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Plutonium management policy in the United Kingdom: The need for a dual track strategy

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HIGHLIGHTS

- Policy and technology developments in US plutonium disposition programme are analysed.
- The vulnerabilities of the UK policy for plutonium reuse as MOX fuel are assessed.
- Adoption of dual-track approach to management of UK plutonium is recommended.

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ABSTRACT

The United Kingdom holds the largest stockpile of separated civil plutonium in the world, projected to reach 140 t, at the end of this decade, when reprocessing operations are complete. UK Government policy is that this material should be reused as MOX fuel in Light Water Reactors. This policy is re-examined in the light of recent experience of the US plutonium disposition programme, in which the MOX Fuel Fabrication Facility is now considered to be potentially unaffordable. Problematic aspects of US programme, relevant to the UK scenario, are reviewed, to understand the possible impact on UK policy. Based on the US experience and inherent uncertainty regarding the capital and operational costs of MOX fuel fabrication and plutonium immobilisation facilities, and the associated technical risks, it is concluded that the UK policy should explicitly adopt a dual track strategy to plutonium management, with commitment that: *any remaining plutonium which is not converted into MOX fuel, or otherwise reused, will be immobilised and treated as waste for disposal*. This will also ensure that the UK is positioned and prepared to take forward an immobilisation and disposal programme for the plutonium stockpile, should reuse as MOX fuel not prove an economic or viable option.

1. Introduction

The UK holds stockpile of separated plutonium which is projected to exceed 140 t at the end of planned nuclear fuel reprocessing operations in 2020 (Nuclear Decommissioning Authority, 2014), this is the largest stockpile of plutonium under civil safeguards worldwide. Current stocks of UK plutonium are summarised in Table 1 (Office of Nuclear Regulation, 2014).

In the 1960's, the projected growth of civil nuclear energy, and depletion of finite fossil fuel reserves, focused attention on the development of fast reactor systems capable of improving the efficiency of uranium resource utilisation, by breeding Pu-239 from fertile U-238 (99.3% natural abundance). Such fast reactor systems require an initial core of plutonium driver fuel, which, in the UK, was to be produced by reprocessing of nuclear fuel from Magnox, and, later, Advanced Gas Cooled Reactors (AGRs). Ultimately, fossil fuel prices remained largely stable, accessible reserves of uranium ores increased, and the anticipated growth of civil nuclear energy was not realised. In this context, the commercial viability of fast reactor systems could not be demonstrated and development was largely abandoned. Commercial scale reprocessing and MOX fuel fabrication also proved challenging, with throughput below target in the Magnox reprocessing plant, Thermal Oxide Reprocessing Plant (THORP), and Sellafield MOX Plant (Global Fissile Material Report, 2015). The UK cancelled its fast reactor programme in 1994, but plutonium separation continued due to technical constraints and reprocessing contract obligations. This, combined with below target reprocessing and MOX fuel fabrication, led to the accumulation of the current stockpile, in the absence of a

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Table 1
UK civil plutonium inventory as of 31 December 2014, as published by the Office of Nuclear Regulation; of the total reported 23.0 teHM is owned by foreign bodies (Office of Nuclear Regulation, 2014).

Item	Amount (teHM)
Unirradiated separated plutonium in product stores at reprocessing plants	122.1
Unirradiated separated plutonium in the course of manufacture or fabrication and plutonium contained in unirradiated semi-fabricated or unfinished products at fuel or other fabricating plants or elsewhere	0.8
Plutonium contained in unirradiated MOX fuel or other fabricated products at reactor sites or elsewhere	1.9
Unirradiated separated plutonium held elsewhere.	1.5
Total	**126.2**

suitable route for reuse in either light water or fast reactor systems.[1]

In the UK, plutonium management policy is defined by Government, supported by the Nuclear Decommissioning Authority (NDA) who provide the necessary strategic analysis and options for the implementation of policy. The risk and hazard associated with the UK plutonium stockpile has been the focus of considerable debate. An influential report of the Royal Society in 2007, concluded that "The status quo of continuing to stockpile a very dangerous material is not an acceptable long-term option" and urged Government "to develop and implement a strategy for the management of separated plutonium as an integral part of its energy and radioactive waste polices" (The Royal Society, 2007).

The Nuclear Decommissioning Authority (NDA) commissioned a Credible Options Analysis for long term plutonium management, which identified three primary options for plutonium management, that could conceivably be implemented within 25 years (Nuclear Decommissioning Authority, 2010):

- The current strategy of long-term storage (followed by immobilisation disposal);
- Prompt immobilisation and direct disposal;
- Reuse as fuel, with conversion to Mixed Oxide (MOX) fuel for burning in current Light Water Reactor (LWR) designs as the reference scenario[2].

NDA later concluded that plutonium reuse as MOX in the CANDU EC6 heavy water reactor and reuse in the GE Hitachi PRISM fast reactor, were also credible options, but acknowledged significant technical and commercial risks in implementation of all reuse and immobilisation options (Nuclear Decommissioning Authority, 2014). The science and strategy of plutonium immobilisation and disposal are briefly summarised in Box 1.

Box 1–Plutonium disposition by immobilisation.

The aim of plutonium disposition by immobilisation is to incorporate plutonium, at the atomic scale, within a suitable host material, yielding a passively safe and proliferation resistant waste package for final disposal. In this approach, the host material, which may be an amorphous glass or crystalline ceramic, may incorporate plutonium by substitution of another chemical element within the framework of its constituent atoms. For example, in the case of the candidate ceramic material zirconolite, $CaZrTi_2O_7$, the mechanism of substitution could involve Pu^{4+} replacing Zr^{4+}, e.g. $CaZr_{1-x}Pu_xTi_2O_7$. Glass-ceramic materials are also considered for plutonium immobilisation, in which plutonium is partitioned within a highly durable ceramic phase encapsulated within a glass matrix that incorporates entrained impurities.

Selection of the host phase and plutonium incorporation mechanism is made against material performance criteria, which typically include: durability – stability toward corrosion by ground water in the disposal environment; waste loading – the quantity of plutonium incorporated per unit volume; radiation tolerance – the resistance to loss of mechanical integrity through self radiation damage; process compatibility – the efficacy of manufacture within the constraints of a nuclear facility; and availability of natural analogues – the existence of corresponding natural mineral phases which demonstrate material longevity for the required service lifetime of $>10^5$ years. A considerable body of evidence has established a tool box of glass and ceramic phases which admirably fulfil these criteria, including the example of zirconolite given above; for authoritative reviews see (Ewing, 2005, 2007; Weber et al., 1998, 1997).

The selection of one or more candidate materials for application in plutonium (or other actinide) immobilisation, is the focus of national programmes which, in addition to providing the fundamental scientific evidence to support selection of a host phase, must also demonstrate compatibility with the nature of the waste feedstock (e.g. metal or oxide form, particle size and habit, entrained contaminants) and deployment within an industrially mature manufacturing process.

Immobilisation and disposal of plutonium in a passively safe tailored wasteform offers two considerable advantages over disposition by irradiation and disposal as MOX fuel (or vitrified waste from MOX reprocessing). First, the thermal output of MOX fuels (or vitrified waste) at the envisaged time of emplacement, demands a much larger repository footprint to separate waste packages than is the case for a tailored wasteform (in order to preserve the integrity of clay buffer material used to surround the waste containers). Second, disposal of MOX fuel demands an environment in which geochemically reducing conditions are maintained for the required timescale (such that uranium is maintained as more insoluble uranium (IV) and oxidation to soluble uranium (VI) is precluded); this is not necessarily a constraint for a tailored wasteform. In the context of geological disposal of radioactive wastes, these factors are important considerations in safety assessment and overall cost of a geological disposal facility, and hence the choice of a MOX or immobilisation strategy for plutonium disposition.

Building on NDA's Credible Options Analysis, the UK Government commissioned a consultation exercise in 2011, to support identification of a preferred plutonium management option (Department of Energy and Climate Change, 2011). The policy position was defined by the Department of Energy and Climate Change in the consultation response published in 2013 (Department of Energy and Climate Change, 2013):

[1] At the time, reprocessing was considered the only feasible approach to the management of Magnox and AGR fuels, due to their susceptibility to corrosion in prolonged wet storage.

[2] MOX fuel comprises a mixture of uranium and plutonium oxides, as a solid solution $(U,Pu)O_2$ and/or a blend of discrete UO_2 and PuO_2 phases. MOX fuels are fabricated in a similar fashion to ordinary UO_2 (UOX) fuels, with a typical reactor grade PuO_2 content of ca. 7% for use in LWRs, which generally operate with a core loading of 30% MOX fuel (Status and Advances in MOX Fuel Technology, 2003). The fissile content of such fuels is equivalent to a ^{235}U enrichment of ca. 4% in UOX fuel (Status and Advances in MOX Fuel Technology, 2003). The World Nuclear Association estimates 40 European LWRs are licensed to use MOX fuel, with more than 30 doing so (World Nuclear Association, 2016). The key strategic driver for adoption of MOX fuel is sustainability of fissile material resources, by production of energy from plutonium created from irradiation of UOX fuels in LWRs. However, the hazard, security and safeguards of plutonium separation, through reprocessing of nuclear fuels, and the attendant proliferation risks, are of international concern. These strategic drivers and the international status of MOX fuel technology are summarised in a recent IAEA Technical Report (Status and Advances in MOX Fuel Technology, 2003).

The UK Government has concluded that for nuclear security reasons the preferred policy for managing the vast majority of UK civil separated plutonium is reuse and it therefore should be converted to MOX fuel for use in civil nuclear reactors. Any remaining plutonium whose condition is such that it cannot be converted into MOX will be immobilised and treated as waste for disposal.

The preference for plutonium reuse as MOX fuel was driven primarily by the perceived maturity of this technology, compared to immobilisation of the stockpile for disposal, plus revenue generation from energy production, which would be expected to make MOX the most cost-effective option. However, the policy statement makes clear that:

Only when the Government is confident that its preferred option could be implemented safely and securely, that it is affordable, deliverable, and offers value for money, will it be in a position to proceed with a new MOX plant. If we cannot establish a means of implementation that satisfies these conditions then the way forward may need to be revised.

The aim of this contribution is to re-examine the UK policy position, in the context of recent experience in the United States of America, which is reconsidering its strategy to disposition 34 t of excess weapons plutonium as MOX fuel, although construction of the MOX Fuel Fabrication Facility (MFFF) is more than 50% complete, at a cost, to date, exceeding $ 4 billion (Department of Energy, 2014). Expert international opinion has also questioned the fundamental technical reliability and economic credibility of plutonium disposition in the US and elsewhere (Global Fissile Material Report, 2015; von Hippel et al., 2012). In the light of the US experience of plutonium disposition as MOX fuel, summarised below, the current UK policy position is considered potentially vulnerable, if the position on reuse as the preferred option were to change. In essence, the UK policy embodies a single-track strategy for management of plutonium, immobilisation is only explicitly considered for plutonium whose *condition* is such that it *cannot* be converted into MOX fuel. It is proposed that UK policy should adopt a more flexible dual-track strategy to plutonium management with explicit advocacy of *immobilisation and disposal for any plutonium which is not designated for reuse as MOX or other nuclear fuel*. Such an amendment to the current policy would provide the required latitude to develop the capability to implement an immobilisation and disposal approach for the whole stockpile, should MOX reuse prove uneconomic or unviable. Indeed, this is recognised in current NDA strategy, with a commitment to "develop an approach to immobilisation of plutonium for that part of the inventory which is unsuitable for re-use and in the event that reuse cannot be successfully implemented" (Nuclear Decommissioning Authority, 2016).

2. Evolution of the US plutonium disposition programme

The Strategic Arms Reduction Treaties committed the US and Soviet Union to substantial reductions in nuclear weapons, leading to ca. 50 t of plutonium being declared excess to requirements by each nation (Department of Energy, 2014). The National Academy of Sciences advised the US Government to adopt a "dual-track strategy" for managing this plutonium inventory, with parallel development of MOX fuel and immobilisation approaches (Committee on International Security and Arms Control, 1994). The rationale of this strategy was twofold: to de-risk the programme given the uncertainties in cost and technical implementation, and to achieve earlier completion of the disposition mission, given that a fraction of the excess plutonium could be unsuitable for use as MOX fuel. Under the Clinton Administration, the US Department of Energy (US DOE) committed to this dual track strategy in 1997 (Department of Energy, 1997), stating that "Pursuing both immobilisation and MOX fuel fabrication… provides important insurance against uncertainties of implementing either approach by itself" (Department of Energy, 1999). The Plutonium Management and Disposition Agreement, signed in 2000, subsequently committed both the US and Russian Federation to each disposition a minimum of 34 t of excess weapons grade plutonium by irradiation as MOX fuel (Department of State), with provision for some US material to be dispositioned by immobilisation and disposal. Following a review of the plutonium disposition programme under the Bush Administration, US DOE cancelled the immobilisation programme in 2002, ostensibly due to budgetary constraints (Department of Energy and National Nuclear Security Administration, 2002). Thereafter, the US was committed to disposition of 34 t of excess weapons grade plutonium as MOX fuel which, crucially, now included 6.5 t of material originally planned for immobilisation (Holt and Nikitin, 2014).

Since 2002, the US has defaulted to a single-track disposition strategy involving construction of the MOX Fuel Fabrication Facility on the Savannah River Site. Work started on MFFF design in 1999, with construction beginning in 2007. The facility was originally estimated to cost $1 billion and be delivered by 2016 (Department of Energy and National Nuclear Security Administration, 2003). By 2014, the cost estimate had grown to in excess of $7.7 billion, with operations expected by 2019 at the earliest (Department of Energy, 2014). A later study by Aerospace Corporation, concluded that construction of MFFF could not be completed before 2100 at the annual funding level assigned in 2014, at a total cost of ca. $27–30 billion (Plutonium Disposition Study Options Independent Assessment Phase 1 Report, 2015) (real year dollars). The divergent estimates of MFFF completion costs were analysed by the US DOE commissioned "Red Team" review, whose report was disclosed by the Union of Concerned Scientists (Final Report of the Plutonium Disposition Red Team, 2015). This analysis highlighted the different programme components, assumptions and methodologies utilised in previous studies to derive cost estimates, including different approaches to evaluating project risks and uncertainties. The Red Team analysis suggests a minimum cost of $12.6 billion would be required to complete MFFF, at an assigned budget of $700–800 M per year, for 15 years, to finish construction, followed by 3 years of commissioning activity, with operations commencing in ca. 2033 (financial year 2015 dollars).

In response to escalating cost and timescale of MFFF delivery, the Obama Administration announced in 2013 that "This current plutonium disposition approach may be unaffordable … due to cost growth and fiscal pressure" (Executive Office of the President of the United States, 2014). In its budget proposal for financial year 2015, the Obama Administration declared: "Following a year-long review of the plutonium disposition programme, the Budget provides funding to place the Mixed Oxide (MOX) Fuel Fabrication Facility in South Carolina into cold-standby. NNSA [the National Nuclear Security Administration] is evaluating alternative plutonium disposition technologies to MOX that will achieve a safe and secure solution more quickly and cost effectively" (Executive Office of the President of the United States, 2015). Although the MFFF project may, in future, be completed, this seems a questionable prospect, given the US DOE commissioned "Red Team" report which advocated the lower cost and uncertainty of plutonium disposition through a "dilute and dispose" strategy (Final Report of the Plutonium Disposition Red Team, 2015). This process involves mixing the plutonium with an unspecified proprietary material (referred to as "star dust") and disposal of waste packages in the Waste Isolation Pilot Plant – the US transuranic geological disposal facility, located in New Mexico, at a depth of 650 m, within a stable

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salt formation (Final Report of the Plutonium Disposition Red Team, 2015).

3. The MOX fuel fabrication facility

To understand the extent to which UK plutonium management policy may be vulnerable to the difficulties encountered in delivering the MFFF, a brief description of the facility is warranted, prior to an appraisal of the problematic aspects of delivery which may be relevant to the UK position. The MFFF is based on the French MELOX plant, developed by AREVA, and comprises plutonium purification, MOX fuel fabrication, analytical chemistry, and buffer storage facilities (Final Report of the Plutonium Disposition Red Team, 2015; Hylko, 2012). The main MFFF building has a foot print of over 45,000 m^2 and is constructed from reinforced concrete (Final Report of the Plutonium Disposition Red Team, 2015; Hylko, 2012). The key functions of MFFF include:

3.1. Aqueous polishing

In which plutonium oxide is dissolved in nitric acid and solvent extraction is used to remove uranium, americium, gallium and other contaminants; the plutonium is then precipitated and calcined to yield (ideally) pure plutonium oxide.

3.2. MOX fuel fabrication

In which plutonium oxide is blended, mixed with uranium oxide, milled, pelletised and sintered, using a heavily automated process; MOX fuel pellets which pass quality control assessment are loaded into Zircaloy fuel pins, which are combined to form fuel assemblies.

In addition, MFFF operations are supported by feed preparation in the H-Canyon facility in which scrap plutonium material is dissolved in nitric acid and sentenced to the aqueous polishing process in MFFF.

It is not anticipated that a UK MOX fuel production plant would require an aqueous polishing process, which accounts for around half of the MFFF budget. In the UK, it is considered that amercium-241, and other impurities, could be managed through blending of plutonium oxide batches for the vast majority of the stockpile.[3] Otherwise, the MOX fuel fabrication lines envisaged for MFFF are likely to be similar to those in a UK counterpart facility, notwithstanding the key differences in the grade of the plutonium and hence criticality considerations, and location dependent design requirements such as seismic qualification. There remains some uncertainty as to whether blending of UK Magnox and AGR derived plutonium could reduce the americium-241 content to $<4\%$, as required for MOX fuel fabrication and reuse in light water reactors (Nuclear Decommissioning Authority, 2010). The proportion of the stockpile which can be reused is clearly time dependent and, given the current absence of commercial interest in utilising MOX fuel in present and future LWR reactors, an aqueous polishing facility may ultimately be required.

An apparent difference between the UK and US scenarios, is the need to manage reactor or weapons grade plutonium, defined according to the plutonium-240 content[4] (Mark, 1993; Nuclear Decommissioning Authority, 2008). Appraisal of the challenge in developing an explosive design for reactor grade plutonium concluded that this would not be "appreciably different", relative to weapons grade material, and, therefore, "the need for safeguards to protect against the diversion and misuse of separated plutonium applies essentially equally to all grades of plutonium" (Mark, 1993). Hence, it is reasonable to expect that a UK MOX fuel fabrication facility would not require appreciably different security and safeguards infrastructure, although the precise design requirements and regulatory controls may be different.

4. Audit analysis of cost and schedule overruns of MFFF

Fundamentally, the escalating cost and delay of the MFFF project was the result of an "approved project baseline which was developed from an incomplete design" in 2007, according to a US DOE audit (Department of Energy, 2014). This resulted in incorrect assumptions regarding skilled labour, equipment specification, installation times, and costs. The audit noted that independent reviewers had previously highlighted that "project cost and schedule estimates were at a significant risk of increasing when using a phased or incremental approach to completing a MOX Facility design" (Department of Energy, 2014).

A recent US Government Audit Office review of the plutonium disposition programme identified several areas of concern, in relation to the increased cost and delay of MFFF, these included (United States Government Accountability Office, 2014):

- Inadequate design of the plutonium glovebox handling systems and support infrastructure, which are integral to fuel fabrication operations. The MFFF design drew heavily on that of the MELOX plant, but the cost of the required adaptations was apparently not well understood prior to design approval.
- Inadequate understanding of the ability of the commercial supply chain to provide skilled labour, components, and equipment, to meet the demanding quality standards required in a nuclear environment.
- Substantive variations to the project scope and construction contract, impacting the cost and schedule of the MFFF.
- The effectiveness of interim project reviews in challenging unrealistic assumptions and cost estimates and the response of project management, in terms of mitigating actions.
- The need for independent assessment and review of the overall life-cycle cost estimates for the plutonium disposition programme.

Major amendments to the initial MFFF scope were required to enable treatment of the 6.5 t of plutonium originally scheduled for immobilisation (Holt and Nikitin, 2014), as reported by Lyman (2014) and von Hippel and MacKerron (2015). To bring this material within the quality specification for use in MOX fuel, supplementary aqueous polishing lines were required to remove the additional contaminants. Modification of MFFF to accommodate this process required additional equipment and infrastructure, increasing plant footprint by ca. 10%. As a consequence of the supplementary aqueous polishing system, the increased projection of transuranic waste demanded construction of a dedicated Waste Solidification Building, which had not been planned for. However, US DOE had previously acknowledged that "there are considerable uncertainties with how much … material will be accepted by the programme due to uncertainties with characterisation data and acceptance of material based on an ability to meet the MOX fuel specification" (Department of Energy). In addition, modification of the original MFFF design was also required to accommodate a Pit Feed Preparation facility, following a decision to cancel a separate

[3] Arising from β-decay of plutonium-241, with a half life of 14 years.

[4] Weapons grade plutonium is characterised by a Pu-240 content of $<6\%$, since this isotope has a high rate of spontaneous fission and hence neutron production, resulting in low explosive yield through premature initiation of the fission chain reaction under implosion (Mark, 1993). Note that some plutonium derived from low burn up Magnox fuel has a much lower Pu-240 content (16.9%) compared to that derived from high burnup Magnox and typical light water reactor fuel (ca. 24%) or AGR fuel (30%) (Nuclear Decommissioning Authority, 2008).

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Pit Conversion Facility on the Savannah River Site (Department of Energy, 2014).

5. Impact on UK plutonium management policy

The US plutonium disposition programme opted to pursue a single-track strategy for reuse of excess weapons plutonium as MOX fuel on the basis of the apparent technical maturity, compared to immobilisation and disposal technology, and, ostensibly, budget constraints that prohibited a dual-track strategy. Nevertheless, adaptation of a technically mature MOX fuel fabrication process has proven prohibitively more challenging than expected. At a fundamental level, failure to adequately design and cost the glovebox infrastructure required for MFFF, poses one plausible challenge to the UK MOX reuse policy, because the preferred option for reuse in LWRs is based on adaptation of the same MELOX reference design. NDA's Plutonium Credible Options Analysis, quite reasonably, used data supplied by MELOX operator, AREVA, and published information from the MFFF project, in bench marking the MOX reuse option (Nuclear Decommissioning Authority, 2010). Review of the design basis assumptions and cost data, for a UK MOX fuel fabrication plant would therefore seem appropriate, in the light of the US experience.

Construction of a UK MOX fuel fabrication plant would require extensive supply chain engagement, as in the construction of MFFF. The UK reuse policy is potentially vulnerable to the same challenge associated with provision of services and equipment to nuclear standards. A significant contributor to the increased cost of MFFF was the excessive turnover of a skilled workforce, which was in high demand. Given the 100 y timescale and £70 billion (discounted) cost of the UK nuclear decommissioning programme (Nuclear Decommissioning Authority, 2015), the demand for skilled nuclear workers is expected to remain high, even in the absence of a UK MOX fuel fabrication plant. Hence, effective planning of workforce needs will be essential to ensuring cost effective delivery of a new MOX plant to cost and schedule. This consideration also applies to delivery of a plutonium immobilisation plant.

The strategic drivers on the UK and US plutonium disposition programmes are very different and it is unlikely that the UK MOX reuse mission would be subject to radical changes in scope, as in the US case, since the option to immobilise and dispose of plutonium unsuitable for MOX use remains open. Nevertheless, in the absence of detailed characterisation data, it cannot be assumed with certainty that all of the plutonium thought to be suitable for MOX fuel manufacture could be so utilised, without aqueous polishing to remove amerciuim-241 and/or other contaminants. Managing americium-241 ingrowth for MOX fuel manufacture, by blending of plutonium produced from reprocessing of Magnox and UOX fuels becomes more problematic with time, increasing the probability that aqueous polishing of plutonium feedstocks would be required. More problematic is the fact that no (potential) commercial operator in the UK has yet indicated an interest in accepting MOX fuel. The price of enrichment and UOX fuel has remained stable over the last decade, and, although demand for uranium has increased, production has increased to meet this demand (Uranium 2009, 2010; Euratom, 2015). This trend is anticipated to be maintained for the foreseeable future (Euratom, 2015; World Nuclear Association, 2015), and the commercial appetite for MOX off take in the UK is expected to remain weak. Electricite de France, the owner and operator of the existing Sizewell B PWR and proposed Hinkley Point C EPRs, which could in principle accept MOX fuel, has expressed no interest in MOX off take. Sizewell B is not currently licensed for use of MOX fuel, and the Generic Design Assessment of the proposed EPRs explicitly excluded consideration of MOX fuel utilisation (Generic Design Assessment, 2011). Consequently, there is a risk to the UK MOX reuse policy from inherent uncertainties in the quality of the plutonium feedstock reuse, the lead time to construct a fuel fabrication plant, and the availability of new reactors willing to accept MOX fuel. The risks to delivery of a plutonium immobilisation programme are associated with the lead time to construct the immobilisation facility and a Geological Disposal Facility for disposition. These risks are highlighted in the NDA Credible Options analysis of 2010 but would now benefit from greater scrutiny, following the US experience.

6. The need for a dual-track strategy within UK plutonium manage policy

The UK policy for plutonium management is essentially a single-track strategy, with reuse in MOX fuel identified as the preferred option, and immobilisation and disposal considered only for material whose *condition* is such that *cannot* be converted into MOX fuel. A vulnerability of this policy is that if, in the future, MOX proves unaffordable or is not accepted by utility operators, then the bulk of the stockpile, whose condition is currently thought to *acceptable* for MOX fuel manufacture, would be effectively stranded without a disposition route. Indeed, the UK Government's policy statement acknowledges that if implementation of the MOX reuse strategy cannot be achieved then “the way forward may need to be revised” (Department of Energy and Climate Change, 2013).

If the current UK policy on reuse of plutonium as MOX fuel were to be superseded by a policy of immobilisation and disposal, the UK would potentially be better placed to implement such a policy, compared to the US scenario, because immobilisation and disposal technology will at least be progressed to address waste plutonium whose condition is unsuitable for MOX fuel manufacture. However, it could not be assumed that such technology could be directly applied or scaled up for the purpose of immobilising the whole stockpile, indeed a ceramic wasteform could be preferable for plutonium stockpile immobilisation, compared to the glass-ceramic wasteform developed for waste plutonium immobilisation, given the more efficient incorporation rate (Squire et al., 2015; Maddrell et al., 2015). The kinetics of plutonium surrogate incorporation within ceramic wasteforms produced by Hot Isostatic Pressing, are known depend on the particle size and habit of the feedstock in combination with the choice of ceramic forming oxides, powder milling parameters, lubricant, and hot pressing conditions (Squire et al., 2015). An existing plutonium waste treatment plant, optimised to produce glass-ceramic wasteforms, would not necessarily be compatible or amenable to cost-effective adaptation to produce optimised ceramic wasteforms for stockpile immobilisation.

Immobilisation and disposal is the only credible option for plutonium management which is capable of addressing the complete plutonium stockpile, including material whose condition is deemed unsuitable for MOX fuel manufacture. The evidence from the US MFFF project is that maintaining the option to immobilise the whole plutonium stockpile, in an explicit dual-track strategy, is desirable to mitigate the considerable technical and cost uncertainties associated with MOX and immobilisation technologies. Ensuring UK policy accommodates a dual-track strategy would provide flexibility to undertake research and development of immobilisation technology, in order to fully leverage data and experience from a small scale waste plutonium treatment programme, for a large scale stockpile immobilisation programme. For example, plutonium incorporation rates are a much more important consideration for immobilisation of stockpile versus waste plutonium, since the number of waste packages, and interim storage space, scales inversely with incorporation rate. Under an amended policy, investigation of very high incorporation rates for

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immobilisation technologies would be clearly justified with regard to potential application to the plutonium stockpile, which is consistent with the aspirations of current NDA Strategy, as highlighted above (Nuclear Decommissioning Authority, 2016). An explicit dual-track strategy of this nature would improve the robustness of the UK plutonium management policy against material and commercial uncertainties.

7. Conclusions and policy implications

A brief and high level consideration of the US plutonium disposition programme has highlighted the benefit of an explicit dual-track strategy to the reuse and immobilisation of plutonium stockpiles. Although there are significant differences in the strategic drivers for the US and UK MOX reuse strategies, the UK reuse policy is vulnerable to some of the problematic issues that have frustrated delivery of the US MFFF to cost and schedule. Review of the design basis assumptions and cost data, for a UK MOX fuel fabrication plant would therefore seem appropriate, in the light of the US experience. The UK is better prepared to adapt to uncertainties in the suitability of plutonium reuse as MOX fuel, and any future change in reuse policy, through development of an immobilisation and disposal approach for waste plutonium. Nevertheless, ensuring UK policy accommodates a dual track strategy would strengthen this position further, by supporting enhancement of immobilisation and disposal research programmes, so as to adequately address the plutonium stockpile, if required. The current policy is challenged by this approach, with its exclusive focus on the application of immobilisation and disposal to plutonium whose *condition* is such that it *cannot* be reused as MOX fuel. Amendment of current UK policy position to address this issue, should also provide flexibility with respect to alternative reuse options for UK plutonium such as deployment as MOX fuel in the CANDU heavy water reactor design or as a metallic fuel in the GE-Hitachi PRISM sodium cooled fast reactor design (Nuclear Decommissioning Authority, 2014). In conclusion, it is recommended that UK plutonium management policy adopt a more nuanced and flexible position on immobilisation and disposal, with a commitment that: *any remaining plutonium which is not converted into MOX, or otherwise reused, will be immobilised and treated as waste for disposal.*

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