Third Generation Irradiated Mixed Oxide Fuel (Conceptual stage)

Summary of Assessment Report

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Introduction

In December 2011, following a period of extensive consultation, UK Government announced that the preferred solution for the management of the UK stocks of separated civil plutonium is to pursue reuse in the form of mixed uranium/plutonium oxide fuel (MOX) for use in civil nuclear reactors[1]. While the UK Government believes it has sufficient information to set out a direction, the available information is not yet sufficient to make a specific decision to proceed with procuring a new MOX plant to fabricate MOX fuel assemblies. The NDA's Strategy function has been tasked to support the Government with the next phase of work, which will provide the information required to make such a decision.

NDA Strategy has embarked on a detailed evaluation of the implications of reusing the UK's plutonium stocks to fabricate MOX fuel. Different MOX reactor systems are being explored for the purposes of burning the MOX fuel. The first option being explored by NDA Strategy is fabrication into thermal MOX fuel for irradiation in third generation Pressurised Water Reactors (PWRs).

To support further decision making for reuse of plutonium as thermal MOX fuel, NDA Strategy is undertaking a full-lifecycle analysis of the implications of using the plutonium in this way, encompassing MOX fuel fabrication, its use in third generation reactors and back-end management of the spent fuel. Currently there are no plans to reprocess spent fuel in the UK beyond the current commitments. Accordingly, spent fuel arisings from new UK sources would be destined for direct disposal in a Geological Disposal Facility (GDF). NDA Strategy has therefore requested Radioactive Waste Management Directorate (RWMD) to assess the compatibility of third generation MOX spent fuel with the requirements for geological disposal.

This Assessment Report provides the basis and findings of the conceptual stage disposability assessment by RWMD for packages containing MOX fuel assemblies irradiated in third generation PWRs. The assessment has been carried out through the Disposability Assessment process, whereby RWMD examines the disposability of proposed waste packages by assessment against the reference case spent fuel concept. This concept has been developed as part of the programme to implement geological disposal for the UK's higher activity wastes. Further information on the Disposability Assessment process is available elsewhere[2].

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1 Department of Energy and Climate Change, *Management of the UK's Plutonium Stocks - A consultation response on the long-term management of UK-owned separated civil plutonium*, December 2011 (http://www.decc.gov.uk/assets/decc/Consultations/plutonium-stocks/3694-govt-resp-mgmt-of-uk-plutonium-stocks.pdf, accessed 7 August 2012)

2 NDA, Guide to the Letter of Compliance Process, NDA Document WPS/650, March 2008

Objectives

The objective of this conceptual stage disposability assessment is to provide NDA Strategy with advice on the compatibility of packages containing third generation irradiated MOX fuel with the reference case geological disposal concept for spent fuel. This information will be used by NDA Strategy to support decision making for reusing the UK's civil plutonium stocks as MOX fuel.

RWMD is not currently in a position to provide endorsement of proposals for packaging spent fuel, as would be signified by the provision of a Letter of Compliance. However, NDA Strategy has not sought endorsement of the proposals to dispose of MOX spent fuel at this time, but simply advice on its disposability. Regardless, the advice given in this assessment report also sets out the future activities that would need to be addressed to allow for such endorsement, once the GDF concept and underlying specifications become better defined for packages containing spent fuel.

Basis of assessment

The material addressed by these proposals encompasses MOX fuel fabricated from the existing and future arisings of separated civil plutonium oxide for which the UK holds title and which is deemed suitable for reuse. Based on current reprocessing schedules, the arisings of separated plutonium available for MOX fuel manufacture extend to approximately 120 tHM plutonium. This material may be sufficient to manufacture around 1,500 tHM of MOX fuel, or approximately 3,000 MOX PWR assemblies for irradiation in a fleet of third generation PWRs, either in the UK or overseas. The plutonium may be treated during MOX fuel manufacture to remove (or reduce) the content of in-grown americium to ensure consistent product quality and reduce operator doses.

RWMD has previously assessed the disposability of irradiated uranium oxide (UOX) fuel that might arise from a 10 GW(e) programme of third generation PWRs[3,4]. This was undertaken to support the regulator-led Generic Design Assessment for two types of new PWR design: the Areva EPR and the Westinghouse AP1000. The current assessment has assumed that MOX fuel assemblies would be irradiated in either type of reactor by substitution of a proportion of the UOX fuel assemblies with MOX fuel assemblies. The assumption in the current assessment is that up to one third of the core of these reactors would be fuelled by MOX. This is simply an assumption for the purposes of assessing the feasibility of disposing of MOX spent fuel, since there are no current plans by power station operators to run new PWRs on MOX fuel. Indeed, the plans for a third generation nuclear programme are not sufficiently developed at this stage to make any detailed plans.

For this assessment, it has been envisaged that MOX fuel assemblies would be used in much the same way as UOX assemblies in a PWR, being run on 18-month cycles, with fuel assemblies either replaced or moved around the core to optimise burn-up between cycles. A typical third generation PWR UOX fuel assembly may experience up to five such irradiation cycles, leading to an average assembly burn-up of up to 65 GWd/tU. Detailed burn strategies for MOX fuel have not yet been established but for the purposes of the current assessment, it has been assumed that MOX fuel would achieve assembly average burn-ups of 50 GWd/tHM, based on three 18-month

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3 NDA, Generic Design Assessment: Summary of Disposability Assessment for Wastes and Spent Fuel arising from Operation of the Westinghouse AP1000, NDA Technical Note no. 11339711, October 2009

4 NDA, Generic Design Assessment: Summary of Disposability Assessment for Wastes and Spent Fuel arising from Operation of the UK EPR, NDA Technical Note no. 11261814, October 2009

cycles. Irradiated MOX liberates greater amounts of heat energy than UOX spent fuel of similar burn-up, which explains why MOX assemblies might be subjected to fewer irradiation cycles than UOX assemblies. Discharged MOX fuel assemblies would then be subject to a period of extended storage to allow for sufficient cooling before being packaged for transport and disposal in a GDF.

The reference case spent fuel concept adopted by RWMD assumes that dried PWR fuel assemblies would be packaged in high integrity canisters, with each canister holding up to four assemblies. A range of alternative packaging variations were also explored for the spent MOX fuel assemblies with the packages varying by the number of MOX assemblies in each canister (between four and one) and also by mixing MOX and UOX assemblies in the same canister. These different variants were developed to account for the greater heat burden of MOX spent fuel.

The reference spent fuel disposal concept relies primarily upon the high integrity disposal canister to provide an engineered barrier that physically isolates the spent fuel from the external environment. The packages would be emplaced in vertical deposition holes in long tunnels. Rings of compacted bentonite clay would be placed around the base and sides of the packages at the time of emplacement. The remaining space at the top of the deposition holes and tunnel voids would then be backfilled with a mixture of crushed rock and bentonite clay buffer. The bentonite buffer would be emplaced in a nominally dry state but would be allowed to slowly resaturate with groundwater after closure of the tunnels. This arrangement has been developed to ensure that the spent fuel would remain physically isolated for many thousands of years, during which time much of the radioactivity within the spent fuel would decay to low levels.

The role of the bentonite buffer is important in the reference case concept since this protects the canisters from exposure to corrosive species that might be present in a disposal environment. One of the requirements of the reference case spent fuel concept is that the temperature of the bentonite buffer in contact with the spent fuel packages should not exceed 100°C. This limit has been set to ensure that the bentonite buffer can maintain its ability to exert a swelling pressure. The swelling pressure is important in closure of potential groundwater pathways and suppression of anaerobic bacteria that can generate corrosive by-products. The degree to which bentonite is able to form the required swelling pressure diminishes with increasing temperature.

The RWMD assessment of disposability encompasses packaging the irradiated MOX fuel assemblies, transport of the packages to a GDF, handling and emplacement operations at a GDF and the extended period beyond closure of the facility. The fuel assemblies would only be consigned for disposal once they are sufficiently cooled to comply with the GDF thermal constraint of 100°C. An important aspect of the assessment is to determine the timescale for interim storage of the fuel assemblies to satisfy this requirement.

Outcome of assessment

Spent Fuel Disposal Concept Design

The reference spent fuel disposal concept was originally developed by RWMD to accommodate a range of legacy UOX spent fuels and vitrified HLW. The isotopic composition of MOX spent fuel is markedly different to UOX spent fuel, with MOX containing a greater inventory of longer-lived heat emitting transuranic radionuclides. As a result, the radiogenic heat output from MOX spent fuel remains greater for a longer timescale than that from UOX spent fuel. This property of MOX spent fuel has an important influence over the way the fuel assemblies would need to be managed for disposal. The RWMD assessment has shown that, to comply with the thermal constraints of the reference case disposal concept, MOX spent fuel assemblies would need to cooled for much longer time periods than UOX spent fuel assemblies to allow sufficient radioactive decay of the main heat generating radionuclides. For example, the reference case package containing four MOX assemblies would need to be cooled for ~1,700 years to satisfy the 100°C requirement of the reference case disposal concept. This compares to cooling periods of around 100 years for high burn-up UOX spent fuels. Clearly, storage periods extending to many hundreds of years would not be feasible.

The thermal impact of MOX spent fuel becomes more pronounced with increasing burn-up. The assessment has shown that reducing the burn-up of MOX fuel would allow for a considerable reduction in cooling requirements. However, RWMD recognises the economic drivers for burning MOX fuel, which is to generate electricity. Further consideration was given as to how the disposal concept could be adapted to accommodate fully irradiated MOX fuel on shorter timescales.

Sensitivity analyses indicate that it should be possible to dispose of MOX fuel assemblies on shorter timescales by certain design modifications being made to the disposal concept, and by adoption of alternative packaging solutions. It has been shown that selective emplacement of MOX packages in arrays between packages containing cooler legacy spent fuel would afford considerable dilution of the thermal load in the disposal environment, and thereby reducing the cooling time required prior to MOX fuel being consigned for disposal. The number of MOX fuel assemblies in any single package also has an important bearing on the required cooling time, simply due to the density of heat in each package. As a result of these findings, RWMD has already initiated further optimisation studies to explore ways and means of modifying the spent fuel disposal concept to better accommodate packages containing MOX spent fuel. It is expected that this additional work could eventually be used to support GDF concept change controls to incorporate the necessary modifications to the reference case concept.

It is possible, nevertheless, that modifications to the disposal concept could have implications on operational complexity and overall cost, and care will therefore be taken to ensure that the most optimised solution is identified. For example, reducing the number of MOX assemblies in each package would tend to increase the overall number of packages consigned for disposal, and hence also increase the required size of a GDF. This effect may be offset by co-packaging MOX with cooler UOX assemblies. These issues are being addressed within the scope of the ongoing MOX disposal optimisation study.

International spent fuel disposal programmes suggest that the 100°C thermal limit specified within the UK reference case spent fuel disposal concept is an acceptable value below which bentonite buffer should still be able to exert an adequate swelling pressure to satisfy its safety functions. The current disposability assessment for MOX spent fuel has identified that considerable benefit could be realised by relaxation of the thermal limit, since this would afford considerable reductions in cooling requirements for all types of spent fuel. The science behind bentonite performance at these higher temperatures is not yet fully underpinned. To adopt a higher thermal limit would therefore require further dedicated research to be undertaken. One of the key recommendations from this assessment is that such research should be undertaken by RWMD as a priority issue.

Transport to a GDF

At this stage in the development of the transport case, there is sufficient confidence that the packages containing third generation MOX spent fuel could be compliant with the transport system design. The outline design of the Disposal Canister Transport Container (DCTC) has been developed for cooler legacy spent fuels and there is a possibility that the design may need to be modified to account for the additional heat load from MOX fuel, for example by the addition of cooling fins. Such modification would only be necessary if plans for disposing of irradiated MOX fuel are carried forward.

The criticality safety case would be reliant upon minimisation of water inside the spent fuel canister, both as a result of water carryover with inadequately dried fuel and as a consequence of ingress under accident conditions. Calculations indicate that the amount of water carried over into the package with each fuel assembly would need to be below 2.5 kg to maintain safely sub-critical conditions. Furthermore, compliance with the IAEA Transport Regulations may rely upon the development of qualified Multiple Water Barriers (MWBs) in the design of the DCTC to ensure absolute elimination of water at all times. This is because, by virtue of the design of PWR fuel assemblies, full water flooding could result in criticality being achieved, particularly for low irradiated material. This situation is not unique to PWR MOX assemblies since similar work by RWMD identified that the DCTC design would need to include MWBs to transport UOX fuel assemblies. RWMD has already initiated work to consider the incorporation of MWBs in the design of the DCTC. RWMD will draw upon the wealth of international experience as it continues to develop the design of the DCTC for the transport of spent fuel.

Handling and Emplacement Operations at a GDF

The doses associated with both routine package handling and design basis accidents were calculated to be well within acceptable levels. This is largely due to the anticipated high integrity of the disposal canisters and the expectation that handling accidents would result in zero release of package contents. Similarly, criticality safety during the GDF operational phase would also be reliant upon the minimisation of water carryover into the package coupled with the canister acting as an enduring barrier to the ingress of water.

It is concluded that it should be feasible to make an operational safety case for handling MOX packages.

Post-Closure Performance

The analysis of post-closure risk in the groundwater pathway indicates that the disposal of MOX spent fuel should not create any significant challenge when compared to other waste streams in the overall inventory of waste that might be consigned to a GDF. This conclusion is valid even if worst case assumptions regarding long-term fuel performance are realised, though it was identified that the MOX fuel fabrication process could have an important influence on the long-term performance. In particular, the degree of homogeneity of fissile plutonium in the ceramic oxide matrix can influence the distribution of fission products and stresses within the fuel that can affect the release of radionuclides from the aged wasteform. This indicates that future disposability would need to be taken into account when developing the fuel fabrication process for third generation MOX fuel.

RWMD believes that the likelihood of post-closure criticality for UOX spent fuel would be low. Whilst the likelihood for criticality to occur for MOX spent fuel is also expected to be low, potentially higher package fissile loadings and reduced fuel matrix stability suggest that the likelihood for criticality might be marginally greater for MOX than for UOX spent fuel. The arguments to support GDF post-closure criticality safety are currently being developed and RWMD is half-way through a two-year project exploring the likelihood for post-closure criticality for a range of wastes, including spent fuel. Although the scope of the likelihood of criticality project does not explicitly include MOX spent fuel, RWMD is exploring the relative post-closure criticality performance of MOX spent fuel against UOX spent fuel as part of a separate MOX disposal optimisation study. RWMD is nonetheless aware of international work which indicates that criticality safety could be demonstrated for disposed MOX spent fuel by the specification of minimum fuel burn-up, which reduces the quantity of fissile radionuclides remaining in the fuel, and by establishing limits on the quantity of MOX fuel in any single package.

Recommendations and Further Work Activities

The disposability assessment has shown that the cooling period for MOX spent fuel could be very long when judged against the reference spent fuel concept. The main finding from the disposability assessment is that RWMD would need to modify the disposal concept to accommodate the higher thermal load from MOX spent fuel to allow disposal on more realistic timescales. As previously noted, a separate workstream has already been initiated to look into optimisation of the disposal concept to accommodate MOX spent fuel. This work would be used to support GDF change control if the proposals to irradiate MOX fuel are taken forward. The optimisation study will explore a number of issues identified in this disposability assessment, including:

- Selective package emplacement strategies – further exploration of different package spatial layouts to effectively dilute the thermal load associated with MOX in a GDF;
- MOX packaging options - the reference case concept assumes that four PWR fuel assemblies would be packaged in each disposal canister, yet the current assessment suggests that it would not be appropriate to package four MOX assemblies in a single package due to both a high package thermal output and fissile content. This finding is consistent with international approaches to MOX disposal, where packages are generally limited to only a single assembly at a time, e.g. in Belgium and Switzerland. The current assessment identified that there may also be merit in co-packaging MOX fuel assemblies with third generation UOX assemblies so further consideration is being given to finding an optimised solution;
- Post-closure criticality for packaged MOX spent fuel – further consideration is being given to the use of burn-up credit as a means for demonstrating that the likelihood of post-closure criticality is low and is within the range of uncertainty as for UOX spent fuels;
- International approaches to MOX spent fuel disposal – further information is being sought to understand how overseas waste management organisations are developing disposal safety cases for MOX spent fuel, in particular those in Belgium, Germany, Sweden, Switzerland and the USA, which could help the UK build its own case.

The operational complexity, costs and GDF footprint of different packaging options and spatial layouts will also be explored as part of the separate optimisation study. The optimisation study is split into a series of work phases, the first of which is expected to report by December 2012. Ultimately, the findings from both this disposability assessment and the further optimisation work would need to be used by NDA Strategy to define a future strategy for burning MOX fuel and its subsequent management for disposal. This would need to balance the requirements for extended cooling periods with GDF design modifications, recognising that there is likely to be a trade-off between the various factors.

This disposability assessment has highlighted a need to better understand the science behind the thermal limit applicable to the engineered barriers of the spent fuel disposal concept. The assessment of thermal impacts of MOX fuel disposal was based on compliance with a 100°C limit for packages in contact with bentonite buffer material. This thermal constraint has been adopted from overseas programmes where site- or waste-specific factors dictate that this is an appropriate limit. In the UK situation, no specific site or detailed concept design has been finalised. The 100°C limit is deemed to be an appropriate limit for use in disposability assessments, yet opportunities still exist to determine whether alternative limits could be adopted, based on site specific factors. A further important recommendation of the current study is for RWMD to fully underpin the science behind the thermal limit(s), recognising that thresholds may differ according to the nature of the geology, disposal concept design and the role of associated engineered barriers.

A further heat-related generic issue identified during the course of this disposability assessment relates to the need to impose limits on fuel cladding temperatures following packaging. It is generally held that fuel cladding must be maintained below a certain temperature in dry storage facilities, typically 400°C, to limit the potential for thermally induced cladding failure. However, the requirements for packaged spent fuel are less clear, largely because the requirements for maintaining the integrity of cladding in packaged fuel are not fully established. This matter becomes more significant as hotter fuel is brought forwards for disposal and it is recommended that RWMD gives further consideration to this matter.

In order to better understand the thermal constraints applicable to the disposal of spent fuel more generally, RWMD has recently established an Integrated Project Team (IPT) to explore aspects of behaviour relating to high heat generating wastes. The focus of the IPT is primarily to generate a better scientific understanding of the thermal constraints imposed on engineered barrier systems to support the selection of disposal concepts for high heat generating wastes, mainly spent fuel but also vitrified HLW. This project is also collaborating with international research programmes to share learning and direct future research into understanding thermal and other issues associated with the disposal of spent fuel and HLW. The findings from this disposability assessment will be used to inform the work of the IPT.

A number of further issues have been identified that would need to be considered for future disposability assessments, but only if the strategy to burn thermal MOX fuel is carried forward in the UK. These include: better definition of fuel assembly design and reactor burn strategy, recognising that the current assessment was based on a series of assumptions; and consideration of packaging arrangements for MOX spent, including plans for pre-treatment such as drying. Given that RWMD would be a key stakeholder in the management of spent fuel from a third generation programme, RWMD should be kept informed of any plans for fabrication, irradiation and storage of MOX fuel, and to provide opportunities to influence quality management arrangements, including records generation that would be used to support future disposal of the spent fuel.

Finally, any plans for pre-treatment of the plutonium stocks to reduce the americium content to support the manufacture of new MOX fuel should be discussed with RWMD. This is because the generation of separate americium-rich waste stream could itself create disposability challenges due to the high specific heat output of the radioisotope Am-241.