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Mixed Oxide Fuel (MOX)

(*February 2008*)

- **MOX is a means to re-use the plutonium remaining in used reactor fuel to provide energy through electricity generation.**
- **MOX provides about 2% of the new fuel used today, and this proportion is expectged to rise to 5% by 2010.**
- **MOX also provides a means of burning weapons-grade plutonium (from military sources) to produce electricity, though using thorium-plutonium fuel is another possible means of achieving this.**

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 or actinide isotopes. 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 (c50% Pu-239, 15% Pu-241). Worldwide, some 70 tonnes of plutonium contained in used fuel is removed when refuelling reactors each year.

A single recycle of plutonium in the form of MOX 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. It is equivalent to about three years supply of natural uranium from world mines.

Inventory of Separated Recyclable Materials

	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

Source: NEA 2007.

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

Recycling uranium fuel

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%). Then the plutonium needs to be separated from most or all of the uranium. All this is undertaken at a reprocessing plant.

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 UO_2+PuO_2)*. MOX fuel, consisting of about 7-9% 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.

* A small amount of recycled uranium may be involved too, though this can give rise to the need for gamma shielding in the MOX plant. ** Some figures for Oskarshamn-3: with 30 GWd/t burn-up: 69% Pu is fissile, 40 GWd/t 61% fissile, 50 GWd/t: 55% fissile and 60 GWD/t: 50% fissile.

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) is increased in high-burnup fuel. It is a strong alpha emitter and a source of spontaneous neutrons. Pu-239, Pu-240 and Pu-242 are long-lived and hence little changed with prolonged storage. (see also paper on plutonium)

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.

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.)

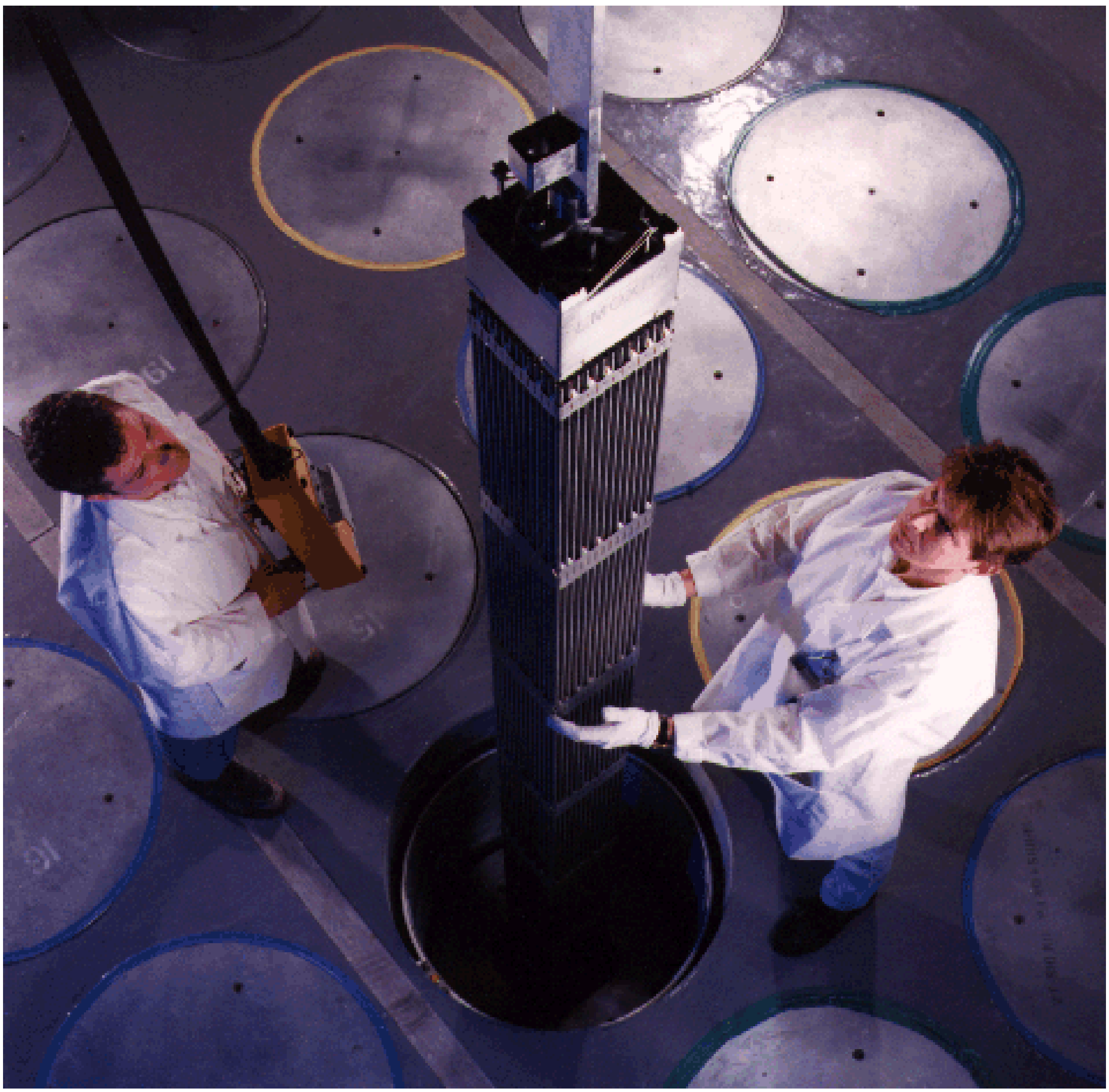
In 2007 EdF said that the plutonium stored at La Hague from reprocessing could provide the start-up fuel for seven Generation IV fast reactors, with 15 tonnes for each.

(Recycled 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, the enrichment level is slightly greater than for mined uranium providing equivalent fuel.)

MOX Use

MOX 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) 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. Japan also plans to use MOX in up to 20 of its reactors. Most reactors use it 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 aims to have one third of its reactors using MOX by 2010, and has approved construction of a new reactor with a complete fuel loading of MOX. Advanced light water reactors such as the EPR or AP-1000 will be able to accept complete fuel loadings of MOX.



A MOX fuel assembly for a PWR

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.

See also Appendix on plutonium recycling from 1999 ASNO Annual Report.

When uranium prices were low, reprocessing to separate plutonium for recycle as MOX was not itself economic, but with the rise in uranium prices coupled with reducing the volume of spent fuel to be managed, it is becoming so. Seven UO_2 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.

MOX Production

Four plants currently produce commercial quantities of MOX fuel. Two are in France, one in Belgium, and a fourth (intended to be 128 t/yr) was commissioned in UK in 2001. In 2005, about 200 tonnes of MOX was produced, incorporating 12-14 tonnes of plutonium. MOX production capacity is presently around 225t/yr, using 15-18 tonnes of plutonium. Since 1963 over 400 tonnes of plutonium has been used in MOX.

World Mixed Oxide Fuel Fabrication Capacities for LWR

(tonnes per year)

Year:	2006	2008	2012
France	145	195	195
Japan	0	0	130
UK*	40	40	40+
Total for LWR	185	235	445

Source: Areva.
** the UK plant has never functioned anywhere near its capacity.*

In 2006 a 40 t/yr Belgian plant closed 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. Japan is planning to start up a 130 t/yr MOX plant at Rokkasho in 2012.

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 worldÕs largest fast reactor Ð the 800 MWe BN-800 Ð 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 reprocessing and further use

Used MOX 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 PuO_2 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.

MOX & disposition of weapons plutonium

For disposal of weapons-grade plutonium, special arrangements are envisaged. A multinational consortium is to finance the construction of a MOX plant in Russia (Tomsk, Siberia), particularly to utilise Russian weapons-grade plutonium (at 2 t/yr), and a similar plant is to be built in USA (Savannah River, South Carolina). These will enable ex military plutonium from disarmament to be permanently destroyed as it is "burned" in reactors as MOX. Meanwhile the first fuel assemblies with MOX from US weapons plutonium and fabricated at the Melox plant in France are being burned on a trial basis in USA.

The objective of this MOX fuel program is to destroy one third of the weapons-grade plutonium and convert the remainder to reactor-grade plutonium (with significant levels of Pu-238 & Pu-240), radically degrading its isotopic quality and potential for weapons.

Plutonium-thorium fuel

Since the early 1990s Russia has had a program 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 program is based at Moscow's Kurchatov Institute and involves the US company Thorium Power and US government funding to design fuel for Russian VVER-1000 reactors.

The program is described in the Thorium paper.

With an estimated 150 tonnes of weapons plutonium in Russia, the thorium-plutonium project would not necessarily cut across existing plans to make MOX fuel.

Sources:
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Appendix**: From the 1999 Annual Report of the Australian Safeguards and Non-Proliferation Office, DFAT:**

PLUTONIUM RECYCLING: THE USE OF 'MOX' FUEL

With the transport and use of MOX (mixed oxide) fuels attracting increasing public attention, readers may find the following background information useful.

Plutonium is formed in uranium fuel during the operation of a reactor. Plutonium has substantial potential as a source of energy, and in fact is a significant contributor to the energy produced in a uranium-fuelled reactor.

The use of MOX fuel reduces inventories of separated plutonium, and is likely to assume increasing importance for degrading weapons-grade plutonium released by disarmament.

Why recycle?

The concept of plutonium recycling involves reprocessing of spent fuel from a reactor, in order to separate the plutonium produced in the fuel, fabricate it into fresh fuel, and use it for further energy production. When uranium is used to fuel a reactor, energy is produced primarily from the fissile isotope U-235, which constitutes only around 0.7% of natural uranium. Plutonium recycling offers substantially greater efficiency, because energy is produced from the most abundant uranium isotope, U-238 (which constitutes around 99.3% of natural uranium), through conversion of U-238 to plutonium. In theory therefore plutonium recycling offers some 150 times as much energy from a given quantity of uranium as the 'once-through' cycle (i.e. use of uranium without reprocessing). Practical factors prevent this theoretical maximum from being reached, but a very substantial increase appears to be practicably attainable. Plutonium recycling would therefore be extremely attractive if uranium were in short supply and high-priced.

Programs for the recycling of plutonium were developed in the 1970s when it appeared that uranium would be in scarce supply and would become increasingly expensive. It was proposed that plutonium would be recycled through fast breeder reactors, that is, fast neutron reactors with a uranium 'blanket', which would produce slightly more plutonium than they consume. Thus it was envisaged that the world's 'low cost' uranium resources, then estimated to be sufficient for about 50 years' consumption, could be extended for hundreds of years.

For a variety of reasons, high uranium prices have not eventuated, and future prices are uncertain. Some of the influences on this situation include:

- the discovery of considerable further deposits of uranium recoverable at low cost;
- the run-down of very extensive uranium stocks which had been accumulated in various countries;

- the high capital cost of nuclear plants, which combined with lengthy licensing processes, and exacerbated by difficulties in public acceptance in many countries, have led to a much lower than anticipated growth in nuclear energy; and
- more recently, arrangements for the gradual release on to world markets of large quantities of uranium from the dismantling of nuclear weapons.

At the moment the consumption of uranium in the world's nuclear energy programs substantially exceeds uranium production (by about 50%), and low cost uranium resources are still equivalent to only about 40 to 50 years' consumption at present levels. These factors might be expected to result in higher uranium prices, but prices remain depressed. In these circumstances there is no impetus to develop fast breeder reactors, particularly since these reactors present major engineering challenges which will be expensive to resolve. Meanwhile, however, around 30% of spent fuel arisings are covered by long-term reprocessing contracts, and the approach of plutonium recycling using light water reactors has been developed as a way of avoiding the accumulation of separated plutonium, and deriving an immediate economic return on this plutonium.

MOX fuel

The term 'MOX' is derived from 'mixed oxides', and refers to reactor fuel made from a mixture of plutonium and uranium oxide. For use in a light water reactor, the proportion of plutonium is about 5%. This is a similar fissile content as low enriched uranium fuel. As is the case with uranium fuel, the MOX is formed into ceramic fuel pellets, which are extremely stable and durable, and which are sealed in metal (usually zirconium) tubes, which in turn are assembled into fuel elements. In most cases about a third of the reactor core can be loaded with MOX fuel elements without engineering or operational modifications to the reactor.

Contrary to suggestions from some commentators, there is nothing unusual in the presence of plutonium in light water reactors. Plutonium is produced during the operation of a reactor. The plutonium content of spent fuel from the normal operation of a light water reactor will be a little less than 1%, usually around 0.8%, when the fuel is unloaded. During the operation of the reactor, plutonium formed in the fuel will contribute an increasing proportion of the overall energy production of the reactor - towards the end of an operating cycle, a substantial proportion of the initial U-235 content of the fuel will have been consumed, and the energy produced by fission of plutonium will be very close to that produced by the remaining uranium.

Use of MOX fuel is expected to significantly reduce plutonium inventories. As an example, the Euratom Supply Agency estimates that the use of a single MOX fuel element consumes 9 kg of plutonium, and avoids the production of a further 5 kg (compared with the use of low enriched uranium fuel). Thus in this example each MOX fuel element used results in a net reduction of 14 kg of plutonium.

Currently plutonium is being recycled with 32 light water reactors in Europe, and this is shortly to commence in Japan. Use of MOX fuels in light water reactors will increase over the next decade. While this will involve mainly reprocessed civil plutonium, the use of MOX fuel to degrade weapons-grade plutonium (There are two ways in which use of weapons-grade plutonium in MOX fuel degrades that plutonium: through the plutonium being associated with highly radioactive fission products in spent fuel (the 'spent fuel standard'); and through changes in isotopic composition during the irradiation process - in normal power reactor useage the plutonium would become reactor-grade), transferred from military programs as part of the disarmament process, will assume increasing importance. By 2010 it is expected that MOX fuels will be used with 45 reactors in Europe, together with 16-18 in Japan, and possibly five in Russia and six in the US, that is, some 15-20% of the world's power reactors.

As noted earlier, plutonium recycling programs were first developed with the breeder cycle in mind. There have been active fast breeder reactor research and demonstration programs in France, Japan and Russia. Future plans for fast breeder reactors are now uncertain, a major factor being economics, especially the price of uranium. At the moment the greatest interest appears to be in operating such reactors, not as *breeders*, but as net *consumers* or 'burners' of plutonium and of minor actinides. Clearly of crucial importance here is the future direction of nuclear energy, which will be determined by a complex range of political and economic considerations. If nuclear energy continues to make a significant contribution to world electricity production, and particularly if this contribution increases, plutonium could become an energy source as significant as uranium is today.

Is the plutonium in MOX fuel 'weapons-useable'?

Opponents of the use of MOX fuels commonly state that such fuels represent a proliferation risk because the plutonium in the fuel is said to be 'weapons-useable'.' This is a complex subject, where there is no consensus amongst experts, but the short answer is that there would be serious technical difficulties in attempting to make nuclear weapons from plutonium of the quality currently used for MOX (reactor-grade), and none of the countries possessing nuclear weapons has ever made weapons using plutonium of this quality.

'Weapons-useable' is not a technical term, and it is not clear what those using it mean, but if it is supposed to imply that reactor-grade plutonium is a material that could readily find its way into weapons, this overlooks two important facts: that there has been no practical demonstration of the use of such plutonium in nuclear weapons, and that rigorous IAEA safeguards apply to this material in non-nuclear-weapon States party to the NPT. It is misleading to conclude, because this material is subject to safeguards, that it is therefore 'weapons-useable'.

To better understand this issue, it is necessary to appreciate that plutonium exists as several isotopes. As noted earlier, longer reactor irradiation times result in the formation of higher plutonium isotopes, Pu-240, Pu-241 and Pu-242 (and also the isotope Pu-238). The mix of isotopes (isotopic composition) of a particular quantity of plutonium will depend on how the plutonium was produced, that is, its irradiation history. The isotopic composition of plutonium affects its suitability for particular purposes, such as use in a reactor or use in nuclear weapons.

The plutonium isotope most suitable for weapons use is Pu-239. Plutonium used in nuclear weapons, 'weapons-grade' plutonium, comprises at least 92%, usually more, Pu-239. This plutonium is produced in dedicated plutonium production reactors, specially designed and operated to produce plutonium of this quality by removal andreprocessing of fuel after short irradiation times.

The plutonium produced in the normal operation of light water reactors, from which MOX fuel is being made, is what is known as 'reactor-grade' plutonium. Because of the very long time fuel is irradiated in a power reactor (typically 3-4 years), reactor-grade plutonium has a substantial proportion of higher plutonium isotopes. Reactor-grade plutonium typically comprises less than 60% of the isotope Pu-239.

Reactor-grade plutonium contains a large proportion of isotopes which create serious technical difficulties for weapons use, namely Pu-238, Pu-240 and Pu-242. These difficulties include 'pre-initiation' (a high spontaneous fission rate leading to the nuclear chain reaction starting too early), and radiation and heat levels which will adversely affect vital weapons components such as high explosives and electronics. While these difficulties could possibly be overcome, to some extent at least, by experienced weapons designers (e.g. from the nuclear-weapon States, with experience from hundreds of tests to draw upon), ASNO is not aware of any successful test explosion using reactor-grade plutonium, typical of light water reactor fuel (There is some confusion over a 1962 test by the US using what was then described as 'reactor-grade' plutonium, but at that time 'reactor-grade' was much closer to weapons-grade than is currently the case. While the US has never revealed the quality of the plutonium used in that test, there are indications that it was of 'fuel-grade', an intermediate category between weapons-grade and reactor-grade, which has been recognised as a separate category since the 1970s).

IAEA definition of 'direct-use' material

The confusion in the public mind regarding the suitability of reactor-grade plutonium for nuclear weapons appears to arise from the fact that, for the purpose of applying IAEA safeguards measures, *all* plutonium (other than plutonium comprising 80% or more of the isotope Pu-238) is defined by the IAEA as a 'direct-use' material, that is, 'nuclear material that can be used for the manufacture of nuclear explosives components without transmutation or further enrichment'. In order to understand what this actually means, it is important to appreciate the following:

- The IAEA is not saying that all plutonium is suitable for nuclear weapons. The IAEA has chosen its terminology very carefully, and refers to 'nuclear explosives', rather than nuclear weapons. While this distinction might seem a fine one, in fact it is very important. It can be shown by theoretical studies that reactor-grade plutonium could be made to explode under certain (technically demanding) conditions. For this reason it is clearly prudent to adopt a conservative approach, and the IAEA applies safeguards measures to all grades of plutonium.
- Theoretical calculations relating to reactor-grade plutonium however do not indicate what happens in real life. There are several characteristics required for a practical nuclear weapon, including reliability, useful yield, a deliverable size and storage life. These requirements would be adversely affected by the difficulties associated with reactor-grade plutonium, mentioned above. It is for good reason that those countries that have made nuclear weapons have done so with plutonium specially produced for the purpose.
- The IAEA definition of 'direct-use' material also applies to plutonium in spent fuel, and to MOX - yet clearly the IAEA is *not* saying that nuclear explosives can be made from spent fuel or from MOX (i.e. without processing to separate the plutonium). 'Direct-use' and 'weapons-useable' are not synonymous.

How does this relate to MOX?

With respect to the use of MOX fuel, arguments about the 'weapons-useability' of reactor-grade plutonium miss the point: as we have seen, MOX is a mixture of uranium and plutonium oxides, with the plutonium being very much in the minority. For light water reactor fuel, the plutonium content is typically around 5%. MOX cannot be used in nuclear weapons or nuclear explosives. IAEA safeguards measures would readily indicate if any attempt were made to process the fuel to separate plutonium.