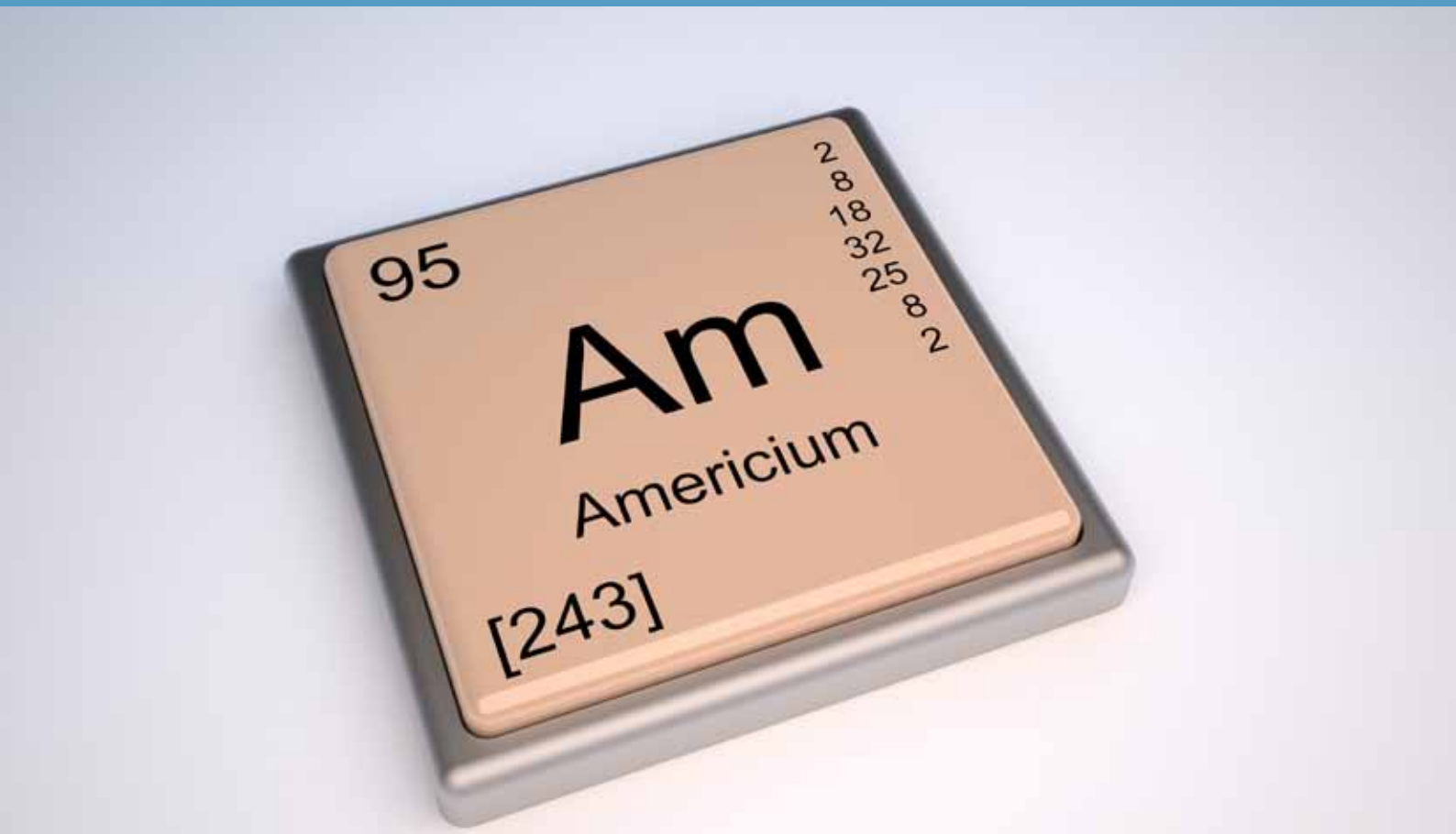
NATIONAL NUCLEAR LABORATORY

Minor Actinide Transmutation

Position Paper



Minor Actinide Transmutation

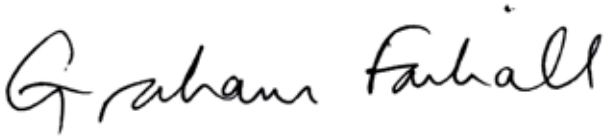
A review

For many years there has been a sustained international interest in partitioning and transmutation of the minor actinides neptunium, americium and curium produced by fission reactors. Although these three elements are produced in relatively small quantities in fission reactors, they are major contributors to the decay heat, neutron output and radiotoxicity of spent nuclear fuel. If spent nuclear fuel is reprocessed conventionally, the heat output, neutron output and radiotoxicity from the minor actinides carries over to the vitrified high level waste (VLHW) in which they are incorporated.

Partitioning involves modifying reprocessing operations so that the minor actinides are partitioned in a separate chemical stream, or perhaps a stream comprising a mix of minor actinides combined with plutonium. Subsequently, they could either be stored or returned into the strong neutron flux of a reactor to be transmuted by fissions. Actinide transmutation would greatly reduce the mass of minor actinides in the geological repository and potentially increase the effective capacity of a geological repository and/or reduce its future environmental and radiological impacts.

Transmutation requires the minor actinides to be irradiated in a very intense neutron field such as can only be attained in a high power fission system such as a thermal reactor, a fast reactor or an accelerator driven sub-critical system (ADS). Transmutation is most effective if the minor actinides are fissioned, producing shorter-lived and therefore more tractable fission products. This can either occur directly, with a single neutron interaction leading to fission, or indirectly via an initial neutron capture event followed by a second neutron capture leading to fission. The reaction cross-sections for both direct fissions and indirect fissions tend to be quite low and therefore high reaction rates require a combination of high neutron fluxes and long irradiation times.

Implementation of minor actinide transmutation on a commercial scale will require major research and development effort sustained over many years and is not likely to be available for at least twenty years. This position paper sets out the view of the UK National Nuclear Laboratory's (NNL) of the potential role of minor actinide transmutation in the context of nuclear waste management in the UK.



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Introduction

Neutron-induced nuclear fission involves a neutron interaction leading to the splitting of a heavy nuclide such as U-235 or Pu-239. The heavy nucleus breaks into two fission products, typically with atomic masses of about 100 and 130. The fission fragments carry away excess energy in the form of kinetic energy, which they pass on to the fuel as heat. Fission products are an unavoidable consequence of fission and most of them are radioactive, with a range of half-lives ranging from fractions of a second to millions of years. In terms of mass, the fission products represent the largest component of high level radioactive waste and are the main contributors to the intense radiation field of spent nuclear fuel. However, after about 500 years, they mostly decay away, leaving the nuclear fuel much less radioactive.

Uranium oxide is the nuclear fuel used in most of the world's commercial power reactors. Most commercial reactors use uranium oxide in which the concentration of U-235 has been enriched to typically 4-5 percent. U-235 is said to be a fissile material, because it fissions readily when it interacts with either slow or fast neutrons and is the biggest contributor to the energy output of the reactor. Most neutron interactions on U-238 involve a neutron capture event, producing the short-lived isotope U-239. This quickly decays via two steps to Pu-239 which is also fissile. The process by which U-238 is converted to fissile Pu-239 by neutron capture is called fertile conversion and is an important process for all nuclear reactors. Fertile conversion is beneficial because it increases the energy that can be extracted from nuclear fuel and it also plays an important role in ensuring reactor stability.

Once Pu-239 has been produced by the initial fertile capture event, further neutron reactions can lead either to fission of the Pu-239 nucleus or the production of higher plutonium isotopes (Pu-240, Pu-241 and Pu-242) as well as the production of various lighter nuclides (notably Np-237 and Pu-238) and higher nuclides (Am-241, Cm-242 and Cm-244). Neptunium, americium and curium are intensely radioactive, featuring both alpha decays and high energy gamma emissions and dominate the total radioactivity of spent nuclear fuel or VHLW once the fission products have decayed at about 500 years after discharge from the reactor. Transmutation of the minor actinides by fission or neutron captures to produce shorter lived products would reduce the burden of radioactivity in a geological repository. Many consider that this would make nuclear fission more acceptable to the public and this is the motivation for studying minor actinide transmutation. A nuclear fuel cycle with minor actinides extracted from spent nuclear fuel and re-irradiated in a reactor could in principle lead to a reduction of up to a factor 100 of the long term radiotoxic burden.

Some countries, especially France, Germany and Japan, see minor actinide transmutation as a very important goal and have made very large R&D commitments to it. This report considers the technical and economic justification for minor actinide transmutation in the context of historic and future nuclear waste management in the UK only and recommends what level of involvement is appropriate for the UK.

In terms of mass, the fission products represent the largest component of high level radioactive waste and are the main contributors to the intense radiation field of spent nuclear fuel.

Minor Actinide Nuclear Characteristics

Of the minor actinides in irradiated nuclear fuel, neptunium, americium and curium are the three that are usually considered as candidates for partitioning and transmutation (P&T). Although there are other minor actinides present, these three are dominant in terms of mass. Irradiated LWR fuel typically contains about 600 g/tHM of neptunium; 850 g/tHM of americium and about 50 g/tHM of curium. Since Am-241 arises from Pu-241 decay and curium isotopes are relatively short lived as well, these proportions vary depending on the cooling time after discharge and they also vary depending on the discharge burnup.

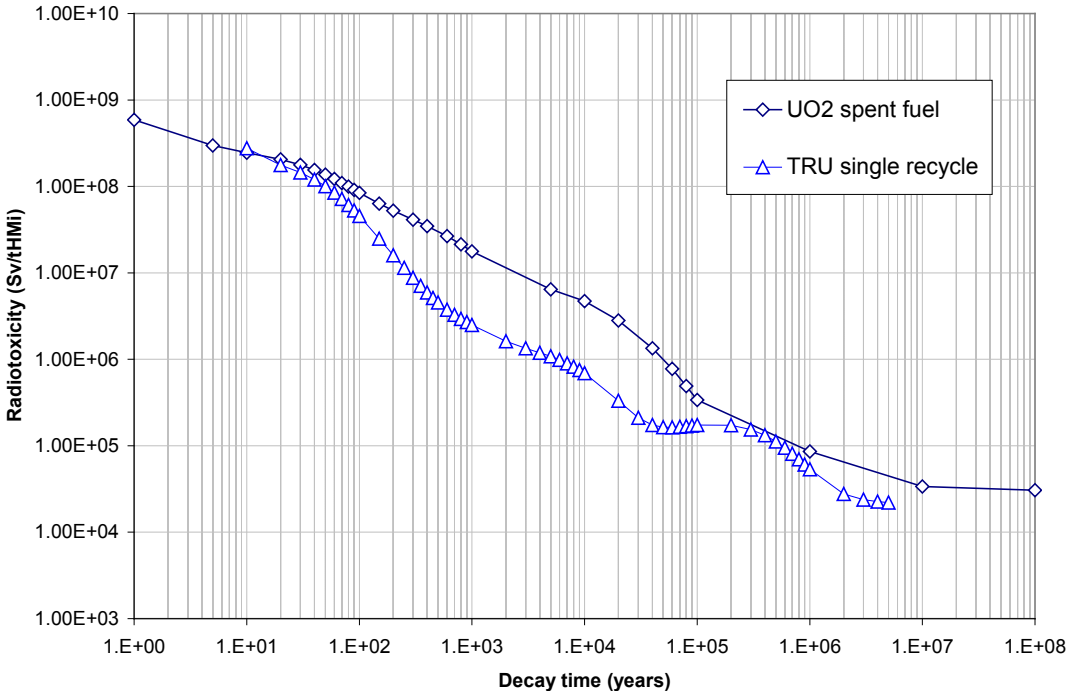
Neptunium, which is predominantly represented by the single isotope Np-237, is a significant contributor to long-term radiotoxicity, because of its very long half-life. However, Np-237 does not contribute significantly to decay heat output. Np-237 can be transmuted in both thermal and fast reactors by mixing it homogeneously with the nuclear fuel. Neptunium transmutation is less problematic in fuel manufacturing than americium or curium but nevertheless, managing radiological doses in fuel manufacturing remains challenging.

Americium is generally considered a prime candidate for transmutation because it is present in relatively large amounts and is a major contributor to gamma activity and radiotoxicity, especially so after about 500 years cooling time, when the contribution of fission products has decreased by several orders of magnitude. All the americium isotopes have a reasonably large nuclear cross-section and are amenable to destruction in an intense neutron flux by a combination of neutron captures and fissions. In irradiated nuclear fuel, Am-241 is the dominant americium isotope, though there are small but significant quantities of Am-242, Am-242m and Am-243.

Curium makes a significant contribution to gamma activity and radiotoxicity and is also a major contributor to neutron emissions. Curium is not well suited to transmutation, because the fission and capture cross-sections of the principal isotopes (Cm-242 and Cm-244) are quite low and it is difficult to transmute them effectively. Although Cm-242 has a very short half-life (163 days), it is continually generated in irradiated fuel from the decay of Am-242m (141 year half-life). The hazard potential of radioactive materials is measured through radiotoxicity. The International Commission on Radiological Protection (ICRP) has published effective dose coefficients ( ) (measured in Sieverts per Becquerel – Sv/Bq, where the Sievert is the unit of biological radiation dose uptake and 1 Bq equates to 1 radioactive decay per second) for inhalation or ingestion of nuclear materials, which combined with the radioactive decay rate, provides the radiotoxic potential in Sv of a given mass of material.

For spent nuclear fuel it is usual to quote the radiotoxicity per tonne of initial Heavy Metal (ie Sv/tHMi) and if spent fuel is to be disposed of in a geological disposal facility (either as an intact fuel, assemblies or processed in some way to encapsulate the wastes), it is desirable that the radiotoxicity should decay sooner rather than later.

Figure 1 illustrates how the radiotoxicity of spent nuclear fuel decays with time for two different scenarios. The first scenario is for a Light Water Reactor (LWR) once-through fuel cycle, where the UO_2 fuel is irradiated once and then subject to direct disposal. The second scenario is a hypothetical limit case in which all the transuranic (TRU) nuclides are almost completely transmuted by being irradiated in a thermal neutron spectrum.



Radiotoxicity profiles for LWR UO_2 once-through and LWR TRU recycle

The TRU recycle case shows a sharp drop in radiotoxicity at relatively short cooling times because both plutonium and the minor actinides are largely destroyed by fission. This illustrates the potential benefit in recycling TRUs, represented principally by plutonium, neptunium, americium and curium. This is the main motivation for minor actinide partitioning and transmutation, though it must be emphasised that this is a hypothetical limiting case that will be difficult, if not impossible to attain in practice. Also, as considered later, repository performance depends on the combination of radiotoxicity and radionuclide mobility and not on radiotoxicity alone. The convergence of the two curves at cooling times between 10^5 and 10^6 years occurs because of the in-growth of daughter nuclides from the U-233 decay chain, governed by the $1.6x10^5$ year half-life of U-233.

Minor actinide partitioning

Conventional reprocessing of spent nuclear fuel involves dissolution followed by chemical separation of the uranium and plutonium from all the fission products and other transuranics. The uranium and plutonium streams are recycled, while the fission products and transuranics are incorporated into the vitrified high level waste steam (VHLW), which is kept in interim storage pending eventual disposal in a geological disposal facility. Minor actinide partitioning would involve additional chemical separation stages such that the neptunium, americium and curium are directed away from the VHLW and into separate streams or co-streams for subsequent transmutation. Modifying reprocessing chemical flow sheets to partition the minor actinides is generally considered feasible, but would require extensive research and development. The chemical properties of the minor actinides are not as conducive to separation as those of uranium and plutonium and developing practical flowsheets is considered very challenging. In particular, it is important that only a very small proportion (about 0.1%) of the minor actinides can be allowed to pass to the VHLW stream, otherwise the benefits of partitioning and transmutation will be adversely affected. If the intention is to reduce the radiotoxicity of the minor actinides to the theoretical minimum of 1% (relative to that of a thermal reactor with a once-through fuel cycle), which would certainly require multiple recycle, losses to the VHLW stream greater than 0.1% per recycle cannot be tolerated. Achieving <0.1% carry-over to the VHLW is regarded as technically challenging.

Implementing minor actinide partitioning on a commercial scale will demand major research and development effort followed by a multi-billion Pound investment in the design and construction of a reprocessing plant with a partitioning capability. The timescales are likely to be protracted, with a minimum 10 year development period and a minimum 10-15 year design and construction period. The earliest possible date for commercial deployment would not be before 2035.

Approaches to Transmutation

Transmutation will involve minor actinides being subjected to very high neutron fluxes for very prolonged periods of time, typically many years. This section briefly reviews the different technical approaches that are being considered to achieve worthwhile transmutation rates.

Homogenous transmutation fuels

Homogeneous transmutation fuels incorporate minor actinides as a minority component of the nuclear fuel. The simplest option that has been considered, for example, is to incorporate Np-237 in uranium/plutonium mixed oxide (MOX) thermal or fast reactor fuel. The Np-237 is subject to the same neutron flux that the fuel sees for the typically 4 to 5 year residence time of the fuel, during which a worthwhile fraction of the Np-237 can be transmuted, depending on the reactor type. Np-237 is considered to be particularly well suited for homogeneous fuels, but the homogeneous approach is considered less suited for americium and curium.

In many ways, homogeneous transmutation is technically the simplest option, because the fuel assembly mechanical design is unaffected and the fuel material properties are only slightly affected by the presence of the Np-237 provided its concentration is limited to a few percent. However, incorporating Np-237 in the fuel will require remote fuel manufacturing techniques to be developed and implemented and the incremental cost of fabricating the fuel is incurred on a large proportion of the fuel in the core, which is likely to be a significant fuel cost penalty.

Heterogeneous transmutation targets

The heterogeneous strategy involves concentrating the minor actinides to be transmuted into "target " assemblies, which are distinct from the normal fuel assemblies in the core that provide the neutron flux which "drives" the target assemblies. Heterogeneous targets are considered better suited to americium and curium transmutation.

Heterogeneous targets complicate the core design, because there are now different fuel types in the core, the driver and the target fuel assemblies and two production lines are required. However the fact that the driver fuel assemblies do not contain minor actinides means that normal fuel fabrication methods can be used for the bulk of the core and only the smaller target region needs remote fabrication. Other advantages are that the target assemblies can be better optimised for transmutation. In particular, if the target fuel assemblies use an inert matrix to carry the minor actinides, production of fresh minor actinides from U-238 captures can be avoided. Heterogeneous targets are also more suited to multiple recycle strategies, which may be necessary to achieve high eventual transmutation fractions. However, heterogeneous non-uranium targets will be very difficult to fabricate and reprocess and are likely to require dedicated fabrication and reprocessing plants.

Fast reactors

In a fast neutron spectrum, the fission to capture ratio of minor actinides is quite favourable and this is the main reason why there is international consensus that fast reactors are well suited for minor actinide transmutation. The cross-sections for transmutation reactions are very low, which in turn demands very high neutron fluxes. But fast reactors do have the high neutron fluxes needed. Fast reactors are also considered to be relatively tolerant of large minor actinide loadings because their reactivity control and reactivity feedback parameters are less sensitive than thermal reactors (though this is heavily design dependent and will need to be verified at a later stage of development).

Approaches to Transmutation cont.

A possible strategy for fast reactor transmutation is to use moderated target assemblies, where a moderating material such as zirconium hydride is used to slow down the neutrons entering the target assemblies from the driver core. At thermal neutron energies the neutron cross-sections are much higher and this gives the possibility of combining the locally enhanced thermal flux with the high thermal neutron cross-sections to boost the transmutation rate.

Thermal reactors

Thermal reactors can achieve worthwhile minor actinide transmutation rates. The balance between neutron fission and captures is less favourable in a thermal reactor and the neutron flux field in thermal reactors is much smaller. However, the thermal neutron cross-sections for minor actinide transmutation are correspondingly larger in a thermal reactor and the transmutation rates are similar. In particular, Am-241 can be transmuted very effectively in a thermal reactor, with up to 70% destroyed within a single irradiation lifetime of a target assembly.
The main limitation of thermal reactors is that the total loading of minor actinide targets may need to be restricted to avoid excessive impacts on core reactivity control and reactivity feedback characteristics. Because of such considerations, the potential for minor actinide transmutation in thermal reactors has largely been overlooked in recent years in favour of fast reactors. However, there is potentially an advantage in favour of thermal reactors because there are already more than four hundred in commercial operation, whereas there are only fast reactor prototypes available. If the international community was to become serious about commercial scale implementation, thermal reactors would be available immediately, whereas a long delay could be expected before the same could be said for fast reactors. Thermal reactors might therefore be useful for early demonstration of minor actinide transmutation on commercially relevant scales, without the delays and uncertainties of having to wait for fast reactor deployment.

Accelerator driven sub-critical systems

An accelerator driven sub-critical system (ADS) uses a high energy (up to 1 GeV) proton beam to produce spallation neutrons on a target. The spallation neutrons are amplified by a sub-critical fissile core. The sub-critical core usually operates with a neutron multiplication factor k in the range 0.95 to 0.98, amplifying the spallation neutron source by a factor 20 to 50 determined by 1/(1-k). A sub-critical core is incapable of operating in steady state without an external supply of neutrons and the spallation source provides the additional neutrons needed to maintain steady neutron flux and power levels. For a given multiplication factor, the power produced scales linearly with the spallation source strength, which in turn is determined by the proton current.
ADS are widely regarded as suitable systems for minor actinide transmutation. The neutron spectrum is flexible and designs are envisaged where the spectrum varies from fast to thermal in different spatial locations, effectively tailored to fit the requirements of minor actinide transmutation. The reactivity control and reactivity feedback characteristics of ADS are widely regarded as being less sensitive to minor actinide loading than those of critical reactors, though this cannot be regarded as demonstrated until the designs are more mature.

The proton beam current required to produce worthwhile power output is much higher than typically used in experimental accelerators and is considered a major challenge. Another challenge will be to achieve reliable steady operation of the proton beam.

Impact on Geological Disposal

A recent OECD-NEA Task Force (2) has reviewed international studies of the impact of partitioning and transmutation in different types of geological disposal facilities. The NEA Task Force concluded that transmutation strategies will not eliminate the need for a deep disposal, because long-lived fission products and other radionuclides will still remain and existing waste streams from historic reactors will still need to be managed.

The geological conditions in a specific facility determine the mobility of different radionuclides. For example, in a facility with reducing groundwater conditions, as would apply in the UK, the solubility of actinide ions tends to be very low and actinides are expected to remain localised near their point of origin, even if the original waste packages have degraded. Peak radiological dose rates are therefore determined by the more soluble fission product ions and would not be significantly reduced by minor actinide transmutation. The NEA Task Force's assessments of disposal facilities sited in unsaturated volcanic tuff (such as Yucca Mountain), in argillaceous formations (impermeable clays and mudstones) and in crystalline formations and repositories in salt formations, all reached similar conclusions.

The Task Force also considered deep borehole disposal and noted that the strong salinity gradient between the deepest part of the bore hole and the sub-surface water will prevent transport of radionuclides to surface water.

Quoting from one of the international studies cited by the NEA Task Force (RED-IMPACT), partitioning and transmutation is found to have "almost no effect on the long term radiological impact under normal (undisturbed) evolution of the repository" and "as geological disposal systems are very effective at retarding the migration of actinides, the contribution of actinides to the effective dose is limited" . Reinforcing this conclusion, the NEA Task Force also noted that package degradation is likely to be temporally incoherent, with different packages deteriorating at different rates. Under these circumstances, the NEA Task Force considered that the radiotoxic inventory would only have a secondary effect, since the rate limiting factor would be package degradation.

The NEA Task Force considered disturbed repository scenarios and noted the difficulty of defining human intrusion scenarios. The Task Force noted that unintentional drilling scenarios would most likely result in only a single waste package being penetrated, so that the radiotoxic inventory of a single package at the time of drilling would determine the radiological source term. Minor actinide transmutation strategies would in this case give a benefit, because the total radiotoxic content of individual packages would decay more quickly, along the lines noted in Figure 1 earlier.

The NEA Task Force also noted that minor actinide transmutation can reduce the decay heat output of waste and therefore potentially reduce the geological disposal facility footprint. Another point is that the reduction in radiotoxicity may reduce the uncertainties in the evolution of a geological disposal facility, which may be a secondary benefit in constructing the safety case.

International Studies

The NEA Task Force's review of international studies highlights a number of important observations:

1. A 1999 OECD-NEA study (3) concluded that scenarios in which fast reactors are used for minor actinide transmutation can reduce the radiotoxicity of waste streams by up to a factor of 100. However, it was noted that the decrease in waste streams would be accompanied by a cumulative increase in the radiotoxic inventory of the reactors and fuel cycle facilities.

2. A 2004 IAEA study (4) found that an optimum transmutation strategy would involve multiple recycle of plutonium and neptunium, but for americium and curium to be transmuted in a deep burn single irradiation step.

3. A 2006 OECD-NEA report (5) highlighted a number potential benefits of minor actinide recycle schemes, including a reduction in repository footprint and decay heat loading. However, the study noted that the maximum dose release from the repository did not vary significantly for any of the fuel cycles examined.

4. The European Union RED-IMPACT study (6) examined five fuel cycles, ranging from LWR once-through to full recycle, to determine the impact on the geological repository. RED-IMPACT concluded that a deep geological repository for High Level Waste (HLW) and Intermediate Level Waste (ILW) is unavoidable for all the fuel cycles. Surface radiological dose evaluations for all the fuel cycles are within the regulatory limits and natural background. The long term impact is mostly determined by long-lived fission products and activation products and that minor actinides are very effectively contained in the repositories because of their low mobility. Under normal repository evolution there is virtually no difference between the various fuel cycles and the only significant impact is that removing the minor wastes from the repository reduces the radiological impact of inadvertent intrusion.

5. A German study (7) corroborates the findings of the 2006 OECD-NEA and RED-IMPACT studies, confirming the unavoidable need for a deep geological repository, indicating a factor 3 reduction in repository footprint from minor actinide recycle and noting the low solubility and high retention of the minor actinides.

6. Various US studies (8, 9, 10) have examined the impact of separation of radionuclides with high heat loads (Sr-90 and Cs-137). Reference (8) indicated a factor 5 reduction in repository footprint with separation of Sr-90 and Cs-137, with further benefits from separation of minor actinides. A separate repository is needed for the separate radionuclides, though there are potentially cost savings because of the relatively short half-life of Cs-137. Reference (9) confirmed these observations, noting that high efficiency recover of minor actinides, including curium, combined with fission product separation has the potential to greatly increase the capacity of the main repository.

7. Various Japanese studies (11, 12) corroborate the above findings on the reduction in repository footprint.

Application to UK Waste Management

The UK has historically reprocessed Magnox fuel and it is expected that this will continue until all legacy spent fuel arisings have been reprocessed. Some oxide fuel from the UK's AGR plants has been reprocessed and some is expected to be retained as spent fuel. The vitrification plants at Sellafield have already converted a significant proportion of the high level waste liquor into vitrified high level waste (VHLW) and the VHLW is being stored in passively safe surface stores. There is no realistic prospect of reworking the VHLW waste packages in any way therefore P&T cannot realistically be applied to historic VHLW arisings. The VHLW packages have not been designed for reworking and even if it was technically feasible, the costs would likely be prohibitive and the logistics very difficult. Therefore, the UK is effectively committed to having to put at least historic VHLW packages into a geological disposal facility and this will not change even if there is a future decision to adopt a P&T strategy.

There are currently plans for a new generation of LWRs to be built in the UK. Facilitating these New Build plants will be one of the priorities for the industry. Currently, the intention is that the spent fuel would be held in long term pond storage or in interim dry storage, awaiting eventual conditioning and geological disposal. This spent fuel, combined with AGR spent fuel that is not planned for reprocessing and spent fuel from Sizewell B could potentially be suitable material for a future P&T programme. Such a programme, however, would clearly involve a very extended timescale. The current priority is to get the New Build plants constructed and operational, with the open fuel cycle against which New Build has been justified. A decision to adopt a closed fuel cycle with P&T would be made later, possibly after a decision to build Generation IV plants.

Commercial scale implementation of P&T is unlikely until towards the middle of the century at the earliest, but could then be applied to spent fuel as it is discharged from the New Build plants or to the accumulation of spent fuel that has built up at that time.

Economics

It is not possible at present to obtain any meaningful estimates of the cost of implementing P&T on a commercial scale. To do so would require actinide separation plant and actinide fuel manufacturing plants to have been designed and at present these designs have not been taken beyond the conceptual stage. However, given that these plants would be processing very high activity materials and will be subject to the most stringent safety and radiological control requirements, it is easy to envisage such plants being major enterprises costing billions of Pounds to build and operate. It is equally difficult to envisage any areas where P&T would actually save on expenditure. It is reasonable, therefore, to assume that P&T will incur a significant incremental penalty on overall generation costs compared with conventional plutonium recycle. Utilities will be reluctant to accept such a cost increment unless obliged by government policy.

Economics is one of the main barriers to P&T and this is acknowledged implicitly in some of the existing P&T research programmes. For example, the French nuclear research organisation CEA envisage a multi-tier approach with LWRs, fast reactors and P&T systems all working in a synergistic fuel cycle. CEA's strategies aim to minimise the number of P&T systems in operation, recognising that they will penalise overall generation costs.

Application to UK Waste Management cont.

Proliferation resistance

Proliferation risk is usually taken primarily to mean the potential of nuclear materials being diverted for a weapons programme. In this context, minimising the proliferation risk of a nuclear fuel cycle is a key goal of advanced fuel cycle research. In the commercial nuclear fuel cycle, the main proliferation risk is considered to be that presented by plutonium. Though neptunium and americium present a theoretical proliferation risk, their inventories are an order of magnitude smaller and they are much more difficult to handle than plutonium. Therefore, minor actinide inventory reduction by P&T is only likely to have a minimal impact per se. However, minor actinide P&T schemes typically involve the recycle of plutonium as well and the reduction in plutonium inventory, coupled with the deterioration in isotopic quality of the plutonium, might nevertheless give a worthwhile overall benefit.

Another aspect of proliferation, however, is the potential for nuclear materials to be diverted or stolen for the purpose of manufacturing a radiological dispersal device. In this case, the separated minor actinides could themselves be regarded as a potential target for theft. It could be argued that having the minor actinides actively circulating in the nuclear fuel cycle could itself pose an increased threat.

There is clearly a need to balance these two aspects and that has not been done to date and it remains an area that will need to be addressed at a future date if P&T is to be taken further.

Justification

Under European Law, all proposals for new nuclear plants need to undergo a formal justification process. The purpose of this is to systematically evaluate all the benefits from a new plant and all the detriments and to demonstrate that the benefits outweigh the detriments. UK New Build has already undergone the justification process and it was successfully demonstrated that the benefits outweigh the detriments. For the New Build plants the main benefits are the revenue from generating electricity, the strategic benefits of assured generation and diversity of supply and of carbon emissions avoidance. These benefits are so overwhelming that justifying New Build was relatively straightforward.

The justification of UK New Build was made specifically assuming an open fuel cycle. Future adoption of a closed fuel cycle is not precluded, but would require a separate justification process. While there are strong arguments in favour of a closed fuel cycle, the position is not nearly as clear cut as for new nuclear capacity and it is probable that the arguments would be more strongly contested. Bearing in mind the limited impact on repository peak doses, extending such a justification process to include P&T is likely to make it more difficult to obtain a successful outcome. The justification arguments for P&T will need to be strengthened considerably to ensure a successful case can be made.

Research and Development

Extensive Research and Development (R&D) in support of P&T will be required in the following areas for the technology to be mature enough for deployment. The areas are grouped into those which would help develop improved theoretical understanding, which would come first and those intended to develop a more detailed understanding at an engineering level:

Research studies

1. Develop detailed understanding of overall behaviour of fuel cycles with P&T, using dynamic modelling of P&T scenarios to determine the benefits in terms of reducing the radiotoxicity and decay heat output of wastes in the geological disposal facility.

2. Development of core design strategies for minor actinide irradiation to meet all design and safety requirements.

3. Develop strategies for storing and treatment of minor actinide target fuels for further recycle or disposal.

4. Develop detailed understanding of wastes generated by minor actinide P&T and their management, particularly the impact on waste streams and geological disposal.

5. Development of reprocessing plant flow sheets that separate the minor actinides in addition to separating uranium and plutonium.

6. Experimental work including minor actinide fuel fabrication, target fuel irradiation in materials test reactors and post-irradiation examination

Engineering studies

1. Detailed engineering of separation plant design.

2. Development of methods for fabricating minor actinide target fuels and/or homogeneous minor actinide fuels. Detailed engineering design of fuel fabrication plants.

3. Design and licensing of transport flasks for handling unirradiated and irradiated minor actinide target fuels.

4. Development of target fuel designs and demonstrate acceptable performance.

5. Develop detailed economic model based on engineered plant designs.

Minor actinide partitioning and transmutation will require a major R&D effort to establish the engineering design of separation plants, methods for fabricating minor actinide target fuels, design and licensing of transport flasks, development of target fuel designs and economic modelling of engineered plant designs.

Conclusions

Based on the arguments presented in this report, a number of conclusions are set out in this section. The conclusions have been grouped under three headings - "International", "UK studies" and "UK specific":

International

This heading captures those conclusions which can be regarded as applying generically to the international community and for which there is also international consensus.

The international community considers that minor actinide partitioning and transmutation is technically feasible, but there are considerable technological uncertainties to address and major R&D investment would be needed both by the international community and by individual countries wishing to implement it. The timescale needed to develop the necessary technologies and prove them on a commercially relevant scale will be long, a minimum of 20 years and realistically longer. Research and development is needed in the areas of chemical partitioning, target design and fabrication, target transport, core design, target irradiation performance, irradiated target management and waste management/disposal.

There is international consensus that minor actinide partitioning and transmutation does not displace the need for a geological disposal facility. However there are scenarios where a strategy of separating minor actinides for recycle can reduce the geological disposal footprint.

There is international consensus that minor actinide partitioning and transmutation would have minimal impact on repository peak environmental doses. The relative contributions to peak dose from fission products and minor actinides depends on the repository conditions. Minor actinides are relatively immobile in all the repository environments under consideration and long-lived fission products control peak doses.

There is international consensus that minor actinide partitioning and transmutation would mitigate repository intrusion scenarios. Actinides would be expected to be major contributors to dose uptake in the event of human intrusion into a repository, though their precise role is thought to be highly dependent on the specific scenario envisaged.

It is widely acknowledged that minor actinide partitioning and transmutation strategies will add to overall capital and operational costs. Utilities would expect to see incentivisation schemes before participating.

There is international consensus that fast neutron spectrum systems are the most suitable for minor actinide transmutation. However, thermal neutron spectrum systems can also achieve worthwhile transmutation rates. Though thermal reactors have some technical disadvantages, they are already in commercial use and a large number of current or new build reactors could potentially be adapted for this purpose. This would allow minor actinide transmutation to start without having to wait for the deployment of new fast spectrum systems.

It is frequently stated that accelerator driven systems (ADS) have theoretical benefits over critical systems, mainly because their reactivity control and reactivity feedback limitations are less restrictive, though it probably is premature to accept this position as proven, because the

studies to date are insufficiently developed. However, it is acknowledged that there will be major research and development requirements and also it is considered likely that ADS will incur capital cost and operational cost penalties relative to critical systems.

UK studies

This heading captures some conclusions which have emerged from past UK studies, which are not yet widely acknowledged internationally:

Theoretical studies of the benefits of minor actinide transmutation are often based on equilibrium fuel cycle studies which consider only the annual material flows in a scenario which has no fixed time horizon. Dynamic studies, which model year by year material flows through realistic scenarios with fixed startup dates and closure dates for individual plants can indicate much less favourable results. Dynamic models, such as NNL's ORION scenario simulation tool (13), are regarded to be much more realistic.

An important observation from dynamic models, that is not widely appreciated, is that minor actinide transmutation unavoidably implies having relatively large inventories of minor actinides actively circulating in the fuel cycle. Depending on the fraction of minor actinides destroyed during a single target irradiation lifetime, the active circulating mass can exceed the mass destroyed per year by an order of magnitude or more. Strategies will have to be developed to draw down the circulating mass towards the end of the lifetime of the transmuter systems. Failure to draw down the circulating mass can potentially undermine the justification of minor actinide transmutation.
In the historic studies which the UK has been involved in, it has proved difficult to achieve net transmutation of curium. While it is possible to partially transmute the curium within heterogeneous minor actinide target assembly, the driver core which provides the neutrons invariably generates curium that leads to net curium production for the complete system.

UK specific

This heading captures conclusions which relate specifically to the UK and these represent the main purpose of this report:

In the UK, the reference concept for geological disposal of spent fuel and VHLW has yet to be finalised. However, it is currently assumed that waste packages will be emplaced in alkaline backfill, which will ensure minor actinide chemical species are relatively immobile. In such a repository fission products will dominate the peak release rate and there will be very limited benefit from minor actinide partitioning and transmutation.

The capacity of the UK geological disposal facility is likely to be determined mainly by decay heat output and it is possible that minor actinide P&T might provide a strategy for reducing decay heat. However, this would only be a very long term strategy and would probably only be relevant to scenarios with a large nuclear programme where minimising the number of geological disposal facilities would be a major consideration.

NNL consider it impractical to apply partitioning and transmutation retrospectively to existing UK vitrified HLW. New technologies would need to be developed to process vitrified waste and partition the minor actinides, with potentially very high cost and limited benefit. Therefore there is no realistic prospect of being able to reduce the radiotoxicity of existing wasteforms from historic and current waste arisings.

Conclusions cont.

Any new practice involving radioactive materials in the UK needs to be subject to a formal justification process in accordance with European Union law that demonstrates that the benefits clearly outweigh the detriments. It is NNL's view that at present there is insufficient evidence available in relation to minor actinide transmutation for a successful justification argument to be made in support of full recycle of plutonium and minor actinides. Though better justification evidence may emerge in the future, NNL's view is that the prospect of being able to make a convincing justification argument will remain poor for the foreseeable future.

The formal justification for new build in the UK explicitly considers only a once-through fuel cycle. Reprocessing of the spent fuel and partitioning the minor actinides would require a formal justification process to be enacted in addition to that already completed. A minor actinide transmutation strategy in the UK would not be worthwhile unless it involved new build (because retrospective application to historic wastes is not considered practical) and therefore enactment of a justification process for minor actinide transmutation would need to be linked to new build. Since new build plants will store their spent fuel, the option to transmute minor actinides will remain open in principle for many years and might offer a possibility of reducing the decay heat load in the geological disposal facility.

In the very long term minor actinide partitioning and transmutation could conceivably become international best practice. If this was to become the case, the UK could not realistically expect to develop and maintain the necessary supporting infrastructure on its own. The necessary infrastructure requires a level of investment that could only be achieved realistically in a pan-European collaboration. Recognising that international research activities on minor actinide transmutation are likely to continue, the UK needs to retain a low level of involvement to ensure it retains current knowledge and is able to influence the direction of the research.

The reference concept for spent fuel and VHLW disposal has yet to be made definite, but currently assumes an alkaline backfill which will ensure minor actinide chemical species are relatively immobile. In such a repository fission products will dominate the peak release rate and there will be very limited benefit from minor actinide partitioning and transmutation.

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