Plutonium "burning" in LWRs

One of the claims of the plutonium lobby is that MOX fuels can be used to "burn up" the current plutonium surplus, thereby lowering its proliferation risk (which is then suddenly admitted). So, let's examine to what extend this claim holds true. From the section about what happens in the reactor, it already became clear that totally "burning" a nuclear fuel in an LWR is impossible. If you haven't read this yet, my advice would be to do so before turning to the MOX sections. We will now only focus on the PWR. For the BWR, things are similar but with different numerical features.

MOX fuels characteristics

In uranium (UOX) fuels, the initial fissile content is given by the enrichment, the U-235 content prior to irradiation. The "enrichment" of MOX fuels should be measured in terms of **fissile** plutonium. Since the fissile Pu-239 and 241 isotopes have a higher capture-to-fission ratio than U-235, the MOX "enrichment" should be higher than the UOX enrichment in order to have equivalent reactivity in both fuels. The latter is needed because in current LWRs only about 1/5 or 1/3 of the reactor core can be loaded with MOX fuel elements, depending on the number of control rod systems such reactors have. MOX elements need to contain a control rod to "ensure safety". Few (recent) reactors may be able to hold 50% MOX fuels. All others would need to be modified in order to have such large loads. Since the use of MOX fuels is clearly a temporary thing for most utilities, reactor modification will probably not be a very attractive option for them.

Current reprocessed plutonium (fuel burn-up 35-40 MWd/kg HM) has a fissile content of some 65%, the rest is mainly Pu-240. So if the MOX "enrichment" is about 5.0%, this means that the total amount of plutonium in the fuel is about 8%. The UOX should have a corresponding U-235 enrichment of some 4.2%. MOX fuels usually contain some 4-7% fissile plutonium, with total amounts of 6-11%. These values may still be rising. Since Pu-239/241 aren't such good fuels as U-235, the corresponding UOX enrichment levels are some 3-6% (U-235 and Pu-239 fission reactivities are like 5:4).

Plutonium content decrease

The plutonium content in a MOX element after irradiation for 3-4 years is determined by the amount fissioned and the amount of fresh plutonium created in the U-238 part of the fuel (some 90%). About half of the fresh plutonium is fissioned, the rest remains and raises both quantity and quality of the plutonium contained in the spent MOX fuel. The first is high enough to compensate for a significant part of the fissioned reprocessed plutonium in the MOX fuel, while the latter is too low to make a second re-use attractive. This essentially is the trouble with thermal MOX fuel: It is neither a good burner, nor a good breeder. You can see the plutonium balance for a MOX fuel element with an initial 5% fissile plutonium content in figure 1.

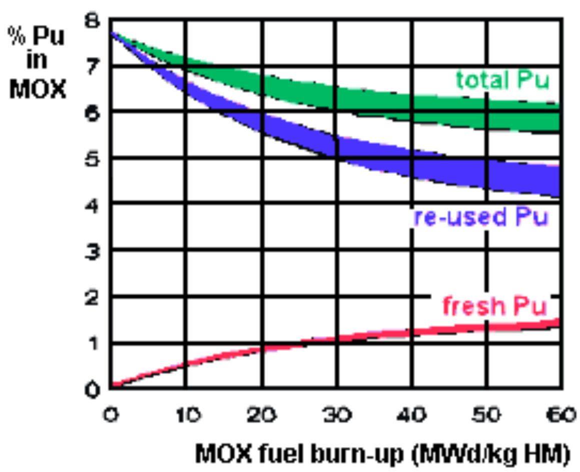


Figure 1: Plutonium balance in MOX containing 5% fissile Pu and natU

Let me explain where the (large) margins come from. The upper limits were my own calculations, the lower limits are consistent with what I've read from the industry. When using MOX, there are two contrary effects which determine the final plutonium content. The first is the easy transmutation of Pu-240 into Pu-241, which is fissile. This is like breeding and the effect will obviously lower the total plutonium content. Since the relative shares of Pu-240 and Pu-241 in normal spent UOX fuels (burn-up ~ 40 MWd/kg, plutonium isotopic composition is already almost in equilibrium then) are like 2:1, one would expect a maximum of about half the Pu-240 to be converted to Pu-241, and about half of that to be fissioned in the end. Including only this effect, the lower limits of the curves appear.

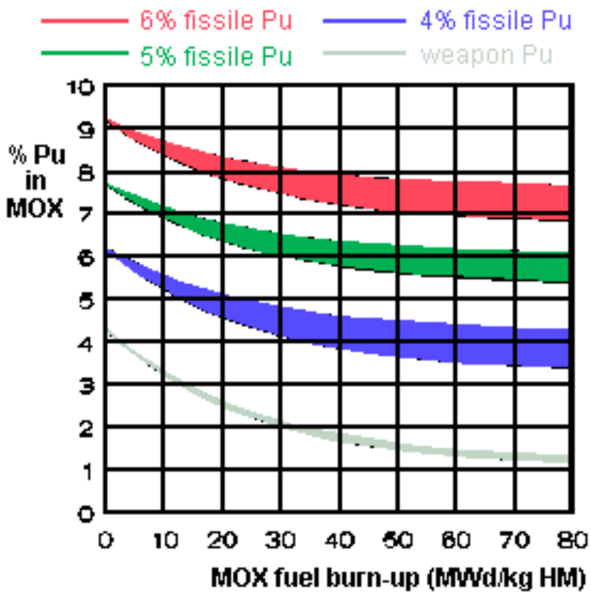
On the other hand, since the fissile Pu-239 and 241 isotopes already have significant fission and capture cross section resonances at higher neutron energies than U-235, the mean neutron energy will remain higher (energy lowering by scattering can be somewhat less). The result of this is that the moderator temperature will become higher, lowering the moderator density. The first will also allow the fuel temperature to be raised, giving rise to a (Doppler) broadening of the cross sections resonance peaks. The latter lowers scattering chances, thereby enhancing absorbing processes. The result of all this will be -- in my view -- an enhancement of both capture and fission in Pu-239 and 241 in the epi-thermal neutron range, and more importantly also an enhancement in the capture process which turns U-238 into fresh Pu-239. In a figure displayed in the section "What happens in the reactor", one can also see that U-238 has capture resonances for neutron energies slightly above the thermal range.

Comparing burn-up rates with fissioned amounts, I figured that the plutonium decreasing and increasing factors would more or less compensate one another. Thus I could use a model essentially treating Pu-240 as if it remains non-fissile -- as if it does not transmute -- which allowed me to use well known PWR plutonium curves for UOX to model MOX behaviour (taking into account the different fission-to-caption ratio for Pu-239 compared to U-235, since this is the major neutron source in UOX fuels). That is the upper limit of the curves in figure 1.

I would consider it a waste of time to argue with the MOX lobby about a few percent more or less. That is why I rather present my results like this. What is important is that on average, **only a net amount of some 20% of the plutonium contained in normal MOX is actually "burnt up".** For a lower initial fissile plutonium content, this will be a little less, for a higher one a little more. The amount of fresh plutonium in a MOX rod will be equal in any case (hence the difference). You can see the plutonium balance for some more MOX fuels in figure 2. Note that the MOX with plutonium from dismantled weapons plutonium logically provides the best plutonium "burning".

Concluding, we can state that in any case **MOX fuels are poor plutonium "destroyers", hence plutonium destruction is not a real objective for the reprocessing industry to manufacture MOX fuels and for utilities to use it.**

Figure 2: Plutonium balance in MOX fuels



Net results

The table below gives you some MOX parameters. In each case, the initial potential energy in terms of fissile atoms is equivalent, and so are the fuel yields in terms of total energy. Burn-ups can become higher through breeding effects (U-238 in both and Pu-240 in MOX). High enrichment levels (be it U-235 UOX or fissile Pu in MOX) provide enhanced neutron sources, neutrons which can breed fresh Pu-239 and some extra Pu-241 in MOX fuels. This is why an enrichment increase can give burn-up results which have relatively improved somewhat more (not assumed in the table below). In other words: Reactor criticality can be maintained longer because the higher U-235 content produces more neutrons available for converting U-238 to Pu-239 (and Pu-240 to Pu-241 in MOX fuels).

Pu in MOX, quality		LWR	LWR	LWR	Weapon
Pu-fis in MOX, start	4.0%	5.0%	6.0%	4.0% (assumed)	
Pu-tot in MOX, start	6.2%	7.7%	9.2%	4.3% (assumed)	
U-235 in UOX, start	3.4%	4.2%	5.0%	3.4%	
UOX burn-up (MWd/kg)	34	42	50	34	
MOX burn-up (MWd/kg)	43	53	63	43	
Pu-tot in MOX, end		~4%	~6%	~7%	~2%
Pu-tot in UOX, end		0.9%	1.3%	2.0%	0.9%

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Break-even MOX share    ~30%    ~43%    ~50%    ~25%
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Assumptions:    1) 65% fissile part in LWR-Pu (1st recycle).
                2) 93% fissile part in weapon-Pu.
Burn-up rates are all equivalent in terms of total energy.
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The last row shows that only for a relatively low plutonium "enrichment" and for plutonium originating from dismantled nuclear weapons, the current general maximum of about 30% MOX in the reactor core can give a net reactor plutonium production of zero -- there is still no net consumption by the system then. The column with 5% fissile Pu probably represents the general majority of current MOX fuels. For today's MOX loading possibilities, such MOX systems will not reach the break-even point. Some PWRs, in Belgium for instance, can only have up to some 20% of the core loaded with MOX. Those utilities can only state that they make less plutonium then they normally would.

So, we may conclude that **in the current situation, the point where the reactor really starts to consume plutonium cannot even be reached.**