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Foreword

As part of our work programme for 2002–2003, RWMAC's sponsoring Ministers asked us for advice on the extent to which partitioning and transmutation (P&T) could assist with the long-term management of the UK's radioactive wastes.

Partitioning is a series of physical and chemical separation processes, while transmutation involves the conversion of one chemical element into another by means of particle bombardment in a nuclear reactor or accelerator. An interesting, perhaps little appreciated, point is that the UK already carries out large scale partitioning at the two nuclear fuel reprocessing plants at Sellafield. These operations separate out uranium and plutonium; extensive modification would be needed if the range of radionuclides to be extracted were to be extended.

At first sight, the P&T concept is very attractive. Potentially, it offers a means of transforming hazardous long-lived waste into less harmful and/or shorter-lived forms – the apparent answer to all our long-term radioactive waste management problems. But there are major practical problems.

Difficulties with P&T include:

– its limitations (at best it could only deal with a limited proportion of the UK's higher activity wastes);

– its development requirements (which are uncertain and inevitably costly);

– the need for new nuclear reactors and/or large accelerator systems which can only be delivered through a long-term commitment to nuclear power.

In this last respect, the UK differs from France, the USA, and Japan (all of which are actively pursuing research and development into P&T) in that our current national energy strategy is equivocal on the future of nuclear power.

In its *Managing Radioactive Waste Safely* consultation document, the first step in a new initiative to identify the best option for managing the UK's higher activity wastes over the long-term, the Government described P&T as one of the options that *could be considered further*. Our conclusion is that P&T cannot realistically be considered to offer a long-term management solution for the UK's current stocks of radioactive waste, and those likely to arise in the future. In our view, the answer has to be found elsewhere.

Charles Curtis

Professor Charles Curtis OBE
RWMAC Chairman

THE RADIOACTIVE WASTE MANAGEMENT ADVISORY COMMITTEE'S ADVICE TO MINISTERS ON PARTITIONING AND TRANSMUTATION IN THE UNITED KINGDOM

EXECUTIVE SUMMARY

Introduction

The context for the study

1. This study was undertaken in response to a request for advice from Ministers in the UK Government and the Devolved Administrations for Scotland and Wales on the potential application of partitioning and transmutation (P&T) technology to radioactive waste management.

2. A further aim of the study is to contribute to the national debate launched by *Managing Radioactive Waste Safely*[1]. This initiative envisages a process of stakeholder and public consultation and participation leading to a recommendation to Government on the option, or options, for the long-term management of the UK's higher activity solid radioactive wastes, that will protect the safety of people and the environment. An independent body, the Committee on Radioactive Waste Management (CoRWM) has been appointed to oversee the process.

3. P&T was included in the *Managing Radioactive Waste Safely* consultation paper as one of the options that "*could be considered further*", i.e., by CoRWM. This report concludes that P&T does not represent a comprehensive solution to the radioactive waste management problem. In the context of the problem as it exists in the UK, P&T cannot be considered as even a partial solution in the absence of a commitment to maintain nuclear power in the long-term.

What is P&T?

4. In simple terms, partitioning is the separation of different radionuclides (radioactive isotopes of different chemical elements) from a mixture. In the nuclear power industry, spent fuel is a complex mixture of radionuclides. Some of these (uranium and plutonium) can be used to make new fuel. Some are also much more potentially harmful and long-lived than others. The existing practice of "reprocessing" – dissolving spent fuel in acid then separating out uranium and plutonium sequentially as individual chemical precipitates – is a form of partitioning.

5. Transmutation is the destruction of radionuclides by converting them to isotopes of lighter elements which are likely to have shorter half-lives and generally lower toxicity. Transmutation is achieved by subjecting the "partitioned"

(separated) radionuclides to intense neutron or proton radiation in either a nuclear reactor or a particle accelerator.

6. In theory, a waste treatment system is possible that fully integrates the partitioning and transmutation processes (termed, in this report, *a complete P&T system design*) that has the aim of maximising the conversion of the most problematic radionuclides while minimising the creation of additional wastes.

Background issues

Why P&T?

7. The major potential benefits of application of P&T technologies are:

- resource conservation by making maximum use of the energy available from the primary fuel material, uranium. This has been pursued through the separation of re-useable uranium and plutonium from spent nuclear fuel by means of reprocessing. The current price of uranium relative to fossil fuels makes this uneconomic and there is perceived to be limited value in extending reprocessing operations to this end alone;

- reduction of the heat generation capacity of wastes. Repository designs can incorporate temperature limits designed to guard against thermal degradation of the surrounding rock and prevention of boiling that impedes natural groundwater movements. The benefit derives from enlarging the capacity of a repository and reducing the number of sites required. This aim underpins R&D in the USA into both partitioning and transmutation (see below and annex E);

- reduction of radiotoxicity of waste. By transmuting elements such as plutonium and americium, it is theoretically possible to transform the spent fuel so that it will decay to the activity of the original uranium in a few hundred (rather than tens of thousands) years, reducing the period over which it is a hazard.

8. All these potential benefits have to be judged against other forms of management. If direct disposal, for example, is a reliable means of isolating the wastes from the environment (thus preventing the escape of the more mobile radionuclides most of which are not suitable for transmutation) the significant additional cost of transmutation technology would have little practical benefit in reducing hazard.

Status of the technology

9. Current reprocessing technology allows the separation (partitioning) *of* uranium and plutonium from spent fuel. The plutonium can then be incorporated with uranium in new mixed-oxide ("MOX") fuel. Key factors affecting the overall plutonium inventory are:

- conventional uranium fuel, when used in reactors, generates new plutonium, adding to the inventory;
- current reactors using MOX fuel both generate new plutonium from uranium and transmute, i.e., eliminate, it by fission. The two processes are usually in approximate balance such that there is no addition to the inventory;
- if MOX-fuelled reactors can be made more efficient, use of MOX fuel could significantly reduce the overall plutonium inventory;
- in theory, recycling MOX fuel several times would further reduce the inventory, but neither the technology nor the economics of MOX recycling have been established;
- if several cycles were to prove possible, the minimum achievable plutonium inventory could amount to no more than that actually being used at any one time by nuclear power generation.

10. France, Japan, USA and the European Union (EU) all have work programmes aimed at extending the capability of partitioning (to separate out elements additional to uranium and plutonium):

- substantial progress is claimed in enhancing capability over the past decade although only on a laboratory scale;
- processes will be tested in pilot plants over the next decade;
- there is reasonable consistency in forecasts that a commercial plant could be available by 2030. This reflects experience of developing existing reprocessing plants, but success cannot be guaranteed until further work is undertaken;
- without worked-up designs, estimates are fairly crude but additional reprocessing can be judged to add perhaps 10 per cent to the cost of an existing reprocessing plant – additional partitioning processes would only

be “add-ons”, and volumes of materials to be handled, relative to existing plant throughput, would be small.

11. Transmutation is *theoretically* possible. The practical challenge is to develop a facility to produce neutrons or protons with the appropriate energy levels to cause the necessary nuclear reactions to take place. Some issues that need to be resolved are:

- the performance of existing thermal reactors;
- the additional benefit derived from additional fast reactors with neutrons of a higher energy level;
- whether dedicated accelerators are required;
- the form (as “targets”) in which the radionuclides are introduced and exposed to the activating fluxes of neutrons or protons;
- the length of exposure required to effect transmutation;
- how multiple cycles of exposure, with intermediate reprocessing, are to be achieved.

12. Limited experimental testing facilities exist worldwide for investigating the issues identified above and, until the work is carried out, uncertainties will remain about the economic value and waste management advantages likely to be produced by a complete P&T system design over more pragmatic solutions.

13. A number of broad conclusions about the requirements and limitations of a complete P&T system may still be drawn:

- P&T is not a waste management technology that can be introduced in isolation from nuclear power programmes and reprocessing plants;
- partitioning would require continued use of reprocessing plants and (almost certainly) investment in new plants;
- the best economic case for transmutation is the use of power reactors, otherwise dedicated accelerators would be necessary;
- the scale of the investments and times required for each separate cycle mean that it is only sensible to pursue P&T if it is coupled to a long-term

commitment to nuclear power and reprocessing (of the order of 100 years).

Why is P&T being pursued in other countries?

14. This study examined P&T management programmes in the USA, Japan, and France (and in the EU). The reasons why each is undertaking R&D are described in the main body of the report and the annexes, the most important of which are:

- for different reasons, each country is committed to nuclear power as an important energy source;
- France currently has the capacity to utilise a substantial part of its plutonium inventory in MOX-burning reactors and introduction of the European Pressurised Water Reactor will increase this capacity further;
- France also sees a benefit in reducing the radiotoxicity of wastes emplaced in a deep repository;
- Japan subscribes to the concept of thermal and fast reactors working in parallel to make optimum use of its uranium stocks – this underpins development of reprocessing plants;
- the USA sees benefit in separating out the key radionuclides in its spent fuel in order to reduce heat-generation from wastes in its Yucca Mountain repository. It proposes storage for the partitioned wastes until transmutation can be achieved.

Main conclusions

15. In relation to the present status of the technology:

- the technology for P&T is not tried and tested except for uranium and plutonium. There are significant practical challenges in applying both technologies to other key radionuclides;
- P&T research programmes focus on spent fuel. It would be much more difficult to separate out the key radionuclides from low, intermediate, and vitrified (i.e., converted to glass) high level wastes, all of which are held in the UK. In LLW, for example, the radionuclides are dispersed through very large volumes of other wastes. Costs would be high and even larger waste volumes inevitably generated by the process;

- proving the technology will take time and will be costly (probably prohibitively);

- P&T cannot achieve the elimination of radioactive wastes: different wastes are generated but these will still remain dangerously radioactive for many, many years and require a conventional waste management programme. P&T could contribute by eliminating some particularly toxic or long-lived radionuclides;

- therefore, P&T does not offer a comprehensive long-term management solution of the type being sought through the *Managing Radioactive Waste Safely* process.

16. In relation to the potential for P&T to make a successful contribution to the UK's radioactive waste management problem:

- its successful exploitation effectively requires a commitment to nuclear power and to reprocessing for a very long period, possibly 100 years;

- unlike the USA, France, and Japan, the UK has no reactors with remaining operational lifetimes sufficient to accommodate the range of materials that would need to be treated for transmutation and to allow the necessary number of irradiation cycles – in this circumstance, research into P&T seems not to be justifiable;

- without a clear and long-term commitment to nuclear power as part of a national energy policy, P&T could bring the worst of all worlds, incurring high costs, requiring ongoing reprocessing, and delivering no useful product.

17. In the context that any long-term radioactive waste management strategy in the UK should have broad national support, social concerns about a continuing commitment to nuclear power, involving new facilities and untried technology, are likely to give rise to conflict which will impede, rather than facilitate, the development of publicly acceptable policies for radioactive waste management over the long-term.

18. Set against existing waste management technology, deferring waste conditioning in the hope that P&T will provide a solution would mean that extremely hazardous liquid wastes would have to be retained when comparatively simple and well-tried technologies, notably vitrification, are available to greatly reduce the hazard.

MAIN REPORT

1. Introduction

1.1 This report sets out the findings of a RWMAC study undertaken, in response to a request for advice from Ministers in the UK Government and the Devolved Administrations for Scotland and for Wales, on the potential application of partitioning and transmutation (P&T) technologies to the management of radioactive materials and radioactive wastes in the UK.

1.2 The study fieldwork was carried out by a RWMAC Working Group, the membership of which is set out at Appendix 1. A number of meetings with UK and overseas radioactive waste management practitioners took place; details of which are set out in Appendix 2. The final form of the report was agreed at a plenary meeting of the Committee in September 2003, and submitted to Ministers the following month.

"Managing Radioactive Waste Safely" and public engagement

1.3 The *Managing Radioactive Waste Safely* initiative (often abbreviated to MRWS) was launched by the UK Government and the Devolved Administrations in September 2001 to provide a framework for public involvement in decisions on the option, or combination of options, for long-term management of higher activity radioactive wastes that would protect the health of people and the environment. MRWS made clear that all possible options would be considered and a brief summary of P&T was included in the MRWS consultation document[2].

1.4 The 1999 *Consensus Conference on Radioactive Waste* (a forum essentially composed of ordinary members of the public) identified P&T as an option that should be more actively pursued. Responding to this, UK Nirex Limited* decided that further consultation was needed to establish a public view. In October 2001, Nirex convened a Citizens' Panel as part of this process, the conclusions of which were published in November 2001[3].

1.5 RWMAC hopes that the public, as well as Ministers and the scientific community, will find this report helpful to their understanding of the extent to which P&T can be regarded as a potential contributor to solving the problem of managing radioactive waste in the UK.

*Nirex is a company owned by the nuclear industry which, until 1997, carried out research into the deep disposal of some radioactive wastes. Its main activities now mainly comprise advice on waste conditioning and packaging.

1.6 P&T presents a challenging issue for public engagement. Neither the science, nor its technological application, are easy to understand. RWMAC agrees with the conclusion of the Citizens' Panel that the process of public engagement with complex scientific issues should be conducted in stages, ensuring that the public learning curve, at appropriate stages, is assisted by input from the scientific community. This has influenced the wording of this report, particularly its Executive Summary – which is couched in language that is meant to be easily understandable.

What is P&T?

1.7 P&T was first suggested over 30 years ago as a means of reducing the long-term hazard associated with radioactive wastes. Partitioning (perhaps better termed "separation") is a process undertaken to isolate the different components of radioactive waste to permit their segregated treatment. Transmutation, the process applied to the separated components, is defined by the IAEA as "*nuclear conversion transforming one element into another . . . as a result of nuclear bombardment with ionising radiation or nuclear particles*"[4].

1.8 The two processes are at different stages of development:

- partitioning is a series of conventional physical and chemical separation processes that could equally be applied to non-radioactive materials, and already achieves the extraction of uranium and plutonium through the reprocessing of spent nuclear fuel;

- transmutation is a process involving the conversion of one chemical element (or isotope) into another as a result of bombardment by nuclear particles in a reactor or accelerator.

1.9 Perhaps the most commonly perceived objective for P&T is to reduce the hazard associated with the management of radioactive waste to any given level over a much shorter time period. It seeks to achieve this by converting radioisotopes in the waste to others that are either inherently less harmful and/or whose radioactivity decays in a much shorter period to safe levels. The ideal is for stable isotopes to be produced, which are not radioactive. As an example, it is theoretically possible to transmute Technetium-99, a radionuclide with a half-life of 210,000 years, into the stable nuclide Ruthenium-100.

Why promote research into P&T?

1.10 One conventional approach to waste management is to rely on containing and shielding the radioactive waste until the radioactivity has decayed to some predetermined level. The hazardous radionuclides are simply not allowed to escape

into the environment and thence be taken in by people. This approach requires protection against both natural and deliberate intrusion (or disruption) for long time periods – in some cases, thousands of years. Another approach is to release radionuclides into the environment such that they will be so diluted as to offer no threat. The emphasis today is more on containment than discharge to the environment.

1.11 An alternative, which is the subject of this report, is to convert the most radiotoxic (therefore the most hazardous) nuclides to different, less radiotoxic and/or shorter-lived radionuclides – by transmutation. This approach deserves careful evaluation because it offers an active response with an apparent reduction in the inherent hazard posed by the wastes.

1.12 A number of countries and international organisations are pursuing research and development into P&T. While they are doing so from a number of different perspectives, they have clear objectives in mind.

1.13 First, there is the view that the successful application of P&T to the waste products of the production of electricity by nuclear power would make nuclear energy more sustainable and give it a cleaner image.

1.14 Second, they see it as offering the prospect of managing the problems associated with national inventories of radioactive wastes by, for example, reducing their radiotoxicity (defined by the IAEA as "*the ability of a radionuclide to produce injury*"[5]).

1.15 Third, in relation to inventory components that are, or may come to be declared as, radioactive wastes, P&T can help in the development of a management strategy. In this respect, it may be viewed as an end in itself (since, in theory, radioactive nuclides can be transmuted into stable ones). It can also form part of wider programmes. The problems posed by managing wastes over the long-term may be eased, for example by reducing heat-loading on an underground repository, or limiting the potential for the migration of radionuclides away from the repository, and therefore for radioactivity to return to the surface.

1.16 Fourth, P&T is seen as an anti-proliferation tool, particularly in the potential offered to transmute plutonium, a vital component of nuclear weapons, into a form which has no such use.

1.17 Fifth, countries may see support of P&T research and development as a means of retaining their nuclear skills during periods when no new nuclear build is underway.

1.18 Lastly, some see transmutation as fundamental physics worthy of exploration in its own right.

1.19 Practical interest in P&T is restricted to countries with nuclear programmes. The degree of commitment being shown depends on a number of factors. These include the composition of the inventory – particularly the way in which historic wastes have been segregated, stored, and conditioned – which imposes practicability constraints, and whether R&D is required by law (as in France), state-sponsored, or left to the private sector. These issues comprise major themes of this report.

2. Partitioning and transmutation – the social context

2.1 Aside from overcoming the scientific challenges, no national government is likely to adopt P&T as part of a radioactive waste management policy unless its public can gain a reasonable understanding of the technology that needs to be developed, and the implications of doing so.

Public concerns

2.2 Worry about practices that involve radioactivity is well known and well recorded. For the general public, this encompasses (although is not restricted to) nuclear weapons and the activities of the civil nuclear industry, including power generation and reprocessing of spent nuclear fuel, together with management of the resulting wastes. But it is unlikely that most members of the public understand very much about P&T.

2.3 Public concerns derive from the hazard that radiation represents – firstly harm to the health of people and secondly contamination of the environment. High doses of radiation are known to be life threatening. At low doses, radiation has the potential to cause cancer. Uppermost in people's minds is probably the "dread factor" associated with nuclear warfare and catastrophic accidents like Chernobyl.

2.4 But nuclear activities can instil fear whatever the levels of risk and radiation involved. Understanding of hazard is made difficult by the complexity of the science of radiation exposure and radiological protection. The "half-life" of radioactive wastes, the different kinds of radiation they emit, the "pathways" (for example food and inhalation) that lead to exposure, and the steps that can be taken to prevent radiation reaching people, need, as a first step, to be understood. People will look for management solutions that eliminate, as far as possible, the perceived threat.

Describing wastes and evaluating properties

2.5 Proposed solutions will require information to be available about radioactive wastes themselves, and the hazards they pose, such that they enjoy public trust and can be seen to be effective. The first factor should be to describe the intrinsic properties of waste since different bodies, including governments, base their arguments and waste strategies on different properties, thereby creating the potential for confusion.

2.6 The first property considered is the ability of the material to pose an "external hazard", i.e., the waste emits radiation that can be harmful to a person located nearby. This leads to methods of shielding waste (both during transport and at any disposal site).

2.7 When considering storage or disposal, the three most commonly used attributes are:

- volume (in cubic metres – useful in the context of planning facilities for storage or disposal);
- activity (the amount of the radioactivity measured as the number of atomic disintegrations that occur each second and which result in radiation pulses); and
- radiotoxicity (hazard represented by radiation from a radioactive substance if it is taken into the human body).

2.8 Radiotoxicity is more complex than the other two properties; it "depends on the properties of the radiation and on a number of physical, chemical and biological conditions such as the mode of intake (via air, in water or food, through wounds, etc.), the size of the ingested or inhaled particles, their chemical properties (e.g., solubility), metabolic affinity and ecological conditions"[6]. The most radiotoxic elements are those that emit harmful radiations and become concentrated in particular organs within the body from which they are expelled only very slowly. Radium and plutonium are fixed in the bone and effectively give lifetime doses: they are two of the most radiotoxic elements. Other elements can be very much less toxic than plutonium (more than a million times less so).

2.9 A key issue with all the properties is how they convert to damage to the individual as radiation dose and what measures, in terms of radiological protection, may be taken.

2.10 The practices and regulations for protecting the public and nuclear

workers from radiation are based on evaluating both the "external" hazard and the "internal" hazard and the resulting radiation doses, and relating these to the risks of cancer or some serious genetic disorder being caused. Practices are considered to be of no regulatory concern when it can be demonstrated that the risks associated with doses in the workplace or environment are small compared with risks from other causes.

The place of P&T in the national waste management debate

2.11 As this report will make clear, P&T represents a potential means of reducing the hazards posed by some radioactive materials and wastes. It will also be clear that development of P&T is tied to development of the nuclear sector over a long period and, in particular, to continued reprocessing. It is likely that implementation of P&T would generate some new forms of waste.

2.12 The opposition of environmental groups to the UK nuclear sector over the past decade or so has focussed on reprocessing, which involves the separation of uranium and plutonium (both components of nuclear weapons) from spent fuel and gives rise to discharges of radioactivity to the environment. It may be expected that these societal concerns will be articulated by opponents of the nuclear industry and add to scientific and technical reservations about the potential for developing P&T.

2.13 In this context of scientific scepticism and controversy, the possible benefits from P&T may be lost. Potentially, P&T can reduce the timescales over which some waste has to be managed, thereby reducing the burden on future generations (the principle of *intergenerational equity*). By investing in P&T research now, contemporary society could be reducing the risks passed on to future generations. However, the time-scales governing the risks involved, even though they might shortened through P&T technology, are still very long – certainly far beyond the relatively limited timespans of one or two generations that are widely regarded as the limit of people's view of the future. (In other words, there is concern for one's children and grandchildren, but difficulty in grasping the future, in any meaningful way, beyond that.)

2.14 In deciding its view on P&T the UK Government will have to take account of these societal issues. It is almost certain that actively taking up P&T would generate active opposition, whereas a "watching brief" on developments elsewhere probably would not.

2.15 In either case, and whatever the timeframe, a process of public debate would be necessary before a commitment to research in, and development of, P&T technology could be made. As section 1 makes clear, this report, in which the main points addressed are scientific and technical, not societal, aims to inform that

process. If, as part of the *Managing Radioactive Waste Safely* initiative, the potential of P&T as a waste management strategy is to be taken further, it is clear that it must be subjected to various techniques of interactive and deliberative decision making to ensure public understanding of the issues. Public acceptability will be imperative for P&T just as it will be for any other strategy for the long-term management of radioactive waste.

3. The history of UK interest in partitioning and transmutation

Partitioning and transmutation of plutonium

3.1 P&T appears to be regarded as an entirely novel technology that has not been explored in the past. This is not the case. The largest contribution to a reduction in radiotoxicity derives from separation and transmutation of plutonium. Thus, reprocessing and recycling of plutonium as a nuclear fuel is partitioning and transmutation by another name and this has been part of the UK philosophy of nuclear power since its inception. The earliest fuel cycles envisaged thermal reactors producing plutonium as a by-product that would be separated and burned as a fuel in fast reactors, although the case for such a cycle was made on grounds of efficiency of fuel utilisation rather than on the basis of a reduction in radiotoxicity. This was seen as important in the early days of nuclear power when the extent of the world's uranium reserves was not fully appreciated.

3.2 In the event, as thermal reactors were built around the world, uranium exploration was stimulated and extensive reserves discovered. The effect was that uranium prices remained low and the value of plutonium recycling diminished. Direct disposal of fuel, hitherto seen as wasteful, was adopted in many countries and stocks of plutonium began to be viewed as a problem area. The UK's fast reactor development programme was terminated in 1993.

3.3 Today, although some countries retain an interest in fast reactors, development programmes are not being pursued aggressively. Burning of separated plutonium in thermal reactors in the form of mixed uranium/plutonium oxide (MOX) fuel, manufactured in the UK by BNFL (and in France by COGEMA) has been adopted as a means of managing plutonium stocks. There is also interest in immobilising any uranium and plutonium stocks that are declared to be wastes – among other things, this is seen as an anti-proliferation measure.

3.4 A consequence of the successful development of this technology is that the term P&T has come to be applied to the separation and transmutation of other elements such as the minor actinides that contribute significantly to radiotoxicity. However, it should not be forgotten that to make significant gains in reduction of

radiotoxicity, any future P&T cycle must also continue to separate and recycle plutonium *as a starting point*. Research and development programmes are aimed at extending the range of elements that can be treated. As would be expected, the inclusion of additional elements in the developing technology often means diminishing returns for the investment. In principle, much of the benefit of reduced radiotoxicity can be achieved from today's technology.

Other P&T applications

3.5 Some essentially theoretical studies, aimed at the application of P&T beyond uranium and plutonium, commenced in 1973, and ceased in the early 1980s, since when UK work has only been at the review level.

3.6 The early UK work was mainly performed by the United Kingdom Atomic Energy Authority (UKAEA), but also by the Central Electricity Generating Board (CEGB). It began independently, but was later incorporated into a programme with the Netherlands for the European Union. A useful summary of the conclusions of the UK work, along with references for the individual studies, can be found in an International Atomic Energy Agency (IAEA) 1982 review of P&T[7]. The studies were initially wide ranging, but then concentrated on the partitioning, and the transmutation in reactors, of the minor actinides

3.7 Based on the results of both national and international studies, the UK came to the conclusion that the transmutation of the minor actinides as a method of waste management was not justified at that time. The reasons given in support of this conclusion on actinide transmutation, as set out in a study report commissioned from AEA Technology by the Department of the Environment[8], drawing on the IAEA's 1982 review, were:

(i) it would not make a significant contribution to energy resources;

(ii) partition of actinides from the lanthanides (another group of elements with similar chemical properties) would be needed, but would be difficult to achieve;

(iii) new transmutation reactors would probably be needed, which would be expensive to design;

(iv) development of new reactor fuels to hold the minor actinides would be needed, but would only be achievable with difficulty and demonstrating their safety would be a major undertaking;

(v) it would require many cycles of irradiation in reactors, implying the need for very efficient partitioning processes, both for the HLW resulting from reprocessing the fuel and the many secondary waste streams created during reprocessing;

(vi) it would be more important to vitrify existing and fresh arisings of HLW than to wait, over a period of 20 to 100 years, for the necessary P&T technology to be developed, and the transmutation to be achieved over many cycles of irradiation;

(vii) there are simpler, more reliable, and better authenticated options for radioactive waste management, based on vitrification and disposal;

(viii) cost-benefit analyses would be unlikely to be attractive compared to the conventional concepts of waste management based on vitrification and disposal.

3.8 International work at this time concentrated almost entirely on the partitioning and transmutation of the minor actinides and not fission or activation products. Studies now suggest that the latter two would make an important, and possibly dominant, contribution to the risk from a waste repository and that simply transmuting the minor actinides in HLW or spent fuel would not be enough to significantly reduce the risk from a repository. Technical obstacles were identified to introducing P&T. The early studies did not consider accelerator driven systems (ADSs) as a promising technology after an initial review. Conventional reactors use solid fuel and the minor actinides placed in a reactor for transmutation would have to be in a solid fuel matrix. The use of solid fuel meant the need for many cycles of irradiation in a reactor, reprocessing of the fuels containing the actinides, and fabrication of new fuel. The many fuel cycles which would be required also implied the need for high levels of efficiency in the partitioning processes applied to the fuels and secondary wastes, otherwise a significant proportion of the actinides would end up in the secondary wastes needing to be disposed of. It was also concluded that the vitrification of HLW, followed by disposal in a repository after cooling, was sufficiently safe. This represents one of the reasons why the vitrification option for HLW from the reprocessing of spent reactor fuels has become accepted UK practice.

The UK's current position

3.9 After the publication of the IAEA's 1982 review of P&T, interest internationally in the technology waned for a few years. In 1988, Japan began a programme of research into P&T and some other countries and the European Union followed suit. As a result of this resurgence of interest, the 1995 White Paper on

UK radioactive waste management policy (Cm 2919) concluded that the UK Government should keep a watching brief on international work on P&T, although should not initiate further work of its own. This has subsequently led to three Government review studies being commissioned, two of which have been completed.

3.10 The 1996 study by AEA Technology for the UK Department of the Environment[8] examined the potential for safety and financial gains from future application of P&T, concluding that although technical progress had been made, it "*has not been shown to be justified*". Thus, the study supported the Government's position, set out in the Cm 2919 White Paper, that it would continue to maintain a watching brief while believing that "*separate research is unnecessary*".

3.11 A further study undertaken by AEA Technology for the UK Government[9] was designed to fulfil the ongoing watching brief. It looked at work overseas which is exclusively focussed on HLW, concluding that P&T is likely to be a viable management tool only in the long, not the short or medium, terms. It pointed out that industrial scale feasibility has yet to be proven. The report also identified the key radionuclides that, as the greatest contributors to potential long-term radiation exposure of the public brought about by the migration of radionuclides in groundwater away from an underground repository (the "Groundwater Release Mechanism"), were the obvious targets for P&T research.

3.12 A third study, by British Nuclear Fuels plc and NNC Limited, is ongoing. The project is due to complete in late-2003.

4. The reasons behind the continuing research programmes into partitioning and transmutation in the USA, France, Japan and the European Union

4.1 While the UK has taken a cautious view of the potential of P&T and merely maintained a watching brief on developments elsewhere, this has not been the attitude in a number of other countries. Three, in particular, have supported active and substantial research and development programmes, namely, the USA, France and Japan. In addition, the EU has allocated increasing levels of expenditure to P&T from its nuclear budget.

4.2 In order to understand the current status of the technology, it was essential to review recent developments in these countries and, for this reason, visits were made to the USA, France, and the European Commission in Brussels for discussions with experts. The position in Japan has been established from a review of recent literature. Summaries have been prepared on the findings of all four reviews and these are set out in Annexes B–E of this report.

4.3 The principal objective of these reviews was to establish the underlying reasons for the different and more positive attitude taken by others to the potential of P&T. In part, this was found to link directly to national energy policy and, particularly, to the role envisaged for nuclear power in the future. It is the case that, in all three countries examined, the strategic vision of future energy supply sees nuclear power providing a substantial proportion of internal demands. The World Energy Council study of future global energy requirements was also cited in the discussions. This study concluded that nuclear power must make a significant contribution to total world demand in a sustainable energy scenario. It saw much of the growth coming from expansion of energy consumption in the third world rather than from the developed world. However, the USA, France and Japan probably all see themselves as exporters of technology and equipment.

4.4 Overseas interest in P&T is also viewed as a way of helping to develop a waste management strategy, although the direction of the research is different. In France, reduction of radiotoxicity is seen to be an end in itself, given that measurable environmental and public relation benefits may result, while in the USA, there are shorter-term issues of cost saving and political pragmatism bound up with the current repository programme.

4.5 The position in the EU is rather different, as individual Member States have different energy policies. Strong support for P&T research in the EU arises for two quite different reasons. While some Member States retain a commitment to nuclear power, others have policies of phasing out nuclear power, but still have significant quantities of spent nuclear fuel that awaits final disposal. This latter group is interested in the potential of P&T as a means of addressing the existing waste management problem.

4.6 These two main reasons for interest in P&T in the EU are reflected elsewhere and it is important, therefore, to consider both the benefit that P&T can offer to a future nuclear energy programme and its potential as a "stand-alone" waste management technology. This requires a good understanding of the technology and, for this reason, the summaries in Annexes B–E describe, in some detail, the chemistry of separation and aspects of nuclear physics in transmutation processes. The aim here is to identify the key issues that would form the basis of a judgement on the potential of the technology for the UK rather than to assess its merits.

4.7 A close reading of the four reviews, whilst indicating some differences in the scientific approach being taken in the individual national and EU programmes, reveals no major differences of opinion regarding the incentive to pursue P&T research, the status of current capability, and the development work needed to establish the technology fully. Estimates of the timescales necessary to implement a

technology, and its likely overall effectiveness, are more subjective areas. On these matters, there are some differences in view.

5. The current status of the technology

Partitioning technology

5.1 From its infancy, nuclear physics research sought to understand nuclear reactions and to establish the properties of common isotopes. Thus, the ability to use a neutron source to transmute elements has been known for many years. In contrast, the chemical or physical means of partitioning (i.e., separating and isolating) elements relevant to P&T has received little attention. The exception was the ability to separate plutonium. This technology was developed because it was a basic requirement of the nuclear weapons programme. That such technology existed was almost certainly the reason that the early fuel cycles were proposed with the benefit of optimisation of fuel utilisation.

5.2 This position remained substantially unchanged until around 1990 when most of the current P&T programmes began in earnest. The prime need, seen at that time, was to extend the separation capability to incorporate minor actinides and other isotopes occurring in spent fuel, without which the full potential of P&T could never be exploited. Thus, the programmes set this as a key objective and, although separation techniques differ a little, all have achieved considerable success in this area. On a laboratory scale, separation of all of the significant elements has now been achieved at efficiencies high enough to be useable if the same techniques can be scaled up to an industrial level. Scaling up the technology to an industrial process will not be without problems and, in particular, maintaining efficiencies of separation may prove challenging. This will take time to achieve but, given that the basic capability has been demonstrated, it is not unreasonable to suppose that it will be possible within the timescale needed to build the required industrial separation plant. Estimation of the time required to achieve an industrial scale process is a matter of speculation, but all three countries studied have volunteered the view that it will be possible by around 2015–2020. Their view in this regard is largely based on knowledge of the timescale to develop reprocessing plants for nuclear fuel in the past.

5.3 In countries with an existing reprocessing capability (France and the UK), industrial implementation would almost certainly take the form of an additional process line to the new plant through which the Highly Active Liquor (HAL) waste stream from the reprocessing operation would pass. Other countries would need to build a new plutonium extraction plant. The additional process line would be a comparatively small addition to a reprocessing plant because it would be required to treat only a relatively small waste stream and would have a throughput, measured

in tonnes, of only a small fraction of that of the parent reprocessing plant. It follows that the new plant would be small in comparison to the parent plant and that its cost would be proportionately lower. Until further progress is made and designs become available, it is impossible to make more refined estimates of cost.

5.4 Countries which have no reprocessing capacity, notably the USA and Japan, would need to build separation plants tailored to the objectives of their P&T programmes. The USA, in order to achieve reduction in the heat-generating capabilities of the wastes to be disposed of to the Yucca Mountain repository, will need to be able to extract a range of radionuclides from its spent fuel, including americium, curium, technetium, and iodine, in addition to plutonium.

Transmutation and neutron sources

5.5 As discussed briefly above, the principle of transmutation is not in question. The nuclear properties of the main elements considered are known, but this is almost certainly not the case for all the daughter products of transmutation. While this deficiency does not throw into question the overall capability, it could be important in the context of the design of a complete system, as the daughter products could be parasitic in terms of neutron absorption. Nevertheless, it is well understood that the required changes can be produced in particular isotopes if they are subjected to a neutron source of appropriate energy levels. Possible sources of neutrons are the fluxes within fast or thermal reactors, or in dedicated accelerators built for that purpose. There are advocates among the nuclear countries of all three methods, depending on future energy strategy or attitude to waste disposal. Those that see P&T as an integral part of a future nuclear programme envisage most of the transmutation being produced within power reactors. Others will require accelerator driven systems.

5.6 The French believe that it will be possible to transmute plutonium, americium and neptunium in a pressurised water reactor (PWR). In particular, the harder neutron spectrum in the proposed European PWR (EPWR), which is the next plant that the French expect to build, would be particularly useful. This is because it will enable the full core to be fuelled with MOX fuel whereas the currently operating PWRs can only be partially fuelled with MOX. The EPWR would therefore have an increased effectiveness of plutonium utilisation over less advanced light water reactors but fall short of the performance of the high temperature reactor (HTR; see below).

5.7 Dedicated accelerators could be used to deal with isotopes other than plutonium but the cost/benefit of this would need careful consideration because costs would be high and these other elements are not the greatest contributors to radiotoxicity. For this reason, it is possible to envisage that P&T may never be

implemented to achieve the maximum benefit in reduction of radiotoxicity that is theoretically possible.

5.8 Plutonium, as the greatest contributor to radiotoxicity, is central to any P&T strategy. Figure 1 illustrates the benefits that a MOX fuel cycle can bring both for a "once through" cycle and for multiple recycling. Multiple recycling represents an advance on current practice and would need some further development in fuel/ reprocessing technology.

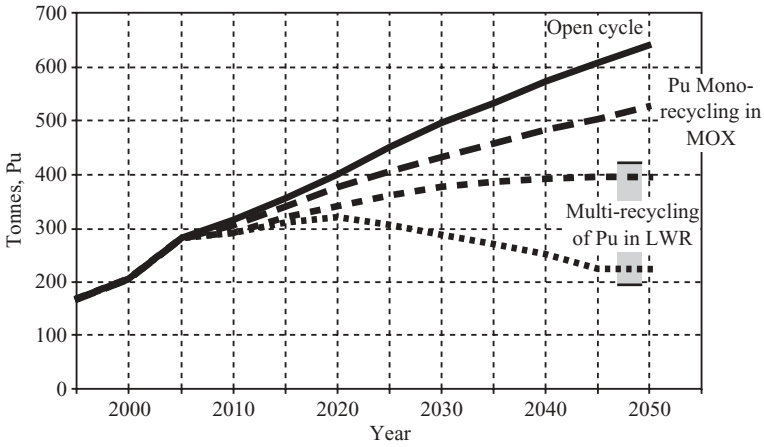

Figure 1. Plutonium inventory with different levels of MOX recycling

5.9 There is no uncertainty about the ability of a fast reactor to contribute to a reduction in overall plutonium stocks. Also, fast reactors can be regarded as proven technology – prototype designs have been operated successfully in several countries. While none remain in service today, their withdrawal has been for technical or economic reasons unassociated with nuclear fuel. The French are currently recommissioning the Phénix fast reactor as an experimental facility for transmutation studies and the Japanese have similar ambitions for their Monju reactor.

5.10 The initial strategy in the USA was focussed on accelerator driven systems but it was realised that a large number would be required to cope with committed waste and this would be expensive. It is now proposed that the existing water reactors would be utilised to transmute plutonium. Commercial fast reactors would have the capability to transmute all americium and curium and accelerator driven systems (ADSs) would only be considered for transmuting technetium and iodine.

5.11 The Japanese programme assumes that the main vehicle for transmutation would be commercial fast reactors.

5.12 Of thermal reactor concepts, a better vehicle for destruction of plutonium is the HTR. Because the reactor core consists of little other than graphite and fuel, this can achieve very high levels of plutonium burn-up in a once through cycle. No commercial plant is yet in operation, but several configurations of HTR are being developed around the world. The Pebble Bed Modular Reactor in South Africa is an example. HTR development is now included in the US Generation lV programme and also forms part of the EU nuclear programme.

5.13 As mentioned above, those countries without a reactor programme that are nevertheless looking to P&T as a waste management process will need ADSs. ADS designs have not progressed beyond the conceptual stage. Work on such designs is proceeding in Europe under the EU 5th Framework Programme and also in Japan.

Fuel and/or targets

5.14 Regardless of whether a power reactor or a dedicated accelerator is used, there is a need to consider the form in which the relevant isotopes are to be introduced and exposed to the neutron source. There are many possibilities for doing so; these include dispersions through a matrix that is the basic fuel for the reactor, or introduction of separate targets into a reactor or accelerator. For simplicity, whatever the precise form envisaged, the term *targets* will be used.

5.15 Clearly, when transmutation takes place there are chemical and physical changes in the properties of the material being exposed. Safety arguments will require all of the original material and products of the nuclear reactions to be effectively contained and this will impose limits on the extent of the exposure and/or the possible levels of isotopes that can be introduced into matrices. This is a major area where R&D is required.

5.16 To illustrate the scale of the challenge, a parallel can be drawn between transmutation and development programmes undertaken to support reactor fuels, of which MOX development is the most recent example. In general, these fuels were exposed to substantial trials and exposure in Materials Testing Reactors before being introduced to a power reactor. Because fuel residence times in reactors are long (typically 5 years), sufficient time must be allowed for proving experiments and, given that problems may be encountered, several cycles of such experiments may prove to be necessary. Also, it is worth remembering that for all three of the reactor systems employed in the UK (Magnox, Advanced Gas-Cooled; AGR and Pressurised Water; PWR) initial tight limits were imposed on fuel burn-up that were

only relaxed with the benefit of considerable operating experience. Thus, it could take time, well beyond that needed for the construction of a commercial facility, for the full benefits of P&T to be realised

5.17 Estimates for the time needed before fully proven targets could be available for routine exposure differ little in the USA, France, and Japan and all fall within a fairly narrow band ranging between 2020 and 2030.

5.18 It is worthy of note that, for this aspect of R&D, the technical challenges are likely to be compounded by the very limited facilities for irradiation and proving of targets. In France, the proposal is to restart Phénix. This is a prototype fast reactor closed several years ago. It is now planned that Phénix should restart in 2003, but it will have only a new lifetime of some four years. As the exposure time required for a full simulation of target irradiation will be long, this would allow little more than one full cycle. Similarly, Japan intends to restart a prototype fast reactor that has been idle for some ten years. They plan to use Monju, a plant that was closed on safety grounds and changes have been proposed recently to address the deficiencies in safety. However, this proposal awaits regulatory approval and there have been challenges to the plan in the Japanese courts. The EU programme tends to place greater emphasis on ADSs, largely because many Member States do not have plans for a future nuclear programme. The current EU programme includes conceptual design of such a system, but no future budget has been allocated to the construction of a facility. Unless a very large increase in funding is approved, the programme could well founder.

Complete P&T system design

5.19 An aspect of P&T that, up to now, appears to have received very little attention is the design of a total system to achieve the full benefits of the theoretical reductions in radiotoxicity. This is an extremely complex area because, to achieve the full benefits, it requires the treatment of many isotopes in parallel, each of which has its own nuclear properties. Of particular importance is the neutron capture cross-section of the isotopes. This is a unique property of the isotope which governs the rate of transmutation that can be achieved in a given neutron flux. If several isotopes are to be processed in the same facility, they will all experience the same neutron flux. Thus to achieve simultaneous transmutation would require isotopes to be present in proportions inversely related to their capture cross-section. This is a serious constraint on the design of targets that could prove inconsistent with the requirements to achieve a high standard of robustness in service.

5.20 More fundamentally, for the overall system to achieve equilibrium, the transmutation rate must, at some stage, match the production rate for each isotope. As indicated above, the transmutation rate will depend on its capture cross-section

while the production rate from the separation process will depend on the proportions present in the spent fuel. These proportions depend, in turn, on the conditions of operation of the power reactors. Achievement of the desired equilibrium would not seem possible without multiple recycling of materials. It could well prove that the most cost effective options will, in practice, fall short of the full theoretical possibilities. Until a coherent plan is available that addresses this aspect, it would be unwise to assume that the full theoretical benefits are achievable.

Timescales

5.21 There are no great differences in the views of the countries consulted regarding timescales. The French position on this is the most clearly stated and the comments below relate to the detail of their programme.

5.22 A key date in their schedule is a review of the feasibility of P&T in 2006. This is a requirement of the Law of 30 December 1991 addressing waste management issues in France. Thus the current programme has objectives and target dates aimed at supporting that review.

5.23 As noted above, the feasibility of separation has now been demonstrated at a basic chemistry level. Between 2004 and 2006, further work is planned using rather larger quantities of materials derived from actual spent fuel samples to achieve what the French describe as a "technological demonstration" of the process. It is then envisaged that scaling up of the technology to industrial application would take until 2015.

5.24 Transmutation aspects have received comparatively little attention over the last decade, but work is now proceeding with preparation for experiments in Phénix. The return to power of Phénix will permit irradiation trials on targets to begin. Because of the short lifetime expected for operation of Phénix, several experiments will need to be conducted in parallel. These will cover core physics and nucleonics, transmutation of minor actinides, transmutation of technetium, and further experiments in support of the American Generation IV programme. No materials are planned to be withdrawn from the reactor before 2005 and most will not be removed before the closure of Phénix in 2007. However, completion of the irradiation trials, and withdrawal from the reactor, do not represent the end of the experiments. The highly radioactive materials withdrawn will then require both non-destructive and destructive examination in order to understand the changes that have occurred and to assess any problems that may have arisen. This is a time consuming business and this phase of the work will not be completed until 2010. Only then can a full implementation scheme be considered and only if these limited experiments have not revealed any unforeseen problems. Experience might suggest that it would be optimistic to assume that all results will be positive and that further irradiation trials

will not be necessary. However, the target dates for implementation of 2020–2030 would appear to take account of the lack of certainty inherent in these assumptions and also the fact that, even when the form of target is agreed, manufacturing facilities will still be required and stocks built to form the initial charge.

5.25 The start date for the implementation phase and the point at which positive benefit is derived from a P&T cycle are not the same. Cycle times will be long, especially if multiple cycles are required. It will certainly be several decades before a net benefit will be seen. Very roughly, the end of the 21st century might be a reasonable target date.

Cost

5.26 Given the uncertainties that surround the technology, it is not surprising to find that there are no detailed cost estimates available. At present, reliance has to be placed on very broad assessments.

5.27 If the technology is to be linked to a future power reactor programme, there are several items that would have the effect of raising the cost of production of the end product, namely, electricity. These include:

- additional fuel manufacture costs because of the need to produce targets;
- reduced power output from a reactor because the targets will carry a reactivity penalty;
- additional reprocessing costs because of the additional plant and processing required.

5.28 Taking account of the contribution that each item makes to current generation costs, a crude estimate might be that, in total, electricity generation costs would increase by something of the order of 25 per cent.

5.29 If P&T was to be applied in the absence of a power reactor programme, ADSs would need to be built. As no fully developed ADS conceptual design yet exists, it is not possible to offer even a crude estimate, but clearly implementation could prove to be very expensive indeed.

6. A complete partitioning and transmutation system design – the current investment gap

6.1 Comparison between the status of existing industrial scale separation and partitioning technologies in France, Japan, and the USA, and what would be

required to achieve a complete P&T system, enables broad conclusions to be drawn on the R&D (and the capital investment) needed:

- P&T is not simply a waste management technology that can be introduced in isolation without consideration of nuclear power programmes and investment in reprocessing plants;

- application would require continued use of existing reprocessing plant with additional capabilities or investment in new plant;

- facilities would be required for the transmutation. Where possible, the best economic case is to use power reactors. Where this is not possible, dedicated accelerators would be necessary;

- the scale of the investments required, and the cycle times for the processes, mean that it is only sensible to pursue P&T as an option if it is coupled to a long-term commitment to nuclear power and reprocessing (of the order of 100 years).

7. Application of partitioning and transmutation in the UK

Nuclear energy and radioactive waste management

7.1 It is noteworthy that all parties actively pursuing P&T have a view of a future in which nuclear power provides a greater share of their own and world energy needs. The UK has recently published a White Paper setting out its energy policy that is equivocal on the future role of nuclear power and reserves its options. Thus, the UK occupies a rather different position from that of most of the protagonists for P&T.

7.2 Apart from the EU, no organisations are actively supporting P&T research in order to develop radioactive waste management options independent of a continuing power reactor programme. Nevertheless, the UK Government has charged the newly created Committee on Radioactive Waste Management (CoRWM) with examining all the options for the long-term management of long-lived radioactive wastes. Thus, it is important for the UK to be able to consider P&T as a radioactive waste management tool in isolation from a future nuclear power programme.

Deep geological disposal

7.3 In principle, if not always in practice, research into radioactive waste management should be directed by a national radioactive waste management

strategy. In France, by virtue of the 1991 Law, the alignment between national policy and P&T research is clear.

7.4 Until 1997, when the UK Nirex Ltd programme collapsed, the UK actively pursued the concept of the deep geological disposal of its more radioactive and longer-lived wastes. Currently, the UK does not have a strategy for the long-term management of long-lived radioactive wastes, although the Government's *Managing Radioactive Waste Safely* initiative, launched in 2001, is designed to achieve this. High level radioactive wastes (HLW), for which P&T is particularly relevant, were not explicitly addressed in the Nirex programme. These are the wastes arising directly from the fuel of nuclear reactors and exist as waste produced by reprocessing (in both unconditioned, i.e., liquid, and in vitrified form) together with some spent nuclear fuel for which there are no plans to reprocess. At present, vitrified HLW and this spent fuel are held in storage pending decisions about their long-term future. This is not a source of delay as it allows a necessary reduction in heat generation before other options could be considered. The commitment, in the 1995 Cm 2919 White Paper on UK radioactive waste management policy, that a national statement of future intent on HLW management would be produced, has now been overtaken by *Managing Radioactive Waste Safely.*

7.5 Thus, deep disposal remains a possible future option for the UK. An important question is the migration of groundwater away from a repository which could carry soluble and mobile radionuclides, such as Chlorine-36 and Iodine-129, with it, leading to radiation exposure of the population. For this reason, there is interest in the extent to which P&T could be used to help make the repository safety case. This contrasts with the position in France where development of the deep disposal concept is required by the 1991 Law, and concerns about corrosion rates of HLW containers have apparently been satisfied (see annex B).

Future scope for utilising P&T as a waste management tool in the UK

7.6 Before considering what P&T has the potential to deliver, it is equally important to understand what it cannot offer in the context of radioactive waste management. UK historic wastes, other than HLW, represent a complex mixture from which it is likely to be difficult to partition and separate out the radionuclides that are key to a repository safety case. Proving the feasibility of doing so would be a major undertaking, involving substantial R&D, and, even if it were to be successful, there would still be doubts about the efficiency of transmuting the radionuclides. Thus, there is a view that P&T technology can offer only limited benefit in terms of the treatment of key radionuclides such as those that are mobile in groundwater. Therefore, at present, P&T could only be considered in the context of the highly active isotopes present in spent fuel and in HLW from reprocessing.

This means that it cannot address the waste streams currently classified as LLW and ILW. Indeed, its impact on the LLW/ILW inventory would be negative in the sense that the additional separation processes, like the reprocessing of spent fuel that takes place at present, would add to the volumes in each of these categories.

7.7 This limitation is extremely important because P&T is not, and cannot be, a solution to the total radioactive waste management problem. It should be remembered that the proposal by UK Nirex Ltd to construct a Rock Characterisation Facility (RCF) in Cumbria failed, at least in part, because of questions relating to the robustness of the safety case for the final repository, which could themselves only be answered by the RCF itself. This was a repository for ILW and some LLW, and a P&T strategy could not have influenced the outcome in any way. As paragraph 7.5 of this section indicates, the limiting factors in proving a repository safety case are generally the mobile radionuclides that can migrate to the biosphere in the long-term.

7.8 At present, the UK has no complete strategy for the management of the HLW that is one product of reprocessing. Following vitrification of the HAL, policy is to store for some 50 years to allow cooling, but the long-term management of this waste is being studied as part of the *Managing Radioactive Waste Safely* process. However, the fact that it is being vitrified will inevitably constrain future options.

7.9 HLW arises from each of the three UK reactor systems. All of the spent fuel from the first generation Magnox reactors is scheduled to be reprocessed with the plutonium extracted and the HAL subsequently vitrified. A reactor closure programme is now in place that will lead to completion of reprocessing of Magnox fuel by 2012. Over 80 per cent of all the spent fuel arising over the lifetime of this reactor system has already been reprocessed. The vitrification plant is common to the treatment of HAL arising from both Magnox and AGR reprocessing and progress on this front needs to be considered jointly. Once HAL is vitrified, P&T options are in effect foreclosed.

7.10 The position with spent fuel from the AGR fleet of reactors (second generation UK reactor) is different. A first tranche amounting to 57 per cent of total expected arisings is to be reprocessed while the balance will be long-term stored pending a decision on its ultimate destiny. Thirty five per cent (35 per cent) of this first tranche has been reprocessed to date through THORP and reprocessing is proceeding to a programme which yields reduction in stored HAL, agreed with the regulators, which must be reduced to buffer levels by 2015. Later tranches of AGR fuel are currently not scheduled for reprocessing, and will be stored. Reprocessing would be necessary for P&T to have any application to this fuel.

7.11 PWR fuel from Sizewell B, clad with zirconium which is very corrosion resistant in water, is currently being stored in ponds at the plant, and its long-term fate is undecided. Again, reprocessing would be necessary in order that P&T options for the PWR fuel could be considered.

7.12 As of August 2003, some 2,900 vitrified waste containers have been produced, which accounts for about 30 per cent of the total HLW expected from the overall reprocessing programmes in terms of activity.

7.13 A number of conclusions are evident from this simple summary of the UK position:

- some 30 per cent of the relevant HAL has already been vitrified and is no longer suitable for treatment by P&T;
- the UK will need a solution for vitrified HLW regardless of P&T options, only the quantities to be addressed will change;
- safety cases for repositories or storage facilities are not strongly dependent on relatively small changes in the quantities of wastes that are involved and thus applying P&T to unvitrified HAL would not reduce risk;
- the remaining Magnox fuel will need to be reprocessed unless a safe alternative, limited in effect to dry storage, can be demonstrated to a very short timescale;
- HAL is not a suitable form to store wastes over the long-term before industrial scale P&T could become available;
- vitrification of HAL from reprocessing should proceed as rapidly as possible;
- maximising the options for P&T would require reprocessing, except for Magnox fuel, to stop as soon as possible;
- but any P&T scheme would include separation of plutonium and a new reprocessing plant.

7.14 From these points, it is clear that there is no sound case for delaying current waste treatment plans while awaiting an alternative solution. This conclusion would appear to be robust regardless of the questions that still surround P&T technology. The foregoing analysis suggests that P&T could well, in practice, offer

substantially less than its theoretical potential and the timescales, over which benefit could be derived, are likely be protracted.

7.15 Without an ongoing power reactor programme, the costs of a P&T programme, while as yet undefined, would be very high. The Nirex-sponsored Citizens' Panel felt that implementing P&T would commit the UK to a nuclear future.

7.16 Dedicated accelerator driven systems would be required for transmutation and, while some energy will be released, its extraction and utilisation is not a prime purpose and is likely to be inefficient. The value of the investment would have to be judged against the marginal safety benefit of reduced waste volumes in a store or repository. It is difficult to see how it could be shown to be cost effective.

7.17 The main conclusion of this report is that, in many ways, P&T would bring the worst of all worlds, incurring high costs, requiring ongoing reprocessing, and delivering no currently useable product.

8. Partitioning and transmutation linked to future nuclear generation

8.1 Under the newly announced UK energy policy, there is clearly no case to consider this aspect of P&T. However, because consideration of the future use of nuclear power is to remain under review, it is worthwhile commenting on the implications of a P&T strategy in order to identify the scale of change in policy, and then the level of commitment to new nuclear generation, that it would require.

8.2 The first requirement would be introduction of reactors that could efficiently burn plutonium. These could be PWRs with the characteristics of the European PWR, fast reactors, or HTRs. Their various merits have been described above. An important feature is the number of cycles that must be used in order to achieve an equilibrium level of plutonium. The goal would be to reduce plutonium stocks to that corresponding to "work-in-progress" i.e., the inventory in fuel manufacture, reactor operation, and reprocessing. In this case, the total plutonium inventory would be proportional to the total installed reactor power. Figure 1 shows that a PWR must employ multi-recycling of MOX fuel to achieve this and that the timescale for it to be realised is some 50 years. Termination at an earlier date would result in an increase in plutonium. A fast reactor or HTR would be expected to be much more efficient in this respect but, as of today, there is no commercial design available.

8.3 The point is that to realise benefits from a P&T strategy requires long and continuous deployment. Typically, it would not be judged worthwhile unless there were to be a firm future commitment in the UK to nuclear power for at least a century.

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Annex A

PARTITIONING AND TRANSMUTATION AND THE UK NUCLEAR INDUSTRY

A1. This annex is designed to provide a short, straightforward, summary of past and present nuclear activities in the UK and the range of radioactive materials and radioactive wastes to which, in principle, P&T technologies might be applied.

A2. Nuclear activities in the UK go back to the late 1940s and the production of plutonium for nuclear weapons. Electricity production using nuclear power began a few years later. UKAEA, a state-owned organisation, also conducted R&D into fast reactor technology between 1955 and 1993. Both UKAEA and British Nuclear Fuels plc have undertaken the commercial reprocessing of spent nuclear fuels and the latter continues to do so.

Production and reprocessing of spent fuels

A3. All reactor operations give rise to spent (irradiated) nuclear fuel that can no longer be burned in the reactor in an efficient way. Three generations of power reactors have been developed in the UK – Magnox; Advanced Gas-Cooled (AGR); and Pressurised Water (PWR). UKAEA operated two fast reactors. There is, in addition, a range of smaller research reactors. Lastly, there are the Royal Navy submarine reactors. Thus, there is a diverse range of spent fuels.

A4. Most of these spent fuels are not considered as wastes because of the potential for recovery of re-useable nuclear materials – recovered uranium and separated plutonium – in chemical reprocessing plants. There are no plans to reprocess some fuels, such as those used in the Sizewell B PWR and in submarines.

A5. As well as the uranium and plutonium, reprocessing produces liquid radioactive wastes known as raffinates. These pose particular problems, partly on account of their mobility, and they are conditioned by fixing in solid matrices of glass (vitrification) or, less commonly, of cement (cementation). The raffinates consist of fissile products and a range of radionuclides known as “minor actinides”, although reprocessing can be managed so that the latter can be formed into separate waste streams. The most active raffinates, for which vitrification is used, are also known as high level liquid wastes (HLLW) or highly active liquor (HAL).

A6. All of the radioactive materials and wastes described above will continue to pose hazards over the very long-term future. They also pose, for one reason or another, significant practical managements problems. For these reasons, most are

considered to fall within the wider parameters of P&T research and development (the main exceptions being uranium and the reprocessing raffinates suitable for cementation).

Present and potential applications of P&T

A7. P&T can, in principle at least, be applied to un-reprocessed spent fuel, plutonium separated out through reprocessing (if it is not to be re-used), and the minor actinide and fissile products of reprocessing whether conditioned or unconditioned.

A8. Section 2 of the main report made clear that the main two attributes of radioactive materials and wastes used for purposes of assessing the value of P&T technology are radioactivity and radiotoxicity. Plutonium and the minor actinides are highly radiotoxic. Although the fissile products in HLLW and the vitrified product are much less radiotoxic, they contain a very high proportion of the activity originally contained in the spent fuel, and, like spent fuel, require very careful management.

A9. Reprocessing and recycling of plutonium as a nuclear fuel, a process already carried out in the UK, is, in effect, P&T by another name. The degree of practical difficulty associated with the wider application of P&T technology varies. Its application to vitrified HAL would, for example, involve breaking down the glass matrix and separating out the fissile products and the minor actinides. This would appear to pose a significant engineering challenge and the need to control doses to workers would be a major consideration. Similar considerations apply to some spent fuels the integrity of which, while in storage following their removal from the reactor, may have deteriorated, and to unconditioned HAL which is highly hazardous and, as a liquid waste, difficult to handle.

A10. R&D in the UK seems, at present, to be mainly focussed on the minor actinides with the aim of their transmutation into fissile products.

A11. As the main body of this report makes clear, P&T does not apply to ILW or LLW, since the management problems associated with these wastes are predominantly of volume, rather than activity and toxicity.

A12. Overall, the complexity of the range of materials and wastes produced by the UK nuclear industry, the limited amount of waste segregation practiced in the past (so that waste "cocktails" are common), and the impact on their physical condition as a result of past storage and treatment, all mean that P&T research tends to exclude historic materials and waste arisings.

Annex B

THE PARTITIONING AND TRANSMUTATION PROGRAMME IN FRANCE

1. Programme management arrangements

B1.1 The French research programme into radioactive waste management is a requirement of the Law of 30 December 1991. This Law created a framework in which decisions on options for the management of the waste would be deferred for fifteen years, thereby allowing a period during which key research objectives could be pursued. The research programme is required to cover three main areas:

- minimisation of the quantity and toxicity of waste;
- feasibility of deep geological disposal (which includes retrievability);
- packaging and conditioning for safe, long lasting containment, and also studies of long-term surface storage.

B1.2 The French Government receives a report each year on the progress with the programme and the reports are placed in the public domain. A body – the Commission Nationale D'Evaluation – was established for the purposes of reporting. This is a body of twelve eminent people chosen to have a balanced cross-section of expertise. The Commission will be responsible for producing the final report in 2006 and for making appropriate recommendations at that time.

B1.3 Responsibility for the direction of the research programmes is shared between two agencies, Commissariat de l'Energie Atomique (CEA) and Andra. CEA is a large technical organisation that fulfils the role that UKAEA originally occupied in the UK. Andra is the French waste disposal agency. CEA oversees research in the first and third areas listed above while Andra is responsible for the geological studies. Partitioning and transmutation form a substantial part of the waste minimisation programme managed by CEA.

B1.4 CEA operates on many sites. For this reason, its internal research programmes are managed by a matrix system that allows elements of the programme to be conducted wherever the facilities and expertise exist, but with overall direction and co-ordination provided by a central programme management division. For radioactive waste management, the relevant programme management division within CEA is the Nuclear Development and Innovation Division. This Division commissions the work programmes that can be discharged either by CEA

alone, or in conjunction with other organisations, including universities, other research organisations such as the Centre National de la Recherche Scientifique, and nuclear industry partners. Wherever possible, international collaboration is sought. The Director of Nuclear Development and Innovation at CEA is Patrice Bernard.

2. Programme objectives and scope

B2.1 The underlying goal of the P&T programme is to provide a means of reducing the radiotoxicity of current arisings of high level radioactive wastes (HLW) and spent nuclear fuel that have to be managed over the long-term future. It is not aimed at low or intermediate level wastes (ILW and LLW). Nor does it address historic arisings of HLW that have already been vitrified (placed in a glass matrix). The main driver for this is the belief that public acceptability of nuclear power will be aided by a change of perception about the longevity of the wastes.

B2.2 The focus of the French programme on radiotoxicity, as the principal parameter, is useful in the sense that it leads to straightforward determination of the priorities for consideration in the development programme. As the largest contributor to radiotoxicity, the first requirement is to manage the plutonium arisings, followed by the minor actinides. Fission products are of much lower radiotoxicity and are therefore seen as much less important. The method used in France for assessing the potential programme benefits is comparison of the times for the radiotoxicity of the waste to decay to that of the initial uranium. With an open cycle, this is of the order of a few hundred thousand years, but it reduces to about ten thousand years if plutonium is the only material treated, and a few hundred years if the minor actinides are transmuted to fission products.

B2.3 The French emphasis on radiotoxicity differs from that of the UK where mobility of isotopes is seen as being the more important parameter in the context of the safety case for a repository. Within this, prime consideration is given in the UK to groundwater contamination. The French response is that they have already demonstrated very low corrosion rates of vitrified waste, equivalent to 0.1 per cent loss in 10,000 years. In consequence, they view a preoccupation with groundwater contamination from such packages as misplaced.

B2.4 A further key assumption underlying the programme is that France will have a substantial nuclear programme well into a future measured in centuries. This is essential to any justification of the level of investment in research being made, as the full cycle of processes involved with partitioning and transmutation has a long time constant. It will be a decade, or more, before application of technology on an industrial scale could be established and several decades beyond that before a net benefit could be secured.

3. Status of the partitioning programme

B3.1 In terms of the basic nuclear physics, the theoretical possibility of transmuting the main contributors to radiotoxicity has been known for many years. For this to be a practical proposition, however, it is also necessary to be able to separate the various elements. It was the lack of a demonstrated capability to effect this separation that was seen, in 1991, as the main barrier to establishing P&T as a viable technology capable of exploitation on an industrial scale.

B3.2 Considerations of radiotoxicity led CEA to set as a first goal the establishment of the scientific feasibility of extraction of americium, curium, neptunium, caesium, technetium and iodine. As a lower priority, extraction of the most abundant and possibly mobile long-lived fission products – caesium, technetium and iodine have also been investigated. While it is possible for a Purex process to be adapted to extract neptunium, technetium and iodine, new reagents were required to extract the other elements. The significant progress that CEA claim is that in 2001 they successfully achieved separation, on a laboratory scale, of all of their target elements. The experiments were performed on actual solutions of spent fuel and an extraction efficiency of 99.9 per cent was achieved. This required novel reagents to be synthesized for the purpose. To achieve extraction of all elements required in, total, two diamides, an organic acid, and a special chemical of the calixarene family for caesium. This has been reported to the scientific community. CEA's next goal is to demonstrate capability with representative process equipment and to evaluate the economics of industrial implementation. The target for this is 2005, in time for the final report required under the 1991 Law.

B3.3 Scaling up the process to an industrial plant will present major additional challenges. Based on their experience with the development of the reprocessing plant at La Hague, which took ten years from a pilot demonstration to full implementation, CEA estimate that a similar period will be required. On this basis, they could consider construction of an industrial plant to be feasible by 2015. It is the view of CEA that these timescales are conservative as the physical size of the plant will be much smaller than a fuel reprocessing plant – reflecting the very much smaller volume throughput required, i.e., about 0.1 per cent of the 1200 tonnes of fuel throughput (or one tonne per year).

Status of the transmutation programme

B4.1 The issues to be resolved with respect to transmutation are very different. As stated above, the basic feasibility is not in question, but it will be necessary to decide the optimum means of exposing the separated elements to the neutron source and whether this should be in a reactor or accelerator. In addition, exposure to neutrons can cause physical changes in the size and properties of the materials used

to encase the material to be transmuted. Developing targets for exposure to neutrons will be as challenging as developing and proving fuel elements for reactor service. The CEA assumption is that ten years is a realistic timescale.

B4.2 In order to pursue such a development programme, a facility for neutron irradiation is essential. In 1998, France closed its large fast breeder reactor Super-Phénix and, at this time, it became necessary to recommission the smaller Phénix reactor to discharge the work programme. Phénix has now been relicensed for six fuel charges and is expected to operate up to 2008. This is an area where the French are seeking to benefit from European and other international programmes. In particular, the High Flux Reactor (HFR) at Petten (in the Netherlands) has been used for studying transmutation of americium, and the main studies of accelerator driven systems will be in a partnership under the 6th European Programme for Research and Development.

B4.3 The irradiation periods required for transmutation in the experiments in Phénix are long. The experiments relating to the transmutation of minor actinides began in the Phénix reactor in 1995 (transmutation of plutonium was possible from the beginning of operations) and the first series of results will be fully available during 2003–2004. Phénix is now restarting power operations. Non-destructive examination will begin again in 2004. Destructive examination will commence in 2005 and although it is scheduled to continue to 2010, CEA believe that significant results should be available by the end of 2006, thereby meeting the requirement, set out in the 1991 Law, for a report to be delivered by that date.

B4.4 There are many variables to be considered in the design of an overall scheme and it will be necessary to consider these in depth in order that low capture cross-sections of some of the elements to be transmuted do not lead to excessive total cycle time. Scenario studies are therefore an important component of the programme and, until this work has identified a practical scheme, costs will remain uncertain.

5. Implementation options

B5.1 If the words partitioning and transmutation are interpreted generally and the goal is taken as the reduction in the radiotoxicity, a range of possibilities exist for implementation, some of which are available today.

B5.2 Plutonium, as the main contributor, could be considered alone and France is already managing its plutonium arisings through use of mixed-oxide (MOX) fuel in its reactors. At present, 20 reactors are partially fuelled with MOX but this is not enough to achieve equilibrium in plutonium stocks. The position could be improved by introducing MOX into a few more reactors, but an even greater step would result

from construction of a European Pressurised Water Reactor (European PWR) that is capable of 100 per cent MOX loading. This would enable a neutral plutonium cycle.

B5.3 It is possible to transmute americium and neptunium in a PWR. Thus, a further stage of implementation is possible without moving to fast reactors or building sub-critical systems or accelerators. Part of the CEA consideration is the introduction of target elements, containing americium and neptunium, into a European PWR fuelled with MOX. This would not be without cost because it would introduce negative reactivity into the reactor and adversely affect output.

B5.4 To achieve the full reduction in radiotoxicity that is theoretically possible, given the developments in extraction technology, would require a fast reactor programme or other dedicated sub-critical systems to be built.

6. Vision and link to Generation IV

B6.1 The truly visionary strategy is now linked to the Generation IV programme, initiated by the United States, but now run as a shared programme with ten other countries. The UK participates through the Department of Trade and Industry.

B6.2 The rationale behind Generation IV is based on views of energy demand on a worldwide scale. The World Energy Council has projected growth in world energy consumption over the next century and it sees large increases in energy consumption in third world countries in particular. This is seen as unsustainable in the light of concerns over global warming goals without nuclear power providing a significant component.

B6.3 Generation IV responds to this overall picture across the energy spectrum. Aspects that are relevant to nuclear power are not just the need for electrical power directly, but also the need for substitutes for oil to power transport in the form of hydrogen and fuel cells. Accordingly, a development programme is proposed covering a range of reactor systems on a “horses for courses” basis.

B6.4 The World Energy Council scenarios assume exponential growth in nuclear output with the mid-case doubling by 2050. An obvious issue that would arise would be the volumes of waste to be addressed. It is in this context that the French see that partitioning and transmutation technology would be invaluable.

Annex C

EUROPEAN UNION POLICY AND RESEARCH AND DEVELOPMENT INTO PARTITIONING AND TRANSMUTATION

1. Programme management arrangements

C1.1 The policy of the European Union must reflect a reasonable consensus view across its Member States. At present, nuclear power provides about 35 per cent of the European Union's electrical power but attitudes to it differ substantially across Member States. Opinions range from those states totally opposed to nuclear power, through those with significant nuclear capacity but a moratorium on new construction, to those who see nuclear power playing a more significant role in the future. In these circumstances, the topics that all states see as important are those relating to improvements in radioactive waste management, radiological protection, and nuclear safety. It is not surprising, therefore, that these form the basis of the European Commission's research and development programme.

C1.2 The European Commission's policy on radioactive waste management is that deep geological disposal is the preferred solution. It regards this option as safe, but acknowledges that chemical separation and transmutation of the most hazardous radionuclides within the waste have the potential to reduce the quantities of radionuclides to be disposed of and to further enhance the long-term safety of an underground repository. Its application would, of course, depend not only on technical feasibility, but also economic attractiveness. Disposal of the less hazardous low and intermediate level radioactive waste at, or near, the surface is well established and implemented in several countries.

C1.3 However, there are differences of view amongst the Member States about the scale of benefit that might be derived from P&T. Some view P&T as so important that progress with disposal to a repository should be delayed. Others see the potential safety gains as more marginal and, since the technology will take considerable time to establish, that it is more important to begin disposal without delay on the basis that there is the possibility of introducing P&T later. Thus, the early objectives of the European Commission's research programme were to examine the feasibility of P&T and to evaluate the potential benefits, timescales, and costs. The programmes are conducted in laboratories across the Member States, particularly within those with a direct interest in the technology.

C1.4 Work on P&T forms part of the radioactive waste management R&D programme. In the EURATOM Third and Fourth Framework Programmes, it

represented about 15 per cent of total expenditure on radioactive waste management R&D (35 million €), but expenditure on P&T in the EURATOM Fifth Framework Programme was substantially increased. This arose because of a shift in the objectives, giving increased emphasis to more comprehensive transmutation studies, whereas the earlier programmes had been heavily focussed on partitioning and strategic studies (see paragraph C2.5).

2. Programme objectives and scope

C2.1 As part of the wider studies of radioactive waste management, the performance of repositories in three geological host formations (clay, salt and granite) have been assessed. These studies provide the basis for the European Commission's preference for deep disposal as the computed doses resulting from migration of radionuclides are well below internationally recommended limits and the P&T scenarios examined have been shown to have only a minor additional effect – it is soluble, long-lived, fission products that determine the dose. This conclusion changes if a human intrusion scenario is invoked because it can then be shown that benefits arise from an accelerated reduction in the radiotoxicity of the waste.

C2.2 Reduction of radiotoxicity, therefore, has become the main driver for the European Commission's P&T research programme and this is an objective held in common with the French national P&T research programme which has strong links with EU research. The EU programme relates to spent nuclear fuel and unconditioned High Level Liquid Waste (HLLW) arising from reprocessing of spent fuel, and to the recovered uranium and separated plutonium brought about by reprocessing. Its focus is on those elements that are the greatest contributors to radiotoxicity. It is not aimed at low or intermediate level radioactive wastes. Unlike the French, it is the European Commission's view that P&T could contribute to management of some historic spent fuel arisings declared as wastes (i.e., not considered a resource). This is because a number of Member States have not reprocessed their spent fuel, which remains in long-term storage underwater and is suitable for treatment by P&T technology. This differs from the position in France where much of this fuel has been reprocessed and the HLLW conditioned by vitrification.

C2.3 The potential users of the results of the programme are seen as the governmental bodies in Member States, which will find it useful to assess the benefits of P&T for their national programmes of nuclear waste management. These governmental bodies could be the waste management organisations or the safety and regulatory authorities. The nuclear power generation industry is viewed as being less supportive because of the implications for its costs. However, it is thought that the reprocessing industry might be more interested because of the

opportunity to exploit patents for the synthesis of new chemical extractants for the selective removal of particular radionuclides.

C2.4 There has been growing expenditure on P&T in the EURATOM Framework Programmes.

Programme	FP3	FP4	FP5
Expenditure M€	4.8	5	~28

C2.5 Research work on P&T has been carried out in three areas, partitioning, transmutation, and strategic studies. Strategic studies address system design for the integration of P&T capabilities with the aim of maximising the reduction of radiotoxicity achieved. FP3 included work on strategic studies and partitioning only, while all three areas were covered in FP4 and in FP5. The significant cost increases result from the inclusion in FP5 of work on accelerator driven systems (ADSs) for transmutation following the proposals of Professor Rubbia.

C2.6 Around 1990, at the beginning of FP3, it was not clear that chemical separation would be feasible and the early goals sought to demonstrate this on a laboratory scale. It is now generally agreed that this capability has, in principle, been established. The objectives of the research work carried out under FP5 are to provide a basis for evaluating the practicability of P&T on an industrial scale. This programme covers the development of efficient processes for the chemical separation of long-lived radionuclides (i.e., partitioning) as well as the gathering of scientific and technical data necessary to enable a detailed engineering design of an ADS demonstrator (for transmutation) in the next Framework Programme (FP6).

3. Status of the partitioning programme

C3.1 The partitioning programme has three main components:

Development of new partitioning techniques for minor actinides (PARTNEW)

This work programme, initiated as part of FP4, is focussed on demonstration of the capabilities of the DIAMEX and SANEX processes. It is led by CEA but involves several other European laboratories and universities (including the University of Reading). It is regarded as a successful project and several patents have been taken out on the results of FP4 that could be exploited by the reprocessing industry at some future date if P&T is adopted. On the basis of work to date, it is now regarded as possible to separate minor actinides from HLLW in quantities of the order of 10 g using solvent extraction processes.

Selective separation of long-lived nuclides by functionalised macrocycles (CALIXPART)

CEA is again the co-ordinator of this programme supported by a number of others, most of which are university departments. The CALIXPART work, dating from FP3, has involved use of computer codes for modelling that are currently used in the pharmaceutical industry to develop new drugs. This pioneering work in radiochemistry has already shed light on some of the mechanisms involved in liquid-liquid extraction. In particular, computations indicate that calixarenes can be tailored for a particular purpose and success has been achieved in demonstrating the separation of caesium. In FP5, the radiolytic and hydrolytic degradation of the solvents will be studied and more innovative extractants will be synthesised with the aim of achieving the direct extraction of minor actinides from HLLW.

Study of pyro-chemical separation techniques (PYROREP)

A strategic study in FP4 recommended that European expertise in pyro-chemical separation techniques should be acquired as a possible method for reprocessing fuels loaded with higher actinides. BNFL is an active partner in this project. CRIEPI is also a partner as the project forms a significant component of the Japanese programme.

4. Status of the transmutation programme

C4.1 Studies on transmutation in FP4 were fairly limited. There were, in essence, two experiments. One examined the transmutation of Americium-241 in a matrix composed of a magnesium aluminate spinel. This revealed mechanical strength problems associated with helium release at high burn-up. The second was a study of the energy distribution in neutrons produced by spallation. The conclusions of the P&T strategic studies, together with the results of these experiments, indicated that the feasibility of ADS needed to be more thoroughly investigated. It was suggested that studies should cover many aspects including safety, neutronic behaviour, nuclear data, radiation damage, compatibility of liquid lead with structural metals, accelerator reliability and, of course, a preliminary engineering design of an ADS. In addition, R&D on fuels and targets for transmutation of long-lived radionuclides and plutonium burning was seen as important.

C4.2 A thematic network on Advanced Options for P&T, ADOPT, is co-ordinating the FP5 R&D activities on P&T. The partners of ADOPT are European research organisations and industries. The objectives of this network are to promote consistency between FP5 projects and national programmes, to review the overall results and to identify gaps, to raise future research proposals, and to maintain

relations with international organisations and countries outside the EU involved in P&T and ADS development.

C4.3 The transmutation research work is mainly focused on the ADS assessment. The main item is a preliminary design study of an experimental ADS, but it also includes necessary work programmes to provide the basic physics data, understanding of potential failure mechanisms and the design of fuels.

C4.4 The preliminary design studies are aimed at selecting the most promising technical concepts. This will help to define the safety and licensing issues and identify research and development needs. It will also enable preliminary cost estimates to be made. Two types of accelerator are being investigated, a cyclotron and a linear accelerator (linac). For the spallation target, two main options are considered depending on whether or not the target liquid heavy metal is separated from the accelerator by a physical barrier (window). Three concepts for the sub-critical core are included: a small core of about 20–40 MW cooled by lead-bismuth eutectic (LBE), a larger core of approximately 80 MW cooled by LBE, and a gas-cooled core.

C4.5 The project should be complete at the end of 2004 at which time it should be possible to begin to plan a more detailed engineering design. It should be remembered, however, that feasibility studies are much cheaper than detailed design and that actual construction is even more expensive. If the programme is to continue beyond 2004, there will need to be a very substantial increase in the budget. No thought has been given to this as yet.

5. Implementation options

C5.1 The options outlined below derive from work carried out as part of strategic studies in FP4.

C5.2 The neutron flux to cause transmutation can be provided by either a power reactor or an ADS. The European Commission is not in a position to comment on the optimum implementation strategy as the Member States have different positions with regard to their future nuclear power programmes and therefore no unique optimum strategy exists. However, the strategic studies that have been undertaken indicate what would be feasible in any individual case.

C5.3 The greatest reduction in radiotoxicity of the waste is obtained through use of plutonium as a fuel. Plutonium is used today in the form of MOX fuel in standard Light Water Reactors (LWRs) to produce electricity. The plutonium consumption could be increased in highly moderated LWRs or in Fast Neutron Reactors (FNRs). The strategic studies undertaken by the European Commission as

part of FP4 show that the multiple recycling of plutonium with neptunium and americium is not possible with highly moderated LWRs alone. However, this recycling seems quite feasible in FNRs. It would reduce the radiotoxicity of the waste inventory by a factor of 10 to 20 (depending on the cooling time) after 150 years of operation with respect to the "once-through" cycle. Further decreases in radiotoxicity could be achieved if the americium transmutation yield was enhanced and the curium also transmuted. For this purpose it is suggested that ADSs would be required.

C5.4 The preliminary assessment of ADSs for transmutation purposes provides guidance on what this might involve. Neutronics studies indicate that fast spectrum and liquid lead (or lead-bismuth) cooled, solid fuel, ADSs have a very large neutron surplus, which would be attractive for transmutation purposes. However, the studies have also revealed some problem areas where further work will be necessary before a full evaluation can be undertaken. The main concerns are:

- the predictive power of high-energy transport codes containing an intra-nuclear cascade model becomes suspect for energies below about 150 MeV and there is a need for accurate nuclear data libraries at these energy levels;

- materials data are also required to assess the radiation damage of the target window for an ADS and hence its lifetime;

- a reliability study of the Los Alamos linac revealed that it had about 40 to 60 trips per day (75 per cent of them being shorter than 1 minute). This is considered to be almost four orders of magnitude more than would be acceptable for a commercial installation. A reduction in the number of trips by a factor of l00 is thought to be achievable with today's technology.

C5.5 From the European Commission's perspective, it seems clear that it is the transmutation aspects that will determine the timescale for implementation of P&T systems. In common with others, it is estimated that a commercial partitioning plant could be in operation by 2020. However, a transmutation capability might lag behind this by a decade or so. Indeed, because the problems to overcome are numerous, it is possible that the timescale could be even more protracted.

C5.6 These concerns over the timescales for development of a "full" transmutation capability would not apply if the ambitions were more limited e.g., to accept the benefits that could be obtained from a fast neutron reactor alone. However, this would obviously restrict the application of P&T to those states with an ongoing nuclear programme.

C5.7 With regard to cost estimates obtained as part of a FP3 strategic study, it is believed that P&T would add 30 per cent to fuel cycle costs – equivalent to about 10 per cent on nuclear generation costs. This figure assumes that a fleet of fast reactors will exist whose full costs are covered by income from the electricity they generate i.e., there is no penalty from the loss of neutrons to the transmutation process. In Member States with no ongoing nuclear programme, dedicated accelerator systems would be required to process all the wastes and such ADSs would have small, if any, revenue stream to support their cost. For them, P&T costs could be very expensive.

6. Vision and link to Generation IV

C6.1 The European Commission acknowledges that to become fully effective, any change in fuel cycle management must be implemented for several decades. In other words, there is an implicit assumption that nuclear energy will be used for a long period of time.

C6.2 Thus, P&T only looks sensible for those states committed to nuclear power. The European Commission has included investigation of possible future nuclear systems in its nuclear programme, using a small part of its budget. Such studies should be an essential companion to any P&T research programme, but the European Commission believes that care has to be taken not to let the two research programmes overlap in order to protect the interests of non-nuclear Member States and those drawing back from nuclear energy. In order to enable some consideration of such issues, it is proposed that the European Commission participates as a full member in the Generation IV International Forum, initiated by the United States, but now a shared programme with ten nations. The UK participates in Generation IV through the DTI.

C6.3 The rationale behind Generation IV is based on views of energy demand on a worldwide scale. The World Energy Council has projected growth in world energy consumption over the next century and it sees large increases in energy consumption in the third world countries in particular. This is seen as unsustainable in the light of concerns over global warming goals without nuclear power providing a significant component.

C6.4 Generation IV responds to this overall picture across the energy spectrum. Aspects that are relevant to nuclear power are not just the need for electrical power directly, but also the need for substitutes for oil to power transport in the form of hydrogen or fuel cells. Accordingly, a development programme is proposed covering a range of reactor systems on a “horses for courses” basis.

C6.5 The World Energy Council scenarios assume exponential growth in nuclear output with the mid-case doubling by 2050. An obvious issue that would arise would be the volumes of waste to be addressed. It is in this context that P&T technology is viewed as potentially useful.

Annex D

THE PARTITIONING AND TRANSMUTATION PROGRAMME IN JAPAN

1. Programme management arrangements

D1.1 The first reference to P&T technology in relation to treatment of long-lived and other nuclides appeared in the Japanese *Long-term Programme for Nuclear Research, Development and Utilisation* in 1972. At that time, the aim of the programme was simply declared as "*to ensure effective processing of radio-active waste*."

D1.2 An updated nuclear programme was issued in 1987 that reaffirmed the importance ascribed to P&T for the purposes of recycling High Level Waste (HLW) and enhancing disposal efficiency. It identified JAERI, the then Power Reactor and Nuclear Fuel Development Corporation PNC, (now JNC) and others as the agents to discharge an R&D programme. CRIEPI (Central Research Institute of the Electric Power Industry) is involved.

D1.3 Further details of the programme, as seen at that time, were spelled out in 1988 in a report by the Japanese Atomic Energy Corporations' (AEC's) Advisory Committee on Radioactive Waste Measures entitled *Long-term Programme for Research and Development on Nuclide Partitioning and Transmutation Technology*. This is known as the OMEGA programme. It presented a plan for R&D that ran from 1988 to 2000, divided into two phases. The first phase, that was to run for the first four to nine years, covered evaluation of the various concepts together with research on all aspects of the underlying technologies. The second phase, also seen as being of four to nine years duration, was envisaged as moving the technology on to an engineering demonstration level.

D1.4 JAERI, JNC and CRIEPI are the active participants in what is a very broad programme covering a wide range of technologies and elements to be considered for transmutation. It includes studies of the both partitioning and transmutation processes as well as reviews of the overall transmutation cycle and development of fuels or targets that contain the elements to be transmuted.

D1.5 Evaluations of each technology were scheduled for the mid-1990s with the aim of determining how to proceed thereafter. The AEC's Advisory Committee on Nuclear Fuel Cycle Back-end Policy undertook these reviews and the outcome was summarised in a report entitled "*Research and Development of Technologies*

for Partitioning and Transmutation of Long-lived Nuclide Status and Evaluation Report" which was issued in March 2000.

2. Programme objectives and scope

D2.1 The declared objectives of the Japanese programme are very broad and include almost all the areas of potential benefit from P&T. The programme is justified at the highest level simply because it is regarded as a social imperative to minimise, as far as possible, the generation of hazardous waste produced by industrial activities.

D2.2 The programme is focussed on future arisings of HLW, particularly spent fuel. It does not encompass less active wastes or historic arisings. Reduction of the long-term radioactive inventory through the removal of long-lived nuclides from HLW by P&T technology is regarded as the prime means of achieving hazard minimisation. Therefore, in common with the French, reduction in radiotoxicity is a key objective. The potential gain in this respect is illustrated by a claim that, if 99 per cent of minor actinides contained in spent fuel can be removed, the radiotoxicity of that spent fuel will fall to the level of the natural uranium used in the production of the original fuel after only several hundred years. It is interesting to note that the claim makes no reference to the benefits of separation and transmutation of plutonium. This is because the nuclear future in Japan is seen as being heavily based on plutonium-burning fast reactors (see paragraph D4.2 below).

D2.3 Another aspect of the long-term vision in Japan is a commitment to geological disposal of waste. Thus, evaluation of the benefits that P&T could bring to the long-term safety of a repository is also an important objective. Three aspects are considered in the programme:

- benefits through reduction in potential doses to the public through contamination and migration of groundwater;
- similar reductions in the risks arising from possible human intrusion at some future date;
- shortening the period of storage for HLW and reduction in the size of a repository required through removal of those elements contributing most to heat generation, that is, caesium and strontium.

D2.4 A further objective is consideration of recovery of "valuable resources." The example given is platinum that has a growing market as a catalyst for reduction of nitrogen oxides in vehicle exhaust gases. A key issue to be resolved in this area is the free release of materials that have been extracted from HLW.

3. Status of the partitioning programme

D3.1 The first phase of the Japanese programme examined a range of partitioning processes with different research institutes taking responsibility in the different areas.

D3.2 JAERI developed chemical techniques in which the elements were separated into four groups:

1. Minor actinides

2. Technetium and platinum group metals

3. Strontium and caesium

4. Others.

D3.3 Initial experiments used simulated High Level Liquid Waste (HLLW) in order to establish the concept, but some tests have been conducted on actual HLLW. They have been on a limited scale of 1/1000 of that expected for an actual plant. A recovery rate for minor actinides of 99.95 per cent or better is claimed, but performance figures for the other groups are not known.

D3.4 JNC focused on developing an improved PUREX process, an advanced version of conventional reprocessing, to recover neptunium. It is also developing a CMPO-TRUEX process to separate minor actinides. To separate technetium and platinum group metals and other elements from aqueous reprocessing solutions an electrolytic extraction method is being developed. Performance figures for the CMPO-TRUEX process research have been published where recovery levels of 99.9 per cent or more for minor actinides are claimed. Again this is laboratory scale work.

D3.5 CRIEPI is developing a reductive-extraction process using molten chlorides and liquid metal solvents for the separation of transuranics (TRUs). Experiments were carried out on a very small scale using some 10 milligrams of TRUs and some 100 grams of chlorides. These achieved recovery rates of more than 99 per cent of the TRUs.

D3.6 The Japanese view phase I as having met its objectives. The research at all three institutes has established processes for partitioning with the "expected performance." However, phase II objectives include a number of goals that suggest that some fairly basic problems remain to be resolved. For JAERI and JNC, which are developing aqueous partitioning processes, these include development of a

method to more efficiently separate minor actinides and rare-earth elements, and technologies to reduce the volume of secondary waste. For CRIEPI, where dry partitioning is being developed, there are technical issues with the handling of molten chlorides, material development, and molten-salt transport technology.

D3.7 Phase II of the programme has been delayed while a review of the fast breeder reactor programme has been undertaken and facilities to handle minor actinides and other materials have yet to be constructed. The principal objectives of future partitioning work, common to the forward programme of all three institutes, is scaling up the processes to a demonstration plant level and evaluation using actual HLLW. Clearly, this will take time and not be without difficulty and considerable expense. Much greater emphasis is now being placed on international collaboration in order that experimental facilities – including those for engineering experiments – can be used efficiently.

4. Status of the transmutation programme

D4.1 The feasibility of transmutation, from a basic nuclear physics perspective, is not in question and the goals of the phase I programme were to aid decisions with regard to the means of exposing the separated elements to the neutron source and to develop the fuels or targets needed for this purpose.

D4.2 There are different strategies implied by the programmes of the three institutes with regard to the neutron source to be used for transmutation. JNC and CRIEPI are studying transmutation technology using fast breeder reactors. In this concept, the aim would be to use fast reactors in which power generation and the transmutation of minor actinides and other elements contained in the fuel is carried out simultaneously. In contrast, JAERI's concept is the "double strata fuel cycle", where a dedicated system for transmuting minor actinides, such as an actinide burner fast reactor (ABR) or an accelerator-driven subcritical system (ADS) is employed. This would allow a commercial power generation cycle and a transmutation cycle to be optimised independently.

D4.3 With regard to facilities for neutron irradiation, Japan has a small experimental fast reactor "Joyo" that is being used. However the main facility to support the JNC/CRIEPI approach was intended to be "Monju," a MOX fuelled prototype fast reactor. This is central to the Japanese fast breeder programme and was built some time ago, but it has had a chequered history and was closed almost ten years ago following discovery of sodium leaks. However, in December 2002, the Minister of Economy announced the intention to modify the plant in order that it could return to operation. The reason given for this decision was to enable research and development in which the transmutation programme is a key element. More recently, the decision has been successfully challenged in the courts and this

is currently the subject of an appeal by Government. Until this is resolved, facilities to support transmutation studies are limited.

D4.4 The position on the accelerator driven approach of JAERI is more positive. Here a proton accelerator has been developed.

D4.5 Meanwhile, much of the work in support of transmutation has been restricted to the development of fuels and targets and the means of processing them after exposure.

D4.6 JNC is developing fuel in which neptunium and/or americium is added to the MOX fuel and would plan to use the same methods for its processing as for partitioning. CRIEPI is engaged in studies of the concept of metallic fuelled reactors and is developing metallic fuel in which minor actinides are introduced into a uranium-plutonium-zirconium ternary alloy. This work is part of an international collaboration and fuel pins have been made on a trial basis, enabling physical characteristics and other basic data to be determined. It has been shown that a minor actinide content of about 5 per cent does not affect the characteristics of the fuel. With regard to processing, molten-salt electro-refining and reductive extraction technology are being studied that are similar processes to those used for partitioning. This is now said to be at the stage of engineering experiments.

D4.7 For its programme, JAERI is developing minor actinide-nitride fuel. It was confirmed that the minor actinide nitrides could be prepared by means of carbothermic synthesis and that uranium nitrides microspheres can be produced via the sol-gel process. In addition, through irradiation tests of U-Pu mixed nitride fuel, produced on a trial basis, it was ascertained that the fuel element was intact after a burn-up of 5.5 per cent. Pyrochemical processing is envisaged.

5. Implementation options

D5.1 No decisions have been taken regarding the use of power-generating fast reactors or the double-strata fuel-cycle concept. These are seen as having their own distinctive features that suggest that, at this stage, it is appropriate to continue the development of both. In fact, future studies include scenarios that blend these two concepts, in order to introduce a feasible P&T technology system into the nuclear fuel cycle.

D5.2 It is acknowledged that, even if P&T technology is employed, some minor actinides and long-lived fission products will remain in the waste, and final disposal of such waste will eventually be necessary. The key questions yet to be resolved relate to the balance of plant to be used and the timescales over which it must

operate. At present, only generalised observations can be made that will bear on the ultimate proposals e.g.,

- an oxide-fuelled or metallic-fuelled fast reactor can transmute minor actinides from more than five or six light water reactors (LWRs);

- an accelerator driven system with one quarter of the thermal output of a LWR can transmute minor actinides from more than ten LWRs (about 250 kg per year).

D5.3 R&D to date has focused on basic studies to obtain fundamental data for designing processes and systems, and no serious work has been undertaken to support a reliable cost estimate for the P&T technology. It is not envisaged that development to an engineering demonstration level could be completed before 2015–20 and that implementation of a practical plant would not be before 2020–30. Nevertheless, very preliminary cost estimates produced by all three institutes indicate that it would add a few percentage points to the cost of electricity generated by LWRs.

6. Vision

D6.1 Japan remains one of the few nations with a very strong commitment to nuclear power and its vision in this respect is unchanged from that of the early pioneers of the nuclear industry. It retains a strong interest in reprocessing technology and sees the introduction of fast breeder reactors as part of a logical evolution. At present, a feasibility study on commercial fast breeder reactors and their related fuel cycle system is being carried out collaboratively by JNC, the electric utilities, CRIEPI and JAERI. The outcome will be reviewed by about 2005.

D6.2 P&T technology is regarded as inseparable from the nuclear fuel cycle, and it is therefore seen as appropriate to conduct R&D in this area on a compatible time schedule. Thus, 2005 is deemed to be an appropriate time to consider options for P&T. Thereafter, reviews might be undertaken every five years or so.

D6.3 On a different level, the Japanese consider research into P&T (and transmutation in particular) as being important fundamental studies in their own right. They see that the ability to transform materials at the atomic level has potential that is not necessarily limited simply to applications in radioactive waste management. They see it as an exciting research area that will attract talented young scientists to the nuclear field and thus help to maintain the vitality of their nuclear programme.

Annex E

THE PARTITIONING AND TRANSMUTATION PROGRAMME IN THE USA

1. Programme management arrangements

E1.1 Unlike France and Japan, the USA does not reprocess spent fuel from power reactors. It was the intention to do so at the outset of the programme of reactor construction and three companies were commissioned to build reprocessing plants, Allied Chemical, General Electric, and Grace Chemical. Only one of these, that at Grace Chemical, progressed as far as active commissioning but that was terminated shortly afterwards. Reprocessing was formally abandoned in 1993. As a consequence, spent fuel remains in its zirconium alloy cladding and is stored underwater.

E1.2 In the USA, liabilities for disposing of spent fuel reside with the Department of Energy (DoE). The arrangement is one where the DoE owns the fuel throughout its lifecycle and leases it to the electricity utilities for the purposes of power generation. In return, the utilities make payments that reflect the value of the energy extracted. The current proposal for dealing with this fuel is that it should be accommodated in chemically protective containers and stored underground in a repository. It is the responsibility of the DoE to identify the site for the repository, develop the design and safety case, and operate the repository, though it will discharge these responsibilities by means of contracts with others.

E1.3 The repository site that has been chosen is at Yucca Mountain and it is planned that 90 per cent of its capacity will be used for spent fuel from the civil reactor programme (45,000 metric tonnes), the other 10 per cent being reserved for military wastes (5,000 metric tonnes). Considerable progress has been made in examining the design of a repository and establishing the safety case. The regulator (the Nuclear Regulatory Commission; NRC) has a list of several hundred items of technical concern that it wishes to see resolved. Recently, the programme has been given new impetus by the Bush administration, but the rate at which these technical issues are being resolved remains too slow for the target date of December 2004 to be met. Indeed, the license application remains to be submitted. It is not clear when waste disposal will actually begin, but informal estimates suggest a date a decade or so later than the current official target. If this proves to be true, it gives rise to an interesting coincidence. The capacity of the Yucca Mountain repository (63,000 tonnes) will match the spent fuel inventory only up to 2015. Thus, in principle, the capacity of Yucca Mountain will be fully allocated by the time it begins operation.

E1.4 On the reactor front, NRC is licensing life extensions for many nuclear power plants well beyond 2015. There is renewed interest in nuclear power in the USA and it is likely that new plants will be constructed. This opens a question about the management of future wastes. Gaining public acceptance for Yucca Mountain has not been easy and, given today's level of concern for protecting the environment, it might be expected that it could prove even more challenging to find the additional repository site, or sites, which would be required to manage the resulting wastes. Potentially, there could be a need for several schemes of the size of Yucca Mountain. It is this issue that is now driving interest in P&T research in the USA.

E1.5 The USA's early interest in nuclear fuel reprocessing meant that the Federal Laboratories already had expertise in that area. Although there was no active interest in applying the technology, work on P&T continued at Los Alamos National Laboratory, funded under the discretionary element of the Laboratory Director's budget. One outcome was that, in the early 1990s, scientists were able to stimulate political interest in the opportunities that P&T might offer. This followed a study by the National Academy of Sciences, partly funded by the DoE, undertaken from 1991 to 1995. The report (the "Green Book" study) was issued in 1995 and contained some very significant conclusions.

E1.6 The conclusion of the report most relevant to this RWMAC study was that although P&T could offer some benefits, it could not obviate the need for a spent fuel repository, nor could it be shown to be economically competitive with the once-through fuel cycle (provided that costs for additional repository capacity were not an issue). Accordingly, it was recommended that the Yucca Mountain project should proceed to the planned timescale. The benefits that P&T might produce related to improvements in the performance of a repository, namely its capacity, measured in terms of the number of spent fuel elements, waste from which could be accommodated in the repository in a transmuted or modified form. Currently, it is believed that the potential increase in repository capacity is by a factor of at least 10 and possibly significantly more, perhaps 50–60.

E1.7 The National Academy of Sciences (NAS) report recommended that research into P&T should be initiated and this eventually gave rise to the current DoE programme. The fast breeder reactor programme in the USA had closed in 1993 and, perhaps because of this, attention focused attention on the potential use of accelerator driven systems (ADSs) as the means of effecting the transmutations. Following this, Congress commissioned a study by DoE into the use of such systems in 1999. This was the genesis of a new and evolving programme of work that has developed and changed direction significantly during its relatively short lifetime. An important conclusion from the first examination of ADSs was that, if accelerator systems alone were to be used, 64 installations of 800MW each would

be required to tackle the scale of the problem presented by the existing spent fuel. This, coupled with a sceptical view about the reliability of such systems, has stimulated a change in the programme to give it much broader objectives – allowing it to take an overview of the total fuel cycle. Under this remit, opportunities for transmutation in existing thermal reactors and possible future fast reactors are now being examined. The overall cost of the programme in 2002 was $80 million.

2. Programme objectives and scope

E2.1 The declared objective of exploiting P&T to extend the capacity of the Yucca Mountain repository differs from that of both the Japanese and French whose primary aim is a reduction in radiotoxicity of the waste. However, this does not mean that there are no overlaps and, indeed, there are many common elements in the detailed technical requirements that need to be satisfied.

E2.2 The central objective is to reduce the heat generated by the wastes so that more can be accommodated within the thermal constraints provided by the safety case. The safety case requires that surface temperatures in the repository cavities should not exceed 200° C and that the temperature at the mid-point between cavities should not exceed 96° C. The reason for the former is to prevent degradation of the rock and for the latter to ensure that boiling does not take place and water flow remains possible. To meet this objective, it is important to remove the americium, as it is a very significant heat source.

E2.3 The preferred option for partitioning is to use an aqueous process. Figure 1 shows a simplified outline scheme indicating the main stages in the overall cycle and the treatment that it is planned to apply to the waste streams. Pyrochemical separation techniques are being pursued as a backup option.

E2.4 The first stage involves the separation of technetium and iodine, as these are highly mobile nuclides that have a significant impact on other aspects of the overall safety case for the repository. (They are, for example, the most important contributors to dose at 25,000 years.) It is planned to develop a transmutation process for these elements. Almost certainly, this would require a dedicated accelerator. As Figure 1 shows, there is a reserve position if this proves to be difficult. Under this position, these nuclides would be immobilised for disposition.

E2.5 The major stage uses a UREX+ process. This is a modification of the established PUREX process, used by British Nuclear Fuels plc, in which the extraction of plutonium is inhibited. The extract at this stage is very high purity depleted uranium that could either be added to other highly enriched uranium and used as a fuel or disposed of as LLW.

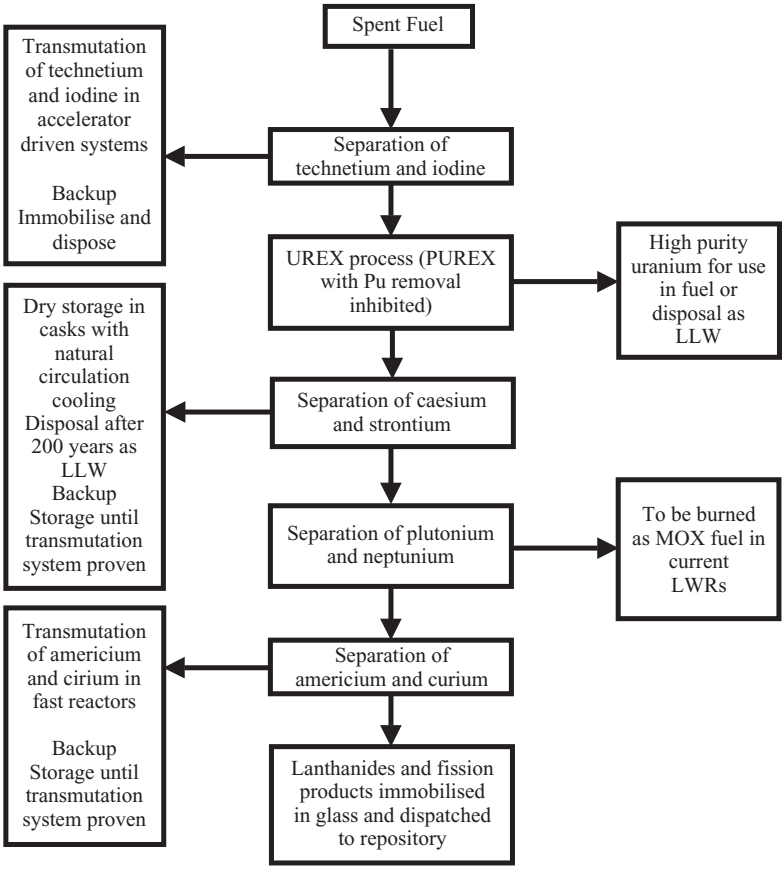

Figure 1. Stages in the proposed US fuel cycle

E2.6 A new process for the removal of caesium and strontium which pose shorter-term heat generation problems for Yucca Mountain would be introduced. However, it would not be proposed to transmute the extracted nuclides, as they could be dry stored and disposed of as LLW after 200 years.

E2.7 The next target nuclides would be plutonium and neptunium. The plan is that these would be incorporated into MOX fuels and burned in the existing power reactors.

E2.8 A key stage for meeting the heat generation capacity goal is the extraction and transmutation of americium and curium as the nuclides that will give rise to heat-loading over the longer-term. As indicated above, it is now believed that the most efficient way of achieving the transmutation of these nuclides would be in existing power reactors or future commercial fast reactors.

E2.9 It would not be proposed to transmute the lanthanides nor the fission products because they are minor contributors to heat generation. These would be vitrified and disposed of in the repository.

E2.10 The pyrochemical partitioning process would not involve all the separation stages – some heat-generators, and also plutonium, would be retained. But the end product, a metal waste form, is thought to be of the order of 100 times more restrictive than glass in preventing the escape of key radionuclides.

3. Status of the partitioning programme

E3.1 The difficulties in developing partitioning technology are no less challenging because the focus is on reduction of heat generation rather than radiotoxicity. There is clearly much international exchange between the countries pursuing P&T in these areas, but there are differences in the approach being adopted in each one.

E3.2 The core of the US proposal is the UREX+ process. This modified PUREX process can be regarded as already largely established. The areas where special developments are still needed are in the extraction of nuclides other than uranium and plutonium. The claim made is that all the necessary separations have now been demonstrated on a laboratory scale. This puts the US technology on a par with other countries. The next stage of development is to prove these processes in a pilot scale plant with a throughput of 10 tonnes per annum. The target date for achieving this is 2008–2011 though this may be an ambitious goal.

E3.3 The current plan would require construction of a full scale reprocessing plant, with a throughput of 3000 tonnes per annum, between 2015 and 2025. This provides for a considerable margin for delay caused by unforeseen problems arising with the pilot plant, that need to be resolved. On this basis, it may be judged to be an achievable goal and, again, is broadly in line with the plans of other countries.

4. Status of the transmutation programme

E4.1 In the transmutation area, the USA derives some benefit from its basic objective of reducing the heat generation capacity of the wastes to be consigned to the repository. From Figure 1, it is clear that not all waste streams are to be

subjected to transmutation. Further, because the volumes of waste intended for transmutation will be relatively small, a period of storage after extraction and before transmutation is seen as a realistic possibility. This enables a very pragmatic approach to the overall cycle and effectively decouples the timescale for establishing the partitioning pilot plant from that of demonstrating transmutation capability. The time period between the two could, if necessary, be extended.

E4.2 The important aim that must be achieved relatively early is demonstration of the ability of the current reactors to accommodate and utilise MOX fuels containing plutonium and neptunium. The overall goal is to manage the inventory of these materials so that it is reduced to the minimum level necessary to maintain an ongoing nuclear power programme. Reactor physics will dictate that multiple cycles for burning MOX fuel will be required. Whilst there is growing confidence around the world regarding the acceptable performance of these fuels in reactors, there are issues relating to both reactor physics and reprocessing that require resolution before such multiple cycles can be said to be a proven option.

E4.3 Apart from the burning of plutonium and neptunium, the overall cycle includes two other stages of transmutation. It is proposed that a fast reactor should be used to address americium and curium and an accelerator to address technetium and iodine. As indicated above, only removal of americium and curium is an absolute requirement from the heat generation capacity viewpoint. Technetium and iodine have been included because of the mobility of the nuclides and their impact on other aspects of the safety case, but are of a second-order of consideration and, with caesium and strontium, might ultimately be dealt with in different ways.

E4.4 The nuclear physics of transmutation is not in doubt, but development work is required to establish the form in which these nuclides should be introduced into the reactor or accelerator. Experimental exposures also need to be carried out to demonstrate that the nuclides will remain stable in the reactor and that all radioactive species will be contained. This can only be done in a facility capable of producing neutrons or protons with the appropriate energy levels. Unfortunately, the USA does not have such facilities at present. Two experimental programmes are therefore planned. Some materials are being exposed in thermal reactors but, because the neutron energy spectrum will be incorrect, these will have only limited value. In addition, some experiments are planned that will be conducted in the restarted Phénix fast reactor in France. However, this facility has only a limited lifetime (it is due to close in 2007). Experiments are also taking place at the Idaho Advanced Test Reactor. New facilities will be needed to fully validate the capability.

E4.5 It may be concluded that fully proving the transmutation aspects will lag behind the development of the partitioning capability. However, before commitment

can be made to investment in a reprocessing/partitioning plant, it will be essential to have confidence that the essential transmutations are achievable. This will require further work between 2003 and 2015. A report on transmutation capabilities and costs is due to go to Congress shortly.

5. Implementation options

E5.1 No immediate decisions are required in relation to the overall waste disposal strategy. The Yucca Mountain scheme is required whatever the outcome from the P&T programmes and this will proceed.

E5.2 The first major decision will relate to the construction of a reprocessing/transmutation plant. This cannot be taken in advance of the completion of the pilot plant programmes nor before the successful demonstration of multiple cycles for burning MOX fuels. But it will, indeed, be a major decision. Conservative preliminary estimates of the cost of the plant, with 2,500 tonnes per year reprocessing capacity and commensurate mixed-oxide fuel fabrication capabilities are $12–15 billion.

E5.3 The DoE will bear the cost of these requirements because disposal of spent fuel is its responsibility. The charge to the electricity generating utilities to cover the cost is $0.001 per kWh. Estimates of the cost of the Yucca Mountain scheme are four times this level. A goal for the P&T programme is to bring costs down to a level where they are fully recovered through the charge to the utilities. Increasing the capacity of the Yucca Mountain repository by a factor of ten will obviously contribute positively to this, but needs to be balanced against the scale of investment needed in the reprocessing plant.

E5.4 The current intention of transmuting americium and curium in a fast reactor has developed because it would require only a few commercial scale plants instead of a very large number of accelerators. The USA had abandoned the development of fast reactors, but this decision has been re-examined as part of the recent energy strategy review. Development of fast reactors is now an integral part of the Generation IV programme. However, if only one plant is built to support the P&T strategy, the full development costs would need to be borne by that one plant.

E5.5 The options to employ a period of storage before disposal that are built into the management plans for the transmuted wastes provide a large amount of flexibility with regard to these aspects of the programme. No early decisions are necessary provided that the ability to achieve the end-point is seen to be secure.

6. Vision and Generation IV

E6.1 Nuclear power is now embedded much more strongly in the forward energy programme of the USA – which has been termed Generation IV. This programme was initiated by the USA, but is now run as a shared programme with ten other countries. The UK participates through the DTI.

E6.2 The rationale behind Generation IV is based on views of energy demand on a worldwide scale. The World Energy Council has projected growth in world energy consumption over the next century and sees large increases in energy consumption in third world countries in particular. This is seen as unsustainable in the light of concerns over global warming goals unless nuclear power provides a significant component.

E6.3 Generation IV responds to this overall picture across the energy spectrum. Aspects that are relevant to nuclear power are not just the need for electrical power directly, but also the need for oil substitutes used in transport applications, e.g., use of hydrogen and fuel cells. Accordingly, a development programme is proposed covering a range of reactor systems on a "horses for courses" basis. Several fast reactor systems have been included because of the now perceived need to support the P&T option.

E6.4 The World Energy Council scenarios assume exponential growth in nuclear output with the mid-case doubling by 2050. An obvious issue that would arise would be the volumes of waste to be addressed. The USA approach to repository design could have broader international relevance.

Appendix 1

MEMBERSHIP OF THE RWMAC PARTITIONING AND TRANSMUTATION WORKING GROUP

Dr Les Mitchell (Chairman)

Professor Andy Blowers

Professor Keith Boddy

Mr David Bonser

Professor Gregg Butler

Dr Martin Courtis

Dr Wynne Davies

Appendix 2

Details of meetings held

20 December 2002	British Nuclear Fuels plc, in Risley
6 March 2003	CEA, in Paris
8 April 2003	European Commission, in Brussels
30 June 2003	US Department of Energy and the Argonne Federal Laboratory (managed by the University of Chicago), in Washington D. C.