Contract Title: Overview of International Work on Partitioning and Transmutation

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Abstract (100-200 words as desired):
This report consists of a review of major international research and development work in the areas of partitioning and transmutation from the period of the beginning of December 2000 to the end of September 2003. A detailed review of this work is given in the annexes to the report. The main body of the report addresses the ten questions raised by DEFRA in the contract specification.

Keywords (5 maximum): transmutation, partitioning, high level waste

The results of this work will be used in the formulation of Government policy, but views expressed in this report do not necessarily represent Government policy.
Overview of International
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for the Period December 2000 to November 2003
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EXECUTIVE SUMMARY

Since the ‘Studies of Partitioning and Transmutation’ report by Bush was published in 1999, there has been a substantial increase in research and development into Partitioning and Transmutation (P&T). The European Union 5th Framework Programme (5FP) provided 27.4 M euro in joint funding for various packages of work in P&T and it is envisaged that the 6th Framework will provide at least the same amount of funding. The results of the 5FP P&T research will be presented at a conference in Belgium in October 2003 and the 6FP will carry research to the year 2006.

Internal programmes of work are still in place in France and Japan, and the French are due to report on their 15 year programme in this area in 2006. The USA has initiated a programme of work (the Advanced Fuel Cycle Initiative) which, in concert with the Generation-IV programme, is due to provide initial results between 2007 and 2010. A formal review of the Japanese P&T research is due around 2007.

This report shows that the main impetus for overseas research in P&T is in the field of radioactive waste management, although there are other areas which individual countries consider important such as power production, anti-proliferation and the development and retention of local nuclear skills.

Differences between UK and overseas operations affect the national view of P&T. This is mainly due to the UK decision to vitrify all highly active waste in combination with a view that no new nuclear build will occur at present. This means that there is very little option to apply P&T to current UK wastes and wastes from the current park of nuclear reactors. The French incentive to research P&T arises from their law of 1991 which obliges them to produce a report on its applicability by 2006. The US driver revolves around their desire to delay the time that a second repository for spent fuel wastes is required.

A new generation of UK reactors would, however, affect the conclusions concerning the UK view of P&T and this is dealt with in some detail here.

The current state of P&T technology, while it has advanced considerably in the last 5 - 10 years, is still mainly at the laboratory stage. However the rate of progress in this area will undoubtedly quicken given the resources being spent, with promising technology advances probably due in the next 3-5 years and the prospect of pilot stage plant being constructed within a decade especially in the area of partitioning.
CONTENTS

1 INTRODUCTION .................................................................................................................. 7

2 QUESTION 1 - WHAT ARE THE MAIN REASONS BEHIND OVERSEAS INTEREST IN UNDERTAKING RESEARCH IN P&T? .................................................................................. 9

3 QUESTION 2 - HAS P&T BEEN CONSIDERED TO DATE IN A RADIOACTIVE WASTE MANAGEMENT SYSTEM CONTEXT OVERSEAS? ............................................................. 12

4 QUESTION 3 - ARE THERE DIFFERENCES BETWEEN UK AND OVERSEAS OPERATIONS WHICH INFLUENCE THE NATIONAL PERSPECTIVES OF THE VALUE OF P&T RESEARCH? .................................................................................................................. 13

5 QUESTION 4 - DO DIFFERENCES IN THE COMPOSITIONS OF OVERSEAS WASTE AFFECT THE CHOICE OF KEY RADIONUCLIDES? ................................................................. 14

6 QUESTION 5 - HOW ROBUST ARE THE CONCLUSIONS ON KEY RADIONUCLIDES? ................................................................................................................................. 15

7 QUESTION 6 - WHAT IS THE EXTENT TO WHICH IT IS LIKELY THAT KEY RADIONUCLIDES CAN BE ISOLATED THROUGH PARTITIONING, EITHER NOW OR IN THE FUTURE? .................................................................................................................. 17

8 QUESTION 7 - WHAT ARE THE PROSPECTS FOR A TOTAL, AS OPPOSED TO PARTIAL, TRANSMUTATION OF HARMFUL RADIONUCLIDES? .......................................................... 19

9 QUESTION 8 - WHAT ARE THE PROSPECTS FOR FUTURE IMPROVEMENTS IN P&T TECHNOLOGY? ............................................................................................................... 20

10 QUESTION 9 - COULD THE INTRODUCTION OF A NEW GENERATION OF REACTORS IN THE UK AFFECT PREVIOUS CONCLUSIONS? .......................................................... 21

11 QUESTION 10 - COULD MORE COMPREHENSIVE STRATEGIES BE USED IN THE LONGER TERM TO IMPROVE THE SCOPE FOR SUCCESSFUL P&T USE? .................................................................................................................. 24

12 BIBLIOGRAPHY ..................................................................................................................... 25

13 ANNEX 1 - COUNTRY ACTIVITIES IN P&T ........................................................................ 26

13.1 INTERNATIONAL ORGANISATION ACTIVITY ......................................................................... 26
13.1.1 Nuclear Energy Agency ........................................................................................................ 26
13.1.2 International Atomic Energy Agency ................................................................................. 27

13.2 EUROPEAN ORGANISATION ACTIVITY ........................................................................ 28
13.2.1 5th Framework Programme ........................................................................................... 28
13.2.2 6th Framework Programme ........................................................................................... 31
13.2.3 European Roadmap ......................................................................................................... 32

13.3 FRANCE .............................................................................................................................. 32

13.4 JAPAN .................................................................................................................................. 33

13.5 USA .................................................................................................................................. 33
13.5.1 Generation IV ................................................................................................................... 33
13.5.2 Advanced Fuel Cycle Initiative ....................................................................................... 35

13.6 RUSSIA .............................................................................................................................. 37
<table>
<thead>
<tr>
<th>Name</th>
<th>Signature</th>
<th>Date</th>
</tr>
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<tbody>
<tr>
<td>Author</td>
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1 INTRODUCTION

This document is the final report to the Department for Environment, Food & Rural Affairs (DEFRA) on a contract (EPG 1/4/58) with British Nuclear Fuels plc\(^1\) to provide information on international work in the partitioning and transmutation (P&T) arena. This report is intended to contribute to a watching brief exercise by DEFRA to maintain current awareness of trends and progress in work on P&T. There have been two previous reports in this series\(^2\).

The contract specified that ten questions should be addressed in the final report. These are

1. What are the main reasons behind overseas interest in undertaking research in P&T?
2. Has P&T been considered to date in a radioactive waste management system context overseas?
3. Are there differences between UK and overseas operations which influence the national perspectives of the value of P&T research?
4. Do differences in the compositions of overseas waste affect the choice of key radionuclides?
5. How robust are the conclusions on key radionuclides?
6. What is the extent to which it is likely that key radionuclides can be isolated through partitioning, either now or in the future?
7. What are the prospects for a total, as opposed to partial, transmutation of harmful radionuclides?
8. What are the prospects for future improvements in P&T technology?
9. Could the introduction of a new generation of reactors in the UK affect previous conclusions?
10. Could more comprehensive strategies be used in the longer term to improve the scope for successful P&T use?

This report is structured such that each of the questions is answered in turn. Detailed information relating to the questions are placed in Annexs to the report.

Since the 'Studies of Partitioning and Transmutation' report by Bush was published in 1999, there has been a substantial increase in research and development into P&T. The European Union 5FP provided 27.4 M euro in joint funding for various packages of work in P&T and it is envisaged that the 6\(^{th}\) Framework will provide at least the same amount of funding. The

\(^1\) Part of the work carried out in this project was sub-contracted to NNC Holdings Ltd (NNC).
results of the 5FP P&T research will be presented at a conference in Belgium in October 2003 and the 6FP will carry research to the year 2006.

Internal programmes of work are still in place in France and Japan, and the French are due to report on their 15 year programme in this area in 2006. The USA has initiated a programme of work (the Advanced Fuel Cycle Initiative (AFCI)) which, in concert with the Generation-IV programme (GEN-IV), is due to provide initial results between 2007 and 2010. A formal review of the Japanese P&T research is due around 2007.

This report shows that the main impetus for overseas research in P&T is in the field of radioactive waste management although there are other areas which individual countries consider important such as power production, anti-proliferation and the development and retention of local nuclear skills.

Differences between UK and overseas operations affect the national view of P&T. This is mainly due to the UK decision to vitrify all highly active waste in combination with a view that no new nuclear build will occur at present. This means that there is very little option to apply P&T to current UK wastes and wastes from the current park of nuclear reactors. The French incentive to research P&T arises from their law of 1991 which obliges them to produce a report on its applicability by 2006. The US driver revolves around their desire to delay the time that a second repository for spent fuel wastes is required.

A new generation of UK reactors would, however, affect the conclusions concerning the UK view of P&T and this is dealt with in some detail in the report.

The current state of P&T technology, while it has advanced considerably in the last 5 - 10 years, is still mainly at the laboratory stage. However the rate of progress in this area will undoubtedly quicken given the resources being spent, with promising technology advances probably due in the next 3-5 years and the prospect of pilot stage plant being constructed within a decade especially in the area of partitioning.
2 Question 1 - What are the main reasons behind overseas interest in undertaking research in P&T?

There are four main reasons behind overseas interest in P&T research.

- Management of radioactive waste
- Power production
- Anti-proliferation of special nuclear materials
- Retention of a nuclear skills base

Management of radioactive waste
Historically, the initial view of P&T was as a radioactive waste management tool and this remains the major reason for overseas interest in this research. The basic idea behind P&T is quite simple. After identifying those radionuclides (key radionuclides) which contribute most to the impact from radioactive waste, these are partitioned from the rest of the waste using chemical engineering techniques. The resultant radionuclides are then transmuted, usually by placing them in a flux of neutrons, to isotopes which are ideally non-radioactive (stable) or to isotopes which have a much shorter half-life than the key radionuclides. This then ensures that the radioactive content of a waste repository would decay to safe levels in a much shorter time than would otherwise be the case.

The simplicity of this view, however, conceals the large amount of detailed R&D that has to be performed in order to secure this vision.

The first stage is to identify the key radionuclides. This is discussed in some detail in the section which deals with question 5. However, briefly, the derivation of the list of key nuclides comes from those radionuclides which would be stored in a repository in the form of spent fuel and includes those nuclides important from both ground water transport and total radiotoxicity perspectives. The nuclides which are transported out of the repository by ground water flow can be identified by various models. However, since repositories are designed to minimise this transport, the calculated effect to the environment is very small.

There is a further scenario which envisages human intrusion into the repository at some unspecified time in the future. In this case the key radionuclides would be those with the highest radiotoxicity and longest half-life.

Having identified the key radionuclides, the next stage is to develop techniques which can partition those from other radionuclides in the highly active waste. The development of such techniques is still at an early stage and is the focus of a significant amount of international effort. This is discussed in detail in the answer to question 6.

The key radionuclides then have to be transmuted to more benign species. Once again the development of necessary techniques is still at an early stage. This is discussed further in the answers to questions 7 and 8.

It is extremely unlikely that P&T would be able to reduce the environmental effect of the key radionuclides to such a level that a repository would be unnecessary. Recent system studies of
P&T\(^3\) have indicated that, in order to obtain a reasonable reduction in the radiotoxicity of waste, the manufacturing efficiency of fuels to be transmuted and the efficiency of partitioning of key radionuclides have to be extremely high and the P&T process would have to be kept in place for several hundred years.

Most of the countries involved in P&T research have waste management as their primary aim. Annex 1 gives a detailed account of research taking place in those countries and international institutions which have a level of R&D in place.

The USA has recently put forward a development plan for P&T through its Advanced Fuel Cycle Initiative. It can be argued the major driver for this work is their desire to extend the capacity of the Yucca Mountain repository for spent fuel and therefore delay the requirement to build another for a significant period of time.

France has a legal requirement to investigate P&T as a waste management tool. In the early 1980s the French Castaing Commission published a report that concluded further investigation into the partitioning of plutonium and the minor actinides from spent fuel, with a view to possible destruction by neutron irradiation, was warranted. It should be noted that there is also a legal requirement to investigate waste management through the use of repositories and conditioned waste.

Historically Japan was one of the first countries to develop a defined programme for P&T research into waste management. It first raised attention to several P&T techniques which are now under active development internationally. It also initiated the first steps in an international information exchange programme through annual conferences and Nuclear Energy Agency (NEA) working groups. It has a large, ongoing internal P&T programme, however no decision has been taken on its applicability to Japanese waste. A formal review of the programme will be carried out in 2007. It should be noted that Japan has not ruled out geological disposal for its nuclear waste.

Korea has a moderate programme of research in P&T. Currently the Korean policy on the disposition of nuclear waste is “wait-and-see”. An intensive review of their P&T programme will be performed in 2003 and, depending on activities in the GEN-IV programme (see Annex 1), the P&T programme could change.

Other countries have smaller programmes which tend to be involved with EU Framework programmes.

**Power production**

In countries where direct disposal of irradiated nuclear fuel is the norm, there remains a significant amount of energy potentially available in the ‘waste’ actinides in this fuel i.e. neptunium, plutonium, americium and curium. The US estimate that fuel currently stored in their country is equivalent to over 6 billion barrels of oil, or about two full years of oil imports.

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The majority of this energy will come from re-utilisation of plutonium and countries that perform reprocessing will only gain a fraction (approximately 5-10% \(^4\)) of this from the minor actinides present in highly active waste.

The energy content of the actinides (and minor actinides) would be released by fission in a nuclear reactor and this would have to occur in a fast neutron spectrum reactor (fast reactor or Accelerator Driven System (ADS)) in order to prevent a build up of higher mass actinides.

**Anti-proliferation of special nuclear materials**

There has long been a view in some quarters of the US scientific community that direct disposal of spent nuclear fuel could be seen as the creation of a ‘plutonium mine’, in that future societies would have access to this material. Although the drive to develop P&T in the USA is centred around their potential capacity problems with Yucca mountain, the proliferation aspect is a contributory factor. However, the USA has had a long standing concern about reprocessing which centres around the potential for misuse of plutonium. Since P&T implicitly implies reprocessing of nuclear fuel, the USA have gone to some lengths to ensure that the partitioning processes which they are developing do not produce plutonium alone, but is co-extracted with other minor actinides to ensure that the material cannot be used for weapon purposes.

**Development of a nuclear skills base**

At a time of general perceived stagnancy in the nuclear industry in the West and Japan, some countries have argued that an additional benefit of P&T research would be the development and retention of a nuclear skills base.

In particular, the USA and Japan see, in P&T research, a way of re-energising the development and training in nuclear related fields which would be required in a new reactor build scenario. It is clear that several of the emerging nuclear nations also hold this opinion.

\(^4\) This is an approximate figure based on the relative amount of plutonium produced in a PWR compared to the amount of minor actinides produced.
3 Question 2 - Has P&T been considered to date in a radioactive waste management system context overseas?

To a great extent this question has been answered in the previous section, although a general answer is given here.

Waste management is certainly a key driver for P&T overseas, although there are few countries considering P&T in a solely waste management context. There are incentives for the US to reduce both the effective bulk and effective lifetime of wastes requiring geological disposal because of the authorised capacity of the proposed Yucca Mountain facility being fully committed by 2035. However, the US is also interested in P&T from an anti-proliferation viewpoint, considering the possibilities of managing the quantity and forms of fissile material available. The Japanese OMEGA initiative surmises that the extra energy available through fissioning separated actinides would cover the cost of developing and implementing the necessary techniques, and that the challenge of researching the appropriate technology would be an inducement to recruiting suitable scientists into the industry. These examples illustrate what appear to be the main contexts in which P&T is being considered; waste management, proliferation, power generation and skills development and retention.
4 Question 3 - Are there differences between UK and overseas operations which influence the national perspectives of the value of P&T research?

The major difference between UK operations in the nuclear power area and overseas operation is that the UK national policy is to vitrify high level waste (HLW). It has been shown in a previous review (see footnote 2) that it would be virtually impossible to apply P&T to vitrified HLW. In addition there is regulatory pressure to ensure that the amount of liquid HLW is kept to an absolute minimum. At the time of that review it was considered unlikely that there would be any nuclear build after the closure of Sizewell B and, therefore, that there would be little potential for P&T in the UK. There has been some change in this view; although the recent UK Energy Review\(^5\) did not contain any proposals for new nuclear build, it did not rule out a new build at some future stage.

While France vitrifies HLW and Japan plan to vitrify, both have different national perspectives on P&T. France’s interest is driven by their law of 1991 and Japan by their long term technology plans which also includes an element of P&T being used to attract young scientists to the nuclear industry.

Most other countries with an interest in P&T have a view which is uncluttered by the ‘problem’ of vitrification. In general, they have a view of P&T that offers ‘clean’ nuclear energy and which has optimised energy production through actinide burning.

\(^5\) Energy White Paper, Cm5761, February 2003
5  Question 4 - Do differences in the compositions of overseas waste affect the choice of key radionuclides?

The key radionuclides considered in P&T arise from two scenarios; those that have the highest mobility in a repository and therefore contribute the most to effects on the environment through the natural evolution of the repository; and those that have the highest radiotoxicity in a repository which would have an environmental effect through direct human intrusion into a repository.

Both classes of key radionuclides would be affected by the composition of overseas waste in the first instance. For example, plutonium would not be regarded as a key nuclide in waste from a reprocessing facility while it would in a scenario involving direct disposal of reactor fuel assemblies. However, unless waste conditioning is performed, there would be a convergence in the waste composition since, for example, if separated plutonium were to be recycled in the form of MOX fuel, eventually the waste from this would have to be processed. Therefore the choice of key radionuclides would remain the same unless the recycling process had reduced the quantity of a particular radionuclide to a level that was no longer considered important.

In addition, the type of nuclear reactor technology would also affect this choice. For example if thorium fuelled reactors were used, the key radionuclides would be different from those derived from uranium fuelled reactors. However it is unlikely that reactor fuel other than uranium or mixed oxide fuel will be used in the vast majority of world power applications at least in the short term.

The list of key radionuclides considered in this report is given in Annex 3.

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6 Waste conditioning is a process where certain radionuclides are separated from bulk waste and encapsulated in material tailored to severely restrain their mobility.
6  Question 5 - How robust are the conclusions on key radionuclides?

The list of key radionuclides is given in Annex 3. The radionuclides were derived from repository modelling studies (see footnote 2, Bush). The importance of key radionuclides is dependent on the breaching scenario considered, i.e. natural evolution or intrusion. The natural evolution scenario is the standard scenario which involves the egress of nuclides from a repository through groundwater flow or other means. Only nuclides with a significant solubility will be released in this way. Since most of the actinides have very low solubility in water, the important radionuclides in this scenario tend to be dominated by the fission products. The potential environmental impact from natural evolution is very low and it is unlikely that P&T would be required to limit this. In addition the environmental impact is dominated by fission products which are very difficult to transmute (see question 7).

The intrusion scenario considers inadvertent human intrusion into the repository at some time in the future. The scenario normally considers the breaching to be caused by some future society drilling through the repository and the resultant dose uptake would be caused by core examination and contamination of the land associated with the drilling. In this case it is the total radiotoxicity of the buried material which is important and this tends to be dominated by the actinides. The figure below shows how the radiotoxicity of a nominal amount of irradiated nuclear fuel varies with storage time.
A detailed discussion of the evolution of radiotoxicity with time is given in Annex 2; however it can be seen from the figure above that the major contribution at long storage periods (> 1000 years) arises from actinides and the fission product contribution is rather small.

Therefore, if repository modelling results alone are accepted and the environmental impact of radionuclides transported out of the repository is negligible, P&T on actinides and long lived fission products can only be justified for human intrusion scenarios and for public reassurance. However there are other reasons for applying P&T in a holistic fuel cycle which are discussed in this document. For example, there is the potential to increase the capacity of a repository through P&T or the use of the minor actinides to produce power.

The conclusions concerning key radionuclides are considered robust in the context of repository post-closure performance assessments, although the relative importance of key radionuclides may vary, as modelling techniques are refined. Other risks however, such as P&T process risks, have not been considered to the same level of detail as repository breaching scenarios, although work is currently ongoing to address this.
7 Question 6 - What is the extent to which it is likely that key radionuclides can be isolated through partitioning, either now or in the future?

The prospects for aqueous chemistry separation of actinides from Light Water Reactor (LWR) fuel have increased in the last few years through the development of the DIAMEX and SANEX processes (primarily by the Commissariat à l’Énergie Atomique (CEA) in France and through the EU 5FP). The DIAMEX process involves extracting the actinides and lanthanide groups from other fission products. The lanthanides, which amount to about one third of the fission products by mass, are then separated from the actinides before transmutation. The SANEX process has a high selectivity for actinides over lanthanides, and is used to separate lanthanides from a mixture of americium and curium. In one way or another, the prospects for a technically feasible separation of the actinides within 5 to 10 years appear good.

The rate of advance in the area of partitioning is expected to increase over the next few years with the formation of the US AFCI (see Annex 1) due to the extra US resources and CEA collaboration with the aim of pursuing actinide/lanthanide separation knowledge. It is however important to note that many of the current proposals for advanced partitioning techniques involve the use of hazardous materials such as crown ethers / calixarenes and require the handling of minor actinides and long-lived fission products that would increase the associated risk and generation of secondary waste.

Where reprocessing is practised, uranium and plutonium are already separated with a view to eventual recycling. Neptunium, which dominates the radiotoxicity of HLW in the extreme long term, beyond 100,000 years, is directed to high-level waste in the PUREX process along with the fission products and remaining transuranic elements. Neptunium could instead be routed to one of the major product streams where its impact on refabrication would apparently be slight and its effect on subsequent fuel performance not necessarily undesirable. While the chemistry involved in this re-routing is considered straightforward, it is unlikely to be possible with the existing plant infrastructure. Therefore the major investment required would add a significant cost penalty. Removing neptunium at the reprocessing stage would also not by itself eliminate this hazard, since a further comparable amount would afterwards grow in through the decay of $^{241}\text{Am}$, with a half-life of 433 years. Curium, americium and the relatively insignificant amounts of higher actinides cannot be removed without a radical change or major extension to current reprocessing technology since they are not extracted under process conditions.

Iodine is already separated at the dissolution stage of the PUREX process. Flowsheets have been described for separating the soluble fraction of technetium, but a substantial proportion remains undissolved as an alloy with platinum-group and other resistant metals, partition of which seems to have received little if any attention. It may arguably be less necessary than other separations, if the alloy were taken to resist natural dispersion processes.

Several processes have been suggested for separating caesium from the general mass of fission products, but unless the long-lived $^{135}\text{Cs}$ is separated from lower mass isotopes by isotope separation techniques, fresh generation of $^{135}\text{Cs}$ in a neutron flux from the lower mass caesium isotopes would be faster than destruction until the lower isotopes are largely consumed. There has been no reported work on the partitioning of $^{128}\text{Sn}$ or $^{79}\text{Se}$. 
In summary, the current prospects for isolating key radionuclides through partitioning are highly dependent on the nuclide in question. However it is possible that this situation will change radically in the next few years with the additional resources of the USA and the European Commission Framework programme.

Specific assessments of the partitioning capabilities for the key radionuclides are given in Annex 3.
8 Question 7 - What are the prospects for a total, as opposed to partial, transmutation of harmful radionuclides?

In absolute terms, the prospect for totally transmuting any nuclide is nil, since the principle of diminishing returns applies as the proportion of a neutron flux absorbed by a susceptible nuclide declines with its remaining quantity. Patterns of loading and rearrangement may be optimised for maximum percentage burn-up, but conditions for this and for high overall rates of consumption are to some extent mutually exclusive.

Beyond a certain point, depending on the nuclide and on whether the neutron spectrum can be tailored to take advantage of any absorption resonances, further destruction depends on separation from the matrix and re-concentration, a process that inevitably involves some losses commonly supposed to be in the region of 0.1 - 1% per cycle. It is these losses which would inevitably end up in a repository.

Curium is a particular problem in that is too radioactive and hot to be easily made into fuel for irradiation. Further details of this are given in Annex 4.

Fission products such as $^{135}$Cs or $^{126}$Sn also present difficulties of one kind or another as noted in the Annex.

In summary, long-lived radionuclides can never be totally eliminated; in time inventories of most could probably be reduced by at most perhaps two orders of magnitude, but probably less. Some fission products would need isotopic separation if transmutation on the generally applicable time-scale were to be effective and a few appear scarcely susceptible to transmutation at all.
9 Question 8 - What are the prospects for future improvements in P&T technology?

Given the dominant position of the PUREX process in industry, and the consequent presence in aqueous solution of the elements to which P&T would be applied, solvent extraction is almost certain to remain the primary means for the foreseeable future, although pyrochemical methods could well be applied between cycles of transmutation. New chemical extractants have been developed (primarily in France and through the EU 5FP) to separate actinides from lanthanides\(^7\) (e.g. the DIAMEX and SANEX processes) and further work will be carried out in this area in the 6FP.

However the extraction processes have only been developed at laboratory scale and considerable development will be required for industrialisation. With vigorous prosecution, it may be reasonable to expect at least a provisional and probably a firm choice with a practical demonstration at fully-active pilot scale within the decade.

The situation with regard to transmutation is less clear. There are effectively two camps in this area; those that believe that sub-critical ADS are the way forward and those that consider shorter term critical reactors (i.e. GEN-III, III+ or IV reactors) hold the best promise.

The US AFCI programme (Annex 1) has recently moved away from long term technology (i.e. ADS) to shorter term solutions. However, at present, it is unclear whether 6FP R&D will concentrate on long- or short-term technology.

In addition, the Japanese are constructing a major proton accelerator complex (J-PARC) which is a joint venture between the Japanese particle physics and nuclear science communities and will have high energy particle physics accelerators together with a high intensity proton accelerator suitable for transmutation research. They plan to have a 1MW beam available by the end of 2006 with a 5MW beam available at some future time.

The prospects for future improvements in P&T technology are promising, however the application of such technology in an industrial environment has still to be assessed.

\(^7\) Lanthanides account for about one-third of fission products by mass
10 Question 9 - Could the introduction of a new generation of reactors in the UK affect previous conclusions?

The current UK practice of reprocessing some spent thermal reactor fuel involves the separation of plutonium and uranium, and the vitrification of HLW. Previous studies have concluded that it would not be feasible to alter current back-end strategies in order to introduce partitioning to the reprocessing of the spent fuel from current reactors, and there is no reason for this conclusion to change.

The role of P & T for a new generation of reactors in the UK will depend on the key decision as to whether the reprocessing of spent fuel is to be continued, or whether a route for the direct disposal of spent fuel is to be established. Reprocessing of Magnox fuel was a necessity for technical reasons because of the properties of the cladding. However the decision to reprocess AGR fuel was primarily due to the desire to extract plutonium from the spent fuel for potential use in a future fast breeder reactor programme. This presupposed a dramatic future rise in oil prices and subsequent rises in uranium ore costs. Such rises have so far failed to emerge. However reprocessing also provides some reduction in the volumes of HLW and ILW for disposal within a repository, compared to the equivalent volume of unreprocessed spent fuel.

P & T in the UK must therefore be seen as part of the wider challenge of managing the current stockpile of separated plutonium, together with plutonium arisings from any future reactor programme and managing long lived actinides and fission products from this programme. UK separated plutonium stocks are currently estimated to be around 150 tonnes by 2030 if the Sellafield THORP plant remains in operation long enough to process all spent AGR fuel arisings.

The introduction of a new generation of reactors in the UK, as postulated in the scenario studies, will certainly require the conclusions regarding P & T to be reassessed. However, this assessment will need to be informed by:

- The UK policy for the management and potential reuse of the legacy stockpile of separated plutonium.
- The decision as to whether reprocessing is continued for any future generation of UK reactors, and if so, what will be the intended role of the plutonium arising and long lived actinides and fission products.
- The UK policy for the management of HLW and spent fuel.

The question therefore needs to be widened to address the issue of the future UK policy regarding the management and role of plutonium and long lived actinides and fission products. Only in this context can conclusions about the role of P & T be fully comprehensive.

The choice of reactor system for future possible deployment in the UK is clearly an important factor in assessing the role of P & T, which would depend on the following key points:

- Whether the fuel from such a system is intended to be reprocessed, and if so, which nuclides can be feasibly partitioned on an industrial scale.
• What is the nuclide composition of the spent fuel
• Whether the reactor system can fully or partially utilise plutonium fuel, and whether the design can be adapted for minor actinide and/or long-lived fission product transmutation

The scenario studies (see Annex 5) have considered two potential reactor systems, a generic 51 GWd/t advanced PWR concept, and a gas-cooled fast reactor concept. Further work would be needed to assess the role of other systems such as CANDU or PBMR, which have, in the past, been identified as potential candidate systems for future UK deployment.

Fast reactors, such as the GCFR concept examined in the scenario studies, provide a means of burning unwanted plutonium. They also have a secondary, but important role as a means of storing plutonium and removing the necessity to store or permanently dispose of it in the medium term. They are also useful for reducing the plutonium stockpile in nuclear phase-out scenarios, but due to their large plutonium core inventories, there are limits on the ultimate level of reduction achievable. Their initial introduction could be driven by their role as a means of legacy or future plutonium stockpile management, and as fast flux transmutation devices for minor actinides and long-lived fission products.

However, they have the flexibility to convert to plutonium breeding fuel cycles where depleted uranium is loaded into fast reactors and converted into plutonium. There are substantial amounts of depleted uranium in the UK leftover from enrichment operations. The need to switch to a breeding fuel cycle is however entirely dependent on the price of uranium ore, and will only be economically justifiable if uranium prices were to escalate dramatically. There is no identified role for fast reactors as plutonium breeders in the medium term in the UK unless this price escalation were to occur.

A new generation of thermal reactors in the UK may have the potential to utilise plutonium MOX fuel. This was illustrated by scenarios 2 and 4 in Annex 5. They could present a ready means of utilising current and future separated plutonium stocks, without the additional commercial and technological costs of early fast reactor introduction.

Thermal MOX reactors are much more limited than fast reactors in the quality of plutonium which they can handle. This is because all isotopes of plutonium are fissionable in the fast neutron flux of a fast reactor, whereas only the odd-numbered isotopes $^{239}$Pu and $^{241}$Pu are fissionable in a thermal flux.

Single MOX recycle followed by direct disposal is often cited as a means of proliferation-resistance, by essentially returning plutonium from a separated form back to that of the ‘spent fuel standard’. The adoption of single MOX recycle in a new generation of reactors would enable the utilisation of the plutonium for electricity production, but would not be compatible with a P & T strategy. MOX recycle followed by reprocessing of spent MOX would be compatible with a P & T strategy. Large scale utilisation of plutonium in this way would however divert plutonium away from early adoption of FRs which could be used as transmutation devices for minor actinides from the high level waste stream.

The contribution to the total radiotoxicity of high level waste streams from long-lived fission products is relatively small compared to the minor actinides and their yield is not as strongly dependent upon reactor type. The introduction of a new generation of reactors in the UK would not greatly affect conclusions regarding these nuclides, and their transmutation would
only be beneficial as part of a comprehensive strategy to reduce the residual radiotoxicity of HLW after removal of the minor actinides.
11 Question 10 - Could more comprehensive strategies be used in the longer term to improve the scope for successful P&T use?

Currently a considerable amount of international work investigating various fuel cycle strategies in connection with P&T has started. These are either from individual states (e.g. France, Japan, Spain, USA, UK) or in the context of NEA working groups or EU 5FP / 6FP. In general, most of the state-based work is starting to be incorporated in the latter international programmes.

Successful P&T implementation relies on the chosen fuel cycle(s) to be sustainable and sustainability depends on three criteria; environmental, economic and social acceptability. Essentially the aim of the programmes is to determine these criteria for a range of fuel cycle strategies.

However there is a current lack of hard technical data on the various fuel cycle components (e.g. neutron production systems, partitioning processes etc.) and therefore the sustainability criteria are difficult to assess.

Studies of P & T, including the UK scenario studies performed here, have shown that P & T can only realistically be contemplated as part of an integrated and coherent nuclear fuel cycle strategy. The benefits of P & T will only begin to be realised after several decades of operation. To achieve this, a continued programme of reactor and fuel cycle facilities planning, construction and replacement is required. A piecemeal approach to partitioning and recycling may not yield any significant influence with regard to environmental impact or improved public acceptability of nuclear waste management.

Many studies have shown the theoretical benefit of P & T for carefully formulated equilibrium fuel cycles. However, detailed analysis is required of the means and timescale by which the transition to a fully integrated fuel cycle in the UK can be achieved. A key boundary condition in any assessment of a future integrated nuclear programme incorporating P & T is the total electricity generating capacity of such a programme. P & T strategies are not arbitrarily scaleable, and any such strategy which entailed significant over-capacity compared to projected electricity demand in the UK would clearly be unviable.

The likelihood and timescale of the final cessation of nuclear energy, due to its hypothetical replacement by another technology (e.g. nuclear fusion), must also be assessed when considering P & T strategies. A flexible strategy must be able to achieve significant radiotoxicity reductions of the final spent fuel arisings of power reactors, without requiring excessive timescales or creation of new waste streams as unwanted by-products. Further work is required to investigate all these issues.

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8 see Annex 1 and the discussion concerning the AFCI report to the US Congress
12 Bibliography


Energy White Paper, Cm5761, February 2003

Energy Projections for the UK - DTI Energy Paper 68


Mid-and-Long-Term Nuclear R&D Programs. KOREA ATOMIC ENERGY RESEARCH INSTITUTE: http://www.kaeri.re.kr/english/


To liaise closely with other NEA working groups such as the Working Party on the Physics of Plutonium Fuels and Innovative Fuel Cycles (WPPR) and to provide advice and support where required.

- To provide advice to the nuclear community on the developments needed to meet the requirements (data and methods, experimental validation, scenario studies) for implementing different P&T scenarios.
  - Publish a state-of-the-art report after the 3 year study
  - Organise biennial Information Exchange Meetings on P&T in co-operation with the NEA Nuclear Development Committee (NDC)

- To maintain, in collaboration with the NDC, an NEA-based Internet Web page providing information about on-going P&T activities.


The first meeting of this expert group was held on the 3rd and 4th of February this year. The NEA’s NDC and Radioactive Waste Management Committee (RWMC) jointly sponsor the group; and the UK representatives are NIREX and BNFL. Unlike other P&T oriented NEA working groups, this one has a membership which draws from both the P&T and geological disposal communities which gives the promise of a much more balanced outcome.

The scope of the group is to analyse a range of future fuel cycle options from the perspective of their impact on waste repository demand and specification. It is intended that the study will focus on:

- Assessment of the characteristics of radioactive wastes arising from advanced nuclear fuel cycle options.
- Repository performance analysis studies using source terms for waste arising from such advanced nuclear fuel cycles.
- Identification of new options for waste management and disposal.

The work of this group has barely started and currently there are ongoing discussions on the basic fuel cycles which will be used to assess the waste management implications.

### 13.1.2 International Atomic Energy Agency

The main current areas of work into P&T by the IAEA are a Co-ordinated Research Proposal (CRP) and the production of a technical document (‘TECDOC’). The IAEA organises CRPs and TECDOCs to bring together experts in a particular field in order to produce a definitive document.

In 2001 the IAEA initiated the production of a TECDOC reviewing the current status of P&T, evaluating from an international perspective the impact of potential options upon waste management strategies. The purpose of the document was given as:

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10 see [http://www.nea.fr/html/ndd/eg-fuel-cycle.html](http://www.nea.fr/html/ndd/eg-fuel-cycle.html) for further details

11 ‘Implications of Partitioning and Transmutation in Radioactive Waste Management’