Plutonium Utilisation in Future UK PWRs

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Abstract

Plutonium recycling in the form of Mixed Oxide (MOX) fuels is already a reality in over 30 reactors in Europe (in Belgium, Switzerland, Germany and France). Japan also plans to use MOX in approximately 30% of its reactors in the near future[1].

This paper describes potential near to mid-term disposition strategies for the United Kingdom's stockpile of plutonium. In order to be confident that MOX fuel can be utilised effectively in Pressurised Water Reactors (PWRs) in the UK, details are given of studies carried out recently at Nexia Solutions on PWR cores loaded with MOX containing typical UK plutonium isotopic compositions. Three dimensional steady state neutronic models of a standard Westinghouse four loop PWR design are constructed using state of the art tools (Studsvik of America's Core Management System[2,3,4]). Initially, a standard 18-month equilibrium UO_2 fuel cycle is generated, followed by safety analyses and fuel performance calculations to demonstrate its feasibility.

This equilibrium UO_2 core is then gradually transitioned through loading patterns containing increasing MOX core loading fractions. Finally, an equilibrium MOX core loading pattern is determined. Technical safety analyses are also carried out on the transition cores and the final equilibrium scenario to ensure that all of the MOX cores are robust from a technical and safety viewpoint. Once these studies are completed the annual fuel throughputs for each scenario can be determined and used to produce options for managing the UK's plutonium stockpile.

This work is part of a wider exercise currently being carried out by Nexia Solutions to explore the options for the safe disposition of the UK civil stockpile of separated PuO_2 .

KEYWORDS: Plutonium, Utilisation, UK, PWR, CMS

1. Introduction

The UK's ~100 tonne plutonium stockpile can be considered an asset or a liability, depending on the politics and long term goals used to characterise this material. The irradiation of plutonium in a reactor can be regarded as a means of complying with both the 'asset' and 'liability' characterisations; by generating electricity it is being used as an asset, but in addition the irradiation of MOX puts the Pu beyond use as regards safeguards.

Although plutonium irradiation programmes are technically feasible in the UK in both MAGNOX and AGR systems, the relatively early closure schedules for these reactors preclude any firm commitment. It was therefore judged that plutonium irradiation in the form of MOX in a PWR is the only viable short term option for current plants if the Pu stockpile is to be irradiated.

This paper describes work carried out using the latest nuclear design techniques, methodology approved for use in the UK and loading patterns developed for a UK PWR. The main objectives of the work were:

- To demonstrate that it is technically feasible to load MOX fuel in a generic UK PWR while staying within the current steady state safety limits.
- To determine the amount of Pu required to maintain equilibrium when ~30% of the fuel assemblies in the core are MOX (the remaining assemblies being composed entirely of standard UO_2).
- To evaluate and compare key core physics operational parameters, such as reactivity coefficients, for a UO_2 core followed by transition cycles and eventually an equilibrium MOX core.
- To generate neutronic representations of UO_2 and MOX cores which could then be interrogated to provide detailed input data for fuel performance analyses and fuel cycle scenario modelling calculations.

The general issues surrounding the use of MOX fuel in PWRs are understood. However, studies using the latest neutronics and UK calculation methodologies are required in order to reflect accurately the UK Pu management options. The Pu used in this work will be UK-sourced to comply with these requirements.

2. Input Data

Previous studies on MOX in PWRs have been carried out in the UK, but these have primarily been in support of BNFL's MOX business or support to European utilities[5]. Furthermore, although it is clear that there is now extensive worldwide experience with MOX in PWRs, this experience is related to a Pu vector that differs from that arising from the reprocessing of the UK Magnox and AGR fuels for example.

A Westinghouse 4 loop SNUPPS (Standardised Nuclear Unit Power Plant System) design PWR was used for all analyses unless otherwise stated. The MOX Pu vector is based on

the UK ex-Magnox Pu stockpile and is therefore at a relatively high quality of ~70% ^{239}Pu and ^{241}Pu.

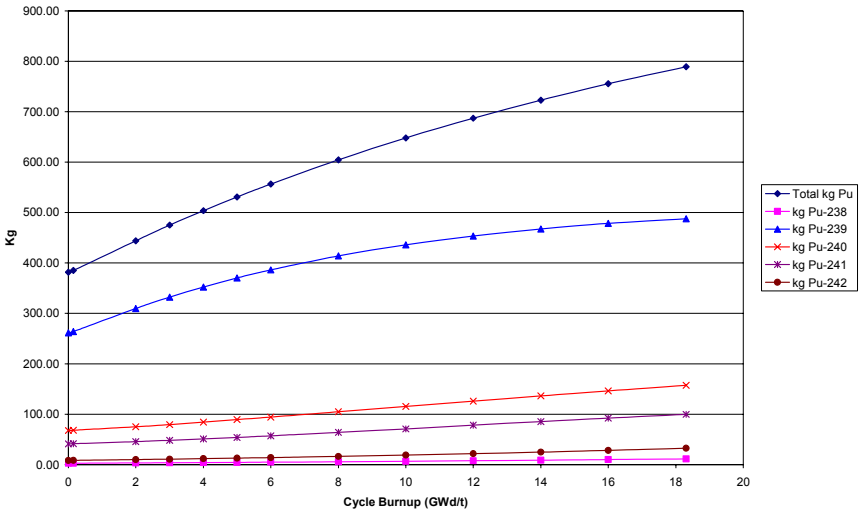
3. Equilibrium UO_2 Core

The first stage in this task was to generate an equilibrium UO_2 core in order to define a basecase scenario. Subsequent MOX cores can then be compared with the equilibrium UO_2 core parameters.

Gadolinia (Gd_2O_3) admixed with the UO_2 was used as a burnable absorber to (i) reduce the excess reactivity early on in the fuel cycle and (ii) to keep the power distribution within the design limits. Loading pattern searches were carried out until an equilibrium UO_2 loading pattern was finally obtained (i.e. Cycle N behaving identically, or very close to Cycle N-1) which satisfied energy requirements, while also remaining within power distribution limits.

The equilibrium UO_2 loading pattern had a burnup of 18.3 GWd/t, which corresponds to 477 Effective Full Power Days (EFPD). This is approximately 18 months with an allowance for reactor trips and refuelling outages. The variation of the total Pu concentration with burnup for the equilibrium UO_2 core developed using CASMO-4[(2)]/SIMULATE-3[(3,4)], along with the evolution of the individual Pu isotopes is given below:

Figure 1 : Variation of Pu vector and total Pu with burnup in the equilibrium UO_2 core



From Figure 1 it can be seen that the equilibrium UO_2 core contains 382 kg of Pu at 0 GWd/t. Although there is zero Pu in the fresh UO_2 fuel when it is initially loaded into the core, the total Pu includes the Pu produced in the irradiated fuel (principally via ^{238}U neutron capture).

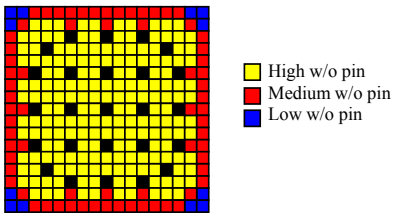
4. Transitioning to ~30% MOX Core

The 30% MOX fraction (i.e. 30% of the fuel assemblies in the core are MOX) is a compromise value (which has been adopted by the MOX burning PWRs in France, for example) at which the majority of the UO_2 safety case remains intact. The results from this study (see Section 7) are consistent with this assumption.

The equilibrium UO_2 core from the previous Section now needs to be transitioned to an equilibrium 30% MOX loading pattern. This was accomplished by gradually introducing MOX fuel to the core. Given that the equilibrium core contains 84 feed assemblies, 24 of the feed UO_2 assemblies were replaced by MOX fuel.

The ex-Magnox Pu vector was used in the MOX fuel assembly design. All fuel assembly geometry and structural materials were retained from the UO_2 assembly design. To avoid unacceptably high local power peaking (due to the influx of thermal neutrons from neighbouring UO_2 fuel assemblies) the plutonium concentrations in the corners and outer rows of fuel pins in the MOX assembly were reduced as shown in Figure 2:

Figure 2 : MOX assembly enrichment zoning



To determine the average MOX enrichment, the lifetime average reactivity of the MOX fuel needed to match that of a ~4.2 w/o UO_2 assembly (the average UO_2 fuel enrichment in the equilibrium UO_2 core) over the lifecycle specified in this particular fuel management scheme. This was estimated using lattice code calculations (CASMO-4 in this instance) and then confirmed using whole-core 3D calculations (SIMULATE-3).

Using depleted uranium at an enrichment of 0.25 w/o ^{235}U as a carrier, CASMO-4/SIMULATE-3 calculations determined that the final assembly average MOX enrichment was 6.125 w/o fissile Pu (8.283 w/o total Pu), yielding the following pin-wise breakdown in each MOX assembly:

Table 1 : Final MOX fuel pin enrichments

Rod enrichment	*Fissile Pu (w/o)*	*Total Pu (w/o)*
High	6.788	9.180
Medium	4.752	6.426
Low	3.734	5.049

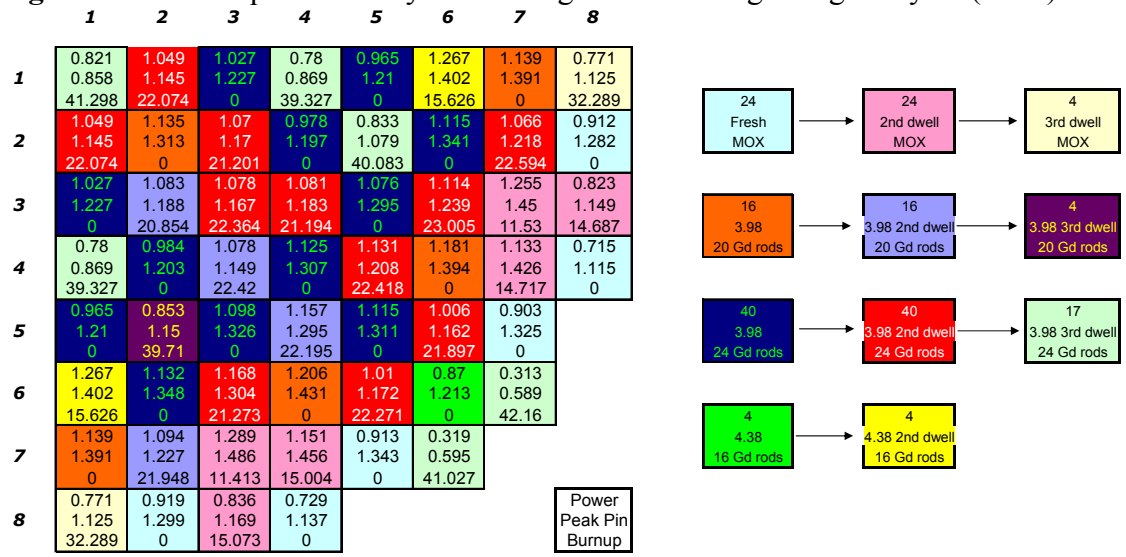
Note the absence of burnable poisons (BPs) e.g., Gd_2O_3, in the MOX fuel. The fact that only 30% of the equilibrium core is MOX, coupled with the neutronic flexibility of Gd_2O_3 as an integral BP in the UO_2 assemblies, permits each of the MOX cores to be operated without BPs in the MOX assemblies. This would simplify the introduction of MOX into a UK PWR since a separate MOX BP manufacturing line would not be required. The disadvantage of not using BPs in MOX is that the loading pattern design becomes more constricted, since fresh MOX fuel cannot be placed in in-board locations without producing unacceptably high peaking factors.

Once a satisfactory loading pattern was achieved for the 1st MOX transition cycle, the process was continued in subsequent cycles, loading more fresh MOX while shuffling the burnt MOX within the core. After the 3rd transition cycle, which contained fresh, once-burned and twice-burned fuel, the core was taken to equilibrium in a similar manner to the equilibrium UO_2 core described earlier.

5. Equilibrium ~30% MOX Core

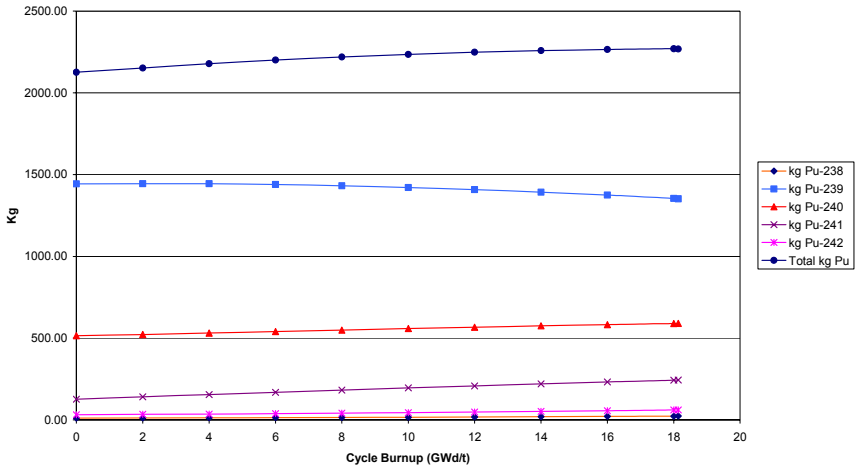
The final MOX equilibrium loading pattern and its associated assembly average burnup, assembly average power and peak pin power distribution at Beginning of Cycle (BOC) is shown in Figure 3:

Figure 3 : MOX Equilibrium Cycle Loading Pattern at Beginning of Cycle (BOC)



The equilibrium MOX core had a cycle length of 18.1 GWd/t which is close to the equilibrium UO_2 value of 18.3 GWd/t and within the tolerance allowed in this study. The variation of the total Pu concentration with burnup for the MOX equilibrium cycle core developed using SIMULATE-3 and described above, along with the evolution of the individual Pu isotopes is given in Figure 4:

Figure 4 : Variation of Pu vector and total Pu with burnup in the MOX equilibrium core



From Figure 4 it can be seen that in the equilibrium MOX core a net increase is seen in the total Pu mass from BOC to EOC of 2268-2126 = 142 kg.

This can be compared with the equivalent value from the equilibrium UO_2 cycle (see Figure 1) which is an increase in Pu mass of 789-382 = 407 kg. So there is a ~65% reduction in the amount of Pu generated from BOC to EOC in the core as a result of moving to a 30% MOX loading pattern.

The decreased Pu production in the equilibrium MOX core can be explained by examining the detailed behaviour of individual MOX and UO_2 fuel assemblies. The combination of the depletion of the fissile Pu isotopes (^{239}Pu and ^{241}Pu) in the MOX assemblies and the relative decrease in the MOX assembly ^{238}U concentration (when compared with the UO_2 assembly) results in a net decrease in Pu production.

The UO_2 fuel however exhibits standard Pu production behaviour, with Pu accounting for approximately 1% of the heavy metal mass of the fuel assembly at a typical fuel discharge burnup of ~ 45-50 GWd/t.

To illustrate these points, the variation of the total Pu concentration with burnup along with the evolution of the individual Pu isotopes for a 6.125 w/o (fissile) MOX assembly is given in Figure 5, followed by the equivalent data for a 3.98 w/o (24 Gd_2O_3 rods) UO_2 fuel assembly (Figure 6).

Since the equilibrium MOX core contains ~30% MOX the net effect is dominated by the UO_2 fuel, which produces Pu, resulting in the 142 kg of Pu production per cycle for the equilibrium MOX core. In order to obtain a net Pu destruction rate these results demonstrate that a core MOX fraction greater than ~35 to 40% would be required. Without developing an explicit loading pattern at this MOX loading it is difficult to determine if a 35 to 40% core is feasible with the MOX fuel design used in this task.

Figure 5 : Variation of Pu vector and total Pu with burnup in a MOX fuel assembly

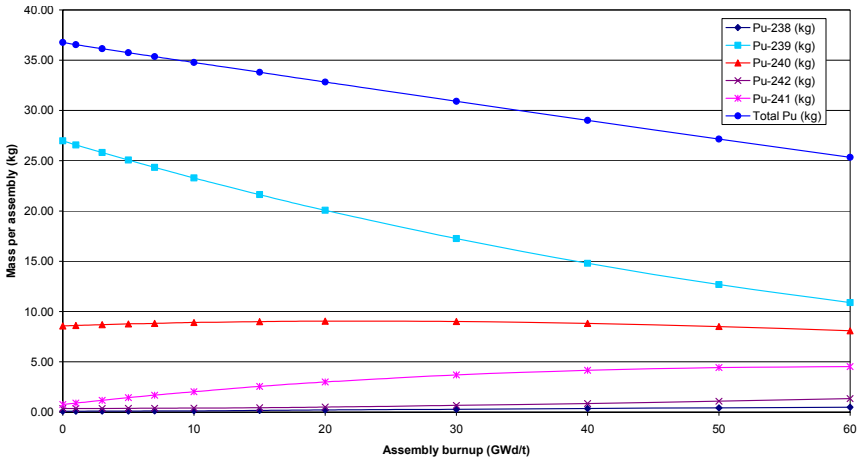
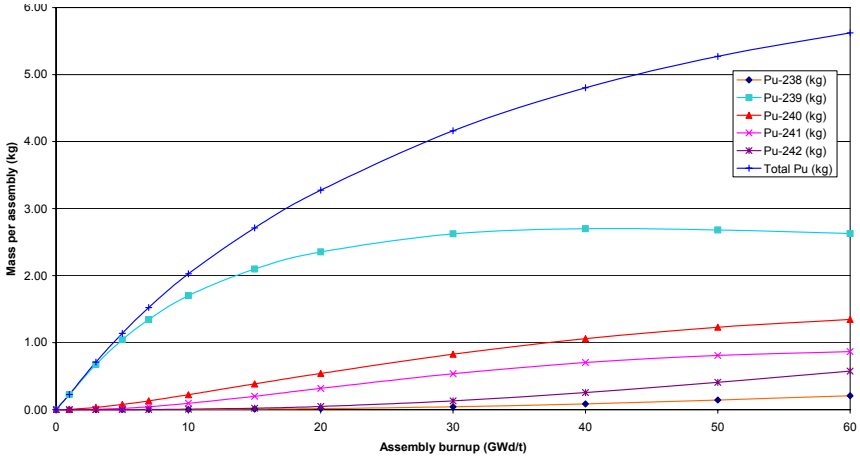


Figure 6 : Variation of Pu vector and total Pu with burnup in a UO_2 fuel assembly



It may be the case that some form of burnable poison is required for the MOX fuel, for example. In addition, a MOX fuel design using a higher moderator to fuel ratio could be investigated where the Pu production rate in ^{238}U is decreased due to the more thermal neutron spectrum (the ^{238}U neutron absorption reaction is primarily epithermal).

6. Safety Analyses

For the purposes of this task it was judged that analyses and inter-comparisons of 'key' design limits (chosen based on past experience) would be sufficient to determine the feasibility of loading Magnox Pu in a UK PWR. If these key design limits are satisfied then it can be argued that the behaviour of a 30% MOX core will approach or lie within the extensive operating experience gained with current UO_2 PWR operating strategies.

The 5 cores developed for this task were assessed against a subset of design limits using SIMULATE-3. The cores were (i) the equilibrium UO_2 core, (ii-iv) MOX transition cores and (v) the equilibrium MOX core.

The core parameters which were assessed against their design limits were:

- Radial Power Distribution Peaking Factor ($F_{\Delta H}$)
- Shutdown Margin (SDM) with One (the highest worth) Stuck Rod
- Moderator Temperature Coefficient (MTC)
- Boron Reactivity Coefficient
- Delayed Neutron Fractions

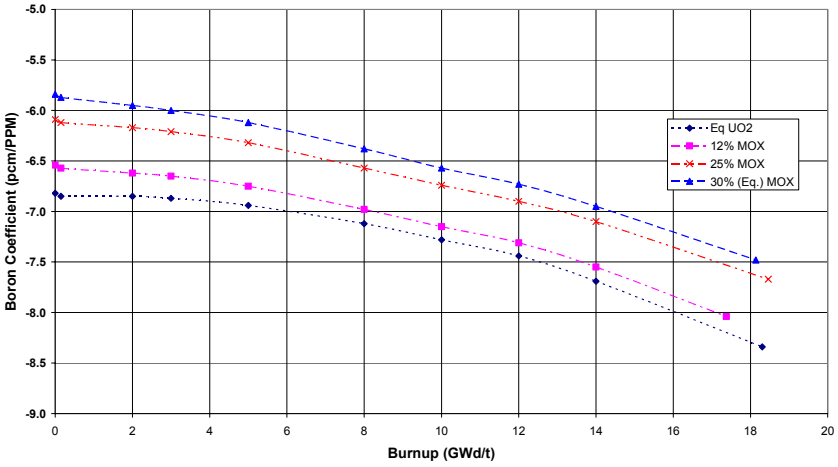
A fuel performance assessment was also carried out using the ENIGMA[6,7] code to determine whether the fuel performance design criteria were satisfied. Fuel performance parameters such as clad stress, steady-state clad strain, circumferential strain ratchetting, clad collapse, clad fatigue, fuel rod fretting and rod internal pressure were addressed.

7. Summary of Results

When each of the 5 cores are compared with typical design limits for a UK PWR, all limits were satisfied with the exception of the boron reactivity coefficients at Hot Full Power (HFP) for the 3rd MOX transition core and at HFP and Hot Zero Power (HZP) for the equilibrium MOX core.

The fact that the current boron reactivity coefficient design limits are not met for the higher MOX loading cores should not be considered prohibitive. The adoption of a new set of limits would require a fault analyses exercise, but this revision procedure has been carried out previously in the UK. In addition, the effect of MOX on some faults, e.g., an inadvertent boron dilution, would actually be to make them less onerous.

Figure 7 : Variation of hot full power boron reactivity coefficients



The expected decrease in boron reactivity coefficient as the MOX fraction increased (see Figure 7) affected the moderator temperature coefficients (MTCs) since, for a given increase in temperature, the positive reactivity effect of a reduction in soluble boron number density is reduced in the MOX cores relative to the UO_2 designs. The negative reactivity effect of a reduction in the moderator number density is therefore more pronounced, making the overall MTCs slightly more negative.

The HZP delayed neutron fractions also became smaller as the MOX fraction increased, but remained within the current limits. Although the limits are satisfied β_{eff} will need careful scrutiny if MOX loadings higher than 30% are used.

It is usual to see the shutdown margins eroded as the MOX fraction of a PWR increases. This is due to the decrease of the control rod reactivity worth as a result of the higher thermal neutron absorption cross section of MOX (cf. UO_2). In the MOX loading patterns developed for this task no such decrease was seen due to the MOX fuel being placed away from control rod locations.

As regards fuel performance, all assessed design criteria were calculated (or judged) to be satisfied with the exception of those pertaining to clad stress and rod internal pressure (for which solutions are readily available e.g., changes in loading pattern, increased plenum volume, advanced clad).

8. Conclusions

A total of five different PWR cores have been developed and analysed for this work; an equilibrium UO_2 core, three MOX transition cores and finally an equilibrium ~30% MOX core.

The results demonstrate that in principle MOX can be safely introduced into an existing UK PWR with very little effect on the steady state core physics. The Pu enrichment of the MOX fuel used in this task was 6.125 w/o fissile Pu (8.283 w/o total Pu) which is in line with current international experience[8]. This gives confidence that problems should not arise during a MOX fuel manufacturing campaign if the fuel design described in this task were to be used. In addition, when maintaining UK design and licensing limits, a similar Pu content, MOX core fraction and fuel burnup were observed to those seen in worldwide MOX experience, particularly in Europe[8]. This gives confidence not only in the completed analyses, but also in the ability of a generic UK PWR to utilise MOX.

The boron reactivity coefficients decrease (as expected) with increasing MOX fraction until the current UO_2 design limits are exceeded. This can be addressed via a standard calculational procedure involving fault analyses which use new limits more appropriate for MOX (i.e. limits which allow smaller boron reactivity coefficients).

The equilibrium MOX core requires 883 kg of ex-Magnox Pu to be loaded into the reactor at the beginning of each 472 effective full power days (EFPD) fuel cycle. This corresponds to ~645 kg of Pu per effective full power reactor year. However, the equilibrium MOX core also produces Pu, such that for a BOC Pu loading (including second and third dwell fuel) of 2126 kg, the EOC (18.1 GWd/t) Pu content is 2268 kg, a net increase of 142 kg.

This can be compared with the equilibrium UO_2 core where the equivalent values are a BOC Pu content of 382 kg (in second and third dwell fuel) and an EOC value of 789 kg,

leading to an increase in Pu of 407 kg per 477 EFPD fuel cycle. This is ~3 times larger than the amount of Pu produced by the equilibrium MOX core.

In order to obtain a core net Pu destruction rate the results indicate that a core MOX fraction greater than ~35 to 40% would be required. Without developing an explicit loading pattern at this MOX loading it is difficult to determine if a 35 to 40% core is feasible with the MOX fuel design used in this task. It may be the case that some form of burnable poison is required for the MOX fuel, for example.

Using the Pu throughputs per year demonstrated for the current PWRs, approximately 13 tonnes of ex-Magnox Pu could be utilised in a UK PWR assuming an irradiation programme lasting 20 years. This demonstrates that if an all-reactor option is to be considered to remove the existing Pu stockpile, then additional reactors are required and with the advent of new designs that can accommodate a higher MOX core fraction (50 to 100%), the mission can be achieved on shorter timescales.

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