is a method of reducing Pu stockpiles. However, in global terms, MOX fuel use in existing uranium reactors only slows down the rate of increase of separated plutonium stockpiles, rather than reducing them. MOX proponents also argue that MOX fuel is a means of utilising fissile Pu created in conventional U reactors. However, a more elegant, safer, efficient, and less expensive method of doing this is the use of high burnup U fuels. This method has been used in the US for decades but ignored in Russia and other countries committed to reprocessing nuclear fuel. It may be argued that US utilities should continue to rely on high burnup fuels rather than convert to its more dangerous and expensive alternative, i.e. MOX fuel. MOX proponents argue that MOX fuel burning is a method of utilising fissile Pu obtained from dismantled warheads. However much safer and less expensive methods (e.g. immobilisation) exist for doing so. MOX proponents argue, finally, that spent MOX fuel is a means of isolating separated Pu and safeguarding it from proliferation concerns. If this were a realistic concern, then the logic of the matter would demand that separating Pu via reprocessing be stopped: this is rarely admitted by MOX proponents.

For safety reasons, a maximum of 30% MOX fuel is permitted in existing reactors, with the rest uranium oxide fuel. During fission, the U component "generates" more Pu than is "incinerated" in the MOX component. The result is that, no matter how much MOX fuel is produced nor how many existing reactors are dedicated to MOX burning, world plutonium arisings will still increase. The only way Pu stocks would decline would be if new reactors were designed to burn new fuel in which inert material replaced U oxide. These fuels and reactors are a long way in the future. No firm plans exist anywhere in the world for constructing test versions: their future remains highly uncertain. They would require much Government funding and Government R&D and testing. In the meantime, plutonium stockpiles will continue to increase.

2. Excess of MOX Production over Use

An examination of anticipated MOX production capacities and MOX fuel loadings in recent years reveals an excess of MOX production capacity over use. Currently, world MOX fuel fabrication capacity is about 200 tonnes per year (not including the 120 tonne/year UK SMP plant yet to be given permission to operate). MOX fuel loadings are about 160 tonnes per year and declining. These production capacities are small compared with ~10,000 tonnes of uranium fuel required annually by world reactors (IAEA, 1996).

MOX fuel use is presently restricted to about 20 or so LWR reactors in three countries, Germany, Belgium and France, constituting about 4% of the world's 430 reactors. This number is unlikely to increase due to continuing difficulties in demonstrating wide safe operation margins; the reluctance by utilities to order MOX fuel because of its high costs and the low burnups allowed by safety authorities; and the refusal of safety authorities in France to license MOX fuel use in load-following reactors because of reduced control during powerups and closedowns. These factors are discussed in more detail below.

3. Safety, Technical, and Economic Constraints on MOX fuel

(a) Reduced shut-down margins

MOX fuel use is associated with logistic, technical and disadvantages compared to U oxide fuel. This applies to MOX whether fuelled by Pu of military[1] or commercial origin. The logistic factor is that in Europe a maximum of 30% MOX fuel may be loaded in LWR reactors. In many cases, the limit is 20%. This restriction has been imposed by European nuclear regulatory agencies to avoid unacceptable shutdown margins and to maintain uniform power distributions in reactor cores. The remaining 70% is uranium oxide fuel which, when irradiated in the reactor, produces more plutonium than is "incinerated" in the plutonium fuel fraction. The net result is that, averaged over a number of years, discharged fuel from MOX-fuelled reactors contains about 16% more plutonium than contained in the original MOX fuel. For reactors limited to 20% MOX fuelling, the Pu increase is about 40%.

The 30% MOX-loading restriction is due to the marked differences between the neutrons from uranium and plutonium fissions, including

- fewer delayed neutrons
- considerably higher neutron cross-sections
- smaller prompt neutron lifetimes
- greater variation in fission neutron yield (particularly when incident neutron energies are low)

Plutonium-239 fission emits about a third fewer delayed neutrons than uranium-235 fission. Delayed neutrons are important in the control of reactors during ramping up and shutting down of reactors and during reactivity incidents (such as loss-of-coolant accidents). Taken together, the above differences reduce the effectiveness of conventional control systems in light water reactors optimised for uranium fuel (OECD/NEA, 1989). Almost all commercial reactors in the world have been constructed and configured for uranium oxide fuel.

To overcome these differences in neutron characteristics, spectra and cross sections, it is necessary to ensure that MOX fuel in the core is surrounded by uranium fuel in such a way that the resulting neutron flux resembles that in a uranium-fuelled reactor as closely as possible. Despite recent advances, the use of plutonium fuel still results in lowered shutdown margins and increased complexity in controlling power ramps and reactivity incidents.

Concern over possible reactivity incidents in French MOX burning reactors has been voiced, unusually, by the IAEA (see IAEA, 1996, page C60). In 1997, tests on the properties of MOX fuel under simulated conditions of a reactivity incident, i.e. loss of control of neutron production rates during powering up, were conducted by the French nuclear safety institute, the Institute pour la Protection et Securite Nucleaire (IPSN) (see Nucleonics Week, 1997). During these tests, ruptures occurred in the metal cladding of tested fuel rods, leading to large releases of fission gas and dispersion of fuel into test channels. MOX proponents in Europe and the US have not seriously addressed these problems. Remedies might be to reconfigure existing reactor cores by inserting more control rods or removing fuel channels in existing reactor cores.

These low shutdown margins and difficulties with power ramp controls have led to French nuclear licensing authorities adopting stringent conditions for the use of MOX fuel. In France, at present only 20 of the 34 older 900 MW reactors, and none of the 20 new 1300 MW reactors or 4 newer 1450 MW reactors are licensed to use MOX fuel. More important, MOX burnup is limited to 41,000 MWdays per tonne, cf 52,000 MW days per tonne for UOX fuel. This 27% difference results in a severe economic penalty on the French national utility, EdF, for using MOX fuel. In practice, the percentage difference is greater than 27%, as most MOX fuelled reactors continue to operate with 33,000 MWdays/tonne burnups, meanwhile UOX fuels with higher burnups up to the maximum allowed are routinely introduced in French reactors.

(b) Pu Toxicity Problems

[1] Military Pu contains slightly more ^{239}Pu and slightly fewer other Pu isotopes. This means that total plutonium weight in weapons MOX fuel is slightly lower than in reactor MOX fuel because the proportion of fissile plutonium is higher in the former. This results in a minor reduction in some problems associated with commercial plutonium handling and use. For example operator doses in MOX production plants may be reduced by 5% to 10%, compared to doses received when producing MOX from commercial Pu.

Safety provisions and safety-related designs required for MOX fuel fabrication plants are more extensive than those required for uranium fuel facilities, due to plutonium's greater specific activity and radiotoxicity. To prevent plutonium dust release, multi-barrier systems supported by systems of low-pressure gradients, glove boxes and remote-handling facilities are necessary. In addition, precautionary procedures and safeguards are necessary against gamma radiation and criticality. These precautions are unnecessary or are significantly reduced in uranium fuel manufacturing. These added safety requirements contribute significantly to the higher costs of MOX fuel compared to uranium fuel.

Plutonium decay is an important factor to be considered in MOX fuel production, particularly the decays of ^{241}Pu and ^{236}Pu isotopes. Appreciable concentrations of ^{241}Pu exist in plutonium separated during reprocessing. For example, ~14% of the plutonium in spent PWR fuel consists of the fissile ^{241}Pu isotope, which has a half life of 14.4 years, decays to ^{241}Am, as below: -

$$^{241}\text{Pu}\ (\beta^-) \rightarrow {}^{241}\text{Am}\ (\gamma, \alpha) \rightarrow {}^{237}\text{Np} \rightarrow\ \rightarrow \ldots.$$

This decay has two adverse effects. The first is that the fissile content of reprocessed Pu is thereby reduced, as Am is not fissile. The second is that the beta decay product, ^{241}Am, is a gamma emitter (maximum decay energy 70 keV) with a relatively long half-life of 430 years. Accordingly, americium build-up in plutonium from the date of reprocessing is an important aspect in the safe manufacturing of MOX fuel.

The percentage of ^{241}Pu in plutonium recovered from warheads is slightly lower, but this problem still exists with military Pu. For example, nuclear warheads still have to be replaced every few years to eliminate ^{241}Am build up.

In addition to ^{241}Pu, separated plutonium contains smaller quantities of ^{236}Pu, whose decay produces the highly radiotoxic nuclides ^{212}Bi and ^{208}Tl with powerful gamma energies of 1.6 and 2.6 MeV respectively. These contribute significantly to operator radiation doses because of their penetrating character. They necessitate expensive additional shielding. Pu which has been separated (ie following reprocessing) for more than three years has to undergo chemical purification to remove ^{241}Am, ^{212}Bi and ^{208}Tl. MOX fabrication utilities will not accept older plutonium because, after then, radiation doses to workers become unacceptably high and the fissile content becomes too low. This purification process is similar to reprocessing; i.e. it is expensive; results in high operator doses from Bi and Tl isotopes; and creates additional streams of radioactivity and highly active wastes. In practice, older stockpiles of separated plutonium are unlikely to be used as feedstock for MOX fuel.

(c) Increased Radiotoxicities

The activities and radiotoxicities of spent MOX fuel are 4 to 5 times greater than those for spent uranium fuel with the same burnups. Similarly, after reprocessing, vitrified HLW from MOX fuel is even more radiotoxic (4 to 12 times) than spent uranium fuel. In other words, using MOX fuel increases the radiotoxicity of resulting wastes by amounts which approximately correspond with the increases in specific activities of the main nuclides of concern, i.e. Am, Pu, Cm. This 4 to 5 fold increase in potential radiotoxicity of wastes from MOX fuel use should be taken into account during the determination of policy on the use of MOX fuel.

(d) Difficulties with Spent MOX Fuel

The radiological hazards of spent MOX fuel are considerably greater than those of spent uranium fuel due to the increased concentrations of higher actinides. These are alpha and neutron, as well as heat, emitters.
These concentrations result from activation of plutonium isotopes in MOX fuel. These present problems during spent MOX fuel handling, particularly during reprocessing, including

- higher levels of criticality,
- solvent degradation by the harder alpha radiation from ^{238}Pu and ^{244}Cm,
- high concentrations of solvent degradation products, and
- three times higher heat output rate compared to spent UOX fuel

The higher heat rate of spent MOX fuel is a serious logistical and cost matter for utilities. According to the French waste agency ANDRA, spent MOX fuel requires three times longer cooling time (i.e. 150 years cf 50 years for U fuel of same burnup) before it can be placed in a repository. If not cooled accordingly, it will require three times as much space to be excavated in future repositories. Volume excavation is widely expected to be the main cost driver in future repositories.

The conclusion is that spent MOX fuel significantly increases the cost of spent fuel management, in terms of both storage and final repositories. It also trebles the time horizons for which utilities will have to manage spent fuel into the future. Whether the US utilities have properly accounted for such extended costs is debatable. The recent report commissioned by the French Government, (the Charpin Report on the Economic Forecast Study of the Nuclear Power Option) estimated extremely high storage costs for MOX fuel over these prolonged time periods.

In 1995, the German government investigated the recycling of high burnup MOX fuel in some detail. Its report concluded that the above problems and the low fissile content of recovered plutonium argued against multiple cycle reprocessing of high burnup MOX fuel. It stated repeated rounds of MOX fuel burning and reprocessing would lead to escalating problems from ever higher actinide concentrations: in practice only one recycle, at most, would be sensible. In 2000, the French government stated that spent MOX fuel will not be reprocessed. The conclusion may be made that, for most MOX fuel fabricators and users, MOX fuel will be a once-through process, and spent MOX fuel will not be reprocessed.

(e) Economic Viability of MOX

A potential advantage of MOX fuel use is that fresh uranium purchases and the need for uranium enrichment are reduced. Against these potential savings must be balanced the capital costs of building MOX fabrication plants and the extra costs of acquiring, fabricating and handling plutonium fuel compared with uranium fuel. Examining system costs of MOX fuel vs uranium fuel is not straightforward. In 1994, German utilities estimated that MOX fuel costs were about 5 times more expensive than uranium fuel: - $2,600,000 per tonne compared with $500,000 per tonne for uranium fuel. German and French nuclear utilities have both complained about high MOX prices compared with uranium fuel prices. Industry observers have stated that although MOX fuel had originally been seen as a resourceful use of recycled plutonium, today its use in light water reactors is not economic and that the use of commercial MOX in German reactors will decrease in future. Because of reduced demand for MOX fuel, the planned Hanau MOX plant in Germany in 1990 and the planned Dessel P1 MOX plant in Belgium in 1996 were cancelled.

An important factor in the operation of MOX fuelled reactors is that burnups are usually restricted to 33,000 MW days per tonne for safety reasons, particularly in France where a significant percentage of nuclear reactors are required to follow load. This restriction is a considerable financial handicap as the fiscal advantages of high burnup regimes are large. Although MOX fuel manufacturers are attempting to produce higher burnup fuels, the same is true, except with greater success rates, of uranium fuel manufacturers.

(f) Transport and Storage Costs of Plutonium Fuel

In 1989, the OECD/NEA stated that the transport and storage costs of spent plutonium fuel are “far” higher than those for spent fuel, due to the requirements for added security, extra shielding and criticality control. It has also estimated (NuclearFuel, 1993) that the cost of storing separated plutonium was £1.5 million per tonne per year. Other analysts (Berkhout and Walker, 1990) have estimated higher costs up to £2 million per tonne per year. These costs fall on electricity utilities.

Conclusions

Alleged justifications for MOX fuel use -plutonium incineration and recycle- do not withstand scrutiny. MOX fuel use suffers from logistical, financial, technical and safety drawbacks. Restriction on MOX loading considerably reduces plutonium incineration rates. MOX production and use, at its maximum estimated annual capacity, would not keep up with the annual output of reprocessed plutonium at current rates. Stocks of separated plutonium will continue to increase, albeit at a slower rate. It is unlikely that older stores of separated plutonium will be used in MOX fuel due to americium build-up and the costs of its removal. MOX fuel is currently 4 to 5 times more expensive per tonne that fresh uranium fuel, and with current expectations that uranium prices are likely to remain stable or fall, this price differential is expected to remain or increase. Technical and safety drawbacks include reduced operating safety margins during power increases and decreases, higher heat outputs requiring added cooling facilities or cooling times, restriction of burnups to 33,000 MW days/tonne with consequent increased fuel costs per GW output, higher operator doses, and difficulties with reprocessing spent MOX fuel. Spent MOX fuel is expected to treble utility costs of spent fuel management.

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