

Nuclear Development

ISBN 92-64-02296-1

French R&D on the Partitioning and Transmutation of Long-lived Radionuclides

**An International Peer Review
of the 2005 CEA Report**

© OECD 2006
NEA No. 6210

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 30 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities takes part in the work of the OECD.

OECD Publishing disseminates widely the results of the Organisation's statistics gathering and research on economic, social and environmental issues, as well as the conventions, guidelines and standards agreed by its members.

* * *

This work is published on the responsibility of the Secretary-General of the OECD. The opinions expressed and arguments employed herein do not necessarily reflect the official views of the Organisation or of the governments of its member countries.

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full member. NEA membership today consists of 28 OECD member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, the Republic of Korea, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

© OECD 2006

No reproduction, copy, transmission or translation of this publication may be made without written permission. Applications should be sent to OECD Publishing: rights@oecd.org or by fax (+33-1) 45 24 13 91. Permission to photocopy a portion of this work should be addressed to the Centre Français d'exploitation du droit de Copie, 20 rue des Grands Augustins, 75006 Paris, France (contact@cfcopies.com).

FOREWORD

An important activity of the OECD Nuclear Energy Agency (NEA) in the field of radioactive waste management is the organisation of independent, international peer reviews on national studies and projects. Member governments have found these reviews of significant value and are now asking for them to cover topics of a broader scope. The independent NEA peer reviews help national programmes to assess work accomplished. The reviews' comments on issues of general relevance are also of potential interest to other member countries.

The French Government requested that the NEA organise an international peer review of the “2005 Report: Partitioning and Transmutation” by the *Commissariat à l’énergie atomique* (CEA). The scope and objectives of the review were laid out in the Terms of Reference. According to the review’s Terms of Reference, the OECD/NEA Secretariat established an International Review Team (IRT) made up of ten international specialists, supported by members of the NEA Secretariat knowledgeable in the field. The peer review should assist the French Government, along with the institutions and organisations involved, in their debate on the role of partitioning and transmutation in the national nuclear waste disposal strategy and on the future work programme and priorities.

Acknowledgments

All of the IRT members would like to thank the CEA staff for their kind hospitality during the visits to France and for their organisational support which greatly facilitated the work of the IRT. The IRT would also like to thank all of the *Commissariat à l’énergie atomique* (CEA) and the *Centre national de la recherche scientifique* (CNRS) staff who took part in the review for the helpful and open manner in which they responded to the review and to the requests from the IRT.

TABLE OF CONTENTS

Foreword.....	3
High-level Summary of the Review	7
Background	7
Overall evaluation from an international perspective	8
Conclusions and recommendations	13
Overview	14
1. Introduction	15
1.1 Background.....	15
1.2 The French nuclear programme	16
1.3 Peer review objective.....	23
2. Review of Specific Aspects: Partitioning.....	25
2.1 Introduction.....	25
2.2 Enhanced aqueous partitioning.....	27
2.3 Pyrochemical partitioning.....	34
2.4 Product conversion	36
2.5 Recovery from glass	38
3. Review of Specific Aspects: Transmutation.....	39
3.1 Introduction.....	39
3.2 Transmutation systems	39
3.3 Supporting R&D	44
4. Conclusions	53
4.1 Scope and limits of the report	53
4.2 Strategy	53
4.3 Objectives	53
4.4 Achievements and IRT agreements	54
4.5 Further developments and alternatives	54

5. Recommendations	57
5.1 Scope and limits of the report	57
5.2 Aqueous partitioning and pyrochemistry.....	57
5.3 Product and fission product management.....	58
5.4 Fuels and targets	58
5.5 Strategy: transmutation	59
Appendix 1. Peer review by the OECD Nuclear Energy Agency: Terms of reference of the international review team	61
Appendix 2. Members of the international review team	73
International members.....	73
OECD/NEA Secretariat.....	80
Glossary.....	83

HIGH-LEVEL SUMMARY OF THE REVIEW

Background

A review has been conducted, at the request of the French Authorities *ministère de l'Industrie* and *ministère de la Recherche*, of the first part of the CEA Report 2005 *Les déchets radioactifs à haute activité et à vie longue – Recherches et résultats*, that is *Axe 1 – Séparation et transmutation des radionucléides à vie longue* (CEA/DEN/DDIN/2004-642). This review has been organised by the OECD Nuclear Energy Agency (NEA) and carried out by an international review team (IRT) of independent specialists representing all the relevant aspects of chemical partitioning, transmutation and nuclear materials technology. The CEA Report 2005 (the Report) represents a key milestone in the programme of work for which the CEA is responsible under Area 1 of the Law of 30 December 1991 that is “research into solutions enabling long-lived radioactive elements present in waste to be partitioned and transmuted”.

An important objective of the review is to inform the French Authorities whether the Report is soundly based and competently implemented in terms of scientific and technical approach, methodology, results and strategy. The Authorities are particularly interested in the provision of detailed recommendations for specific improvements which could be applied, especially if the decision-making process leads to a partitioning and transmutation (P&T) application phase. The reviewers were expected to pay particular attention to:

- the technical feasibility of retrieval of long-life radionuclides from existing vitrified waste;
- the scientific and technical aspects of the partitioning processes;
- the scientific basis for the transmutation processes and their efficiency as a function of neutron irradiation conditions;
- the accelerator driven system (ADS) efficiency for transmutation, and the level of development of such systems.

This Peer Review presents the consensus view of the IRT. It is based on the study of the CEA Report 2005, as well as on supporting documents and on

information received from the CEA and the CNRS, the latter having also contributed to the research. It is based also on answers to questions raised by the review team and on direct interactions with staff from the CEA and the CNRS during meetings in France.

The Terms of Reference for the IRT were agreed between the NEA and the French Authorities. The IRT was presented with copies of the Report 2005, in French and English, together with supporting documentation. An initial meeting between the IRT, the CEA and the CNRS was held from 5 September 2005 to 7 September 2005 in Paris, followed by a visit to the Atalante facility at Marcoule for those members of the IRT who were unfamiliar with it. At this first meeting, presentations were made by the CEA and the CNRS on the contents of the report and further explanatory documents and presentations were provided at the request of the IRT. As a result of this process, the IRT generated a number of written questions followed by a supplementary set; all questions were answered in writing by the CEA on an agreed timescale. An oral presentation of the preliminary key findings of the IRT was made to the CEA, following a three day IRT meeting in Paris, on 30 November 2005.

During this review period, the Peer Review was greatly facilitated by the openness and cooperation of the CEA and the CNRS, who made available the appropriately qualified staff with the necessary knowledge and experience to respond to technical questions. The IRT wishes to confirm that sufficient information was made available such that it was able to fulfil its Terms of Reference.

Overall evaluation from an international perspective

The IRT used the specialist knowledge of its members and its collective understanding of international best practice to evaluate the information provided and to generate findings and recommendations.

General observations

Minor actinide partitioning

- The development of enhanced partitioning methods, in the treatment of PWR spent fuel, for recovery of minor actinides (neptunium, americium and curium) from PUREX raffinate has been carried out with great skill and considerable success by the CEA over the past 15 years and there is reasonable assurance that industrial deployment can be successful. A key experiment will be the kilogram scale trials in the *chaîne blindée procédé* (CBP) facility.

- Groundbreaking work has been done by the CEA on the separation of americium and curium but the decontamination of the separated americium in this process has not been fully demonstrated. The purity requirements will depend strongly on the intended use of the americium, which has not been defined.
- Certain recovery goals were set for minor actinides and selected fission products, apparently based on a reduction in radiotoxicity of the residual wastes to a target level that was not defined in the CEA report. The consideration of alternative criteria is recommended, such as a reduction in heat load imposed on a geologic repository or a reduction in waste volume.

Fission product partitioning

- Processes developed for the extraction of important fission products (specifically iodine and caesium) seem to be reasonable, although the report provides little in the way of process details. No detail is provided of the technetium extraction process. Of greater concern is that the approaches for the immobilisation and ultimate dispositioning of these materials are only vaguely defined. This is particularly important in the case of caesium with its substantial decay heat generation rate.

Pyrochemical partitioning

- Pyrochemical separation of minor actinides from the PUREX raffinate was initially considered but the focus for such techniques is now, correctly in the IRT's view, on possible treatment of innovative fuels and transmutation targets. Considerable development is still required before industrial application can be assured.
- Pyrochemical processes incorporating molten salt techniques have great promise for specialised nuclear fuel cycle tasks. Of the three techniques studied by the CEA, two (pool-cathode electrowinning and salt/metal reductive extraction) are more selective than fractionated precipitation techniques. Much work remains to be done, in particular:
 - Partitioning performance at the 99.9% actinide recovery goal remains to be demonstrated.
 - The stripping of actinides from the Al-Cu reductive solvent in the salt/metal reductive extraction process and the behaviour of fission products (Zr, Cs, etc.) other than noble metals and lanthanides is not developed.
 - The development of main and auxiliary process equipment is at a very early stage.

- A number of uncertainties associated with the partitioning performance, the technological difficulties of implementing high-temperature processes and the corrosive nature of the media must still be overcome before considering the deployment of these methods.

Product conversion

- A decision has been made by the CEA to utilise an oxalate precipitation process for the conversion of product streams to solid form for interim or long-term storage. The reviewers believe this to be a wise decision, especially in light of the extensive experience with the process in recovery of plutonium at the La Hague plant.
- Storage of the recovered actinides would be in powder form in sealed vessels having a design pressure of 45 bars. A vented design, intended to release the build-up of helium pressure from alpha decay of the vessel contents, might be preferable from a safety standpoint.

Recovery from glass

- At present minor actinides are vitrified, together with fission products, in the back-end of PUREX process operations at the La Hague plant. The CEA has considered the issue of further processing of this glass waste in order to reduce the quantity of radiotoxic materials eventually to be sent to a geological repository. Two approaches were evaluated for the separation of minor actinides from glass and consideration was also given to deferral of the vitrification step and simply storing the pre-vitrification calcine product until it could be treated to remove the minor actinides. The CEA has quite correctly concluded that industrialisation of such processes would be extremely difficult, let alone imposing an added expense for little benefit to public health and safety.

Transmutation systems

- The transmutation studies looked at using existing reactors as irradiation sources but with some reference to new reactor technology. Although the various reactor scenarios were excluded from the terms of reference, it seemed to the IRT that some cognisance had to be taken, since they all influenced the P&T programme in some way.
- The development work was recognised as being carried out to a very high standard. The IRT agreed that a range of irradiation facilities, including systems with a fast neutron spectrum, would be required for full management of plutonium and minor actinides. Much work remains to be

done on actinide fuels and targets, especially fabrication aspects; fabrication of fuels containing curium will pose particular problems.

- The impracticability of transmutation of fission products is evident from the arguments presented and was accepted by the IRT; fission product transmutation cannot be justified by radiotoxicity arguments alone. If, however, a reduction of radiological risks or heat production were to be considered, then more prominence ought to be given to alternative routes for disposal of specific long-lived or heat producing fission products.

Transmutation in thermal reactors

- The CEA has studied a broad spectrum of possibilities for managing transuranic elements in PWRs. While PWRs can minimise the continuing production of actinides, their consumption of americium is balanced by a similarly large curium production. They do not have the neutronic potential for “burning” their own minor actinide inventories completely. Further, it appears that the incorporation of small amounts of minor actinides in the fuel can have a serious impact on the fuel cycle. The IRT agrees that the concepts are useful for managing plutonium but not worthwhile for managing the minor actinides.

Transmutation in fast reactors

- The IRT agrees that fast neutron spectra are necessary for a successful transmutation programme. The IRT fully supports the long-term perspective to manage minor actinides in a nuclear park which contains a significant number of fast reactors, but would like to emphasise the need for short and medium term development and demonstrations necessary to achieve the long-term goal.

Transmutation in an accelerator driven system (ADS)

- The IRT agrees that the ADS has a role to play in the double strata system where all plutonium is utilised in commercial power reactors and minor actinides are destroyed in the ADS.
- Significant progress has been made in recent years on ADS technology, proving the scientific feasibility of this concept. At the same time much progress is still required with respect to the accelerator reliability, design studies, fuel development and neutronic validation.
- The CEA and the CNRS participate with other European laboratories in the studies performed in the frame of the EC supported programme IP

EUROTRANS. The IRT supports this approach to integrate the French national programme into the broader European initiative on ADS development and recommends that these efforts should be pursued in the future, in order to enable a sound judgement on the ADS technology and its efficiency for transmutation.

Nuclear data

- The CEA uses a consistent set of nuclear data and calculation methods to analyse transmutation performances; the broad experimental database, coupled with solid validation methodology, leads to trustworthy results. As systems with high minor actinide contents are introduced, emphasis needs to be placed on improving the nuclear data for the relevant minor actinide nuclides.

Fuels and targets

- The research on actinide fuel and targets for transmutation has contributed significantly to the understanding of the effects of incorporation of minor actinides during irradiation and has shown directions for further development. It must be concluded that only the homogeneous recycling of americium and neptunium in mixed oxide fuel for fast reactors has been demonstrated on the basis of experimental fuel pin trials. All other fuel designs need further validation and it is still not possible to evaluate whether these contain truly promising concepts.
- The report does not address sufficiently the difficulties of handling multigram quantities of americium and curium in the fuel cycle, the characteristics of which are significantly different from those of uranium and plutonium. The differences are due principally to the high decay heat and the higher neutron and gamma emissions, as well as other differing physical and chemical properties.
- The fuel and target research is the weakest link in the P&T chain, despite being crucial for both fast reactor (FR) and ADS concepts. Consideration must be given to the continuing availability of an appropriate R&D infrastructure, with adequate fast neutron facilities, as well as an adequate financial resource.

Soundness of basis and competence of implementation

The Report 2005 has a sound technical basis and the reported work has been implemented professionally and to a high standard. The IRT believes that the inclusion of CNRS in the ADS studies was very beneficial and the IRT

encourages continuing participation with relevant European Commission supported programmes as well as with the wider international scientific community. These links will allow a strong scientific foundation to be maintained for future activities.

Consistency with international standards and practices

With regard to the overall scientific work, modelling capabilities and systems development, the efforts of the CEA are seen as following international standards and practices. The lack of discussion of the relationship of this programme with the Generation IV reactor programme was seen by the IRT as an omission which, if corrected, would add significantly to the breadth and understanding of the report.

Conclusions and recommendations

The IRT has made a number of conclusions and recommendations on the work programme described in the report. The most significant conclusions include:

- The report presents many areas of excellent technical work, but it is written in a way which makes it difficult for the reader, especially one who was not well acquainted with the technical areas reported, to follow and to understand easily. It would be helpful to produce a more readable version to inform the non-specialist reader for the forthcoming debate on the new nuclear waste law.
- The development of enhanced partitioning methods for the treatment of PWR spent fuel has been carried out with great skill and considerable success by the CEA over the past 15 years. Aqueous processes for separation of minor actinides (neptunium, americium and curium) from the PUREX raffinate have been brought to a point where there is reasonable assurance that industrial deployment would be successful.
- The IRT fully supports the long-term perspective for the management of minor actinides in a reactor fleet which contains numbers of fast reactors. However the IRT was concerned that shrinking R&D infrastructures and especially a lack of fast neutron irradiation facilities would endanger progress.
- The IRT agrees that ADS systems have a potentially useful role to play in the double strata system, where all plutonium is utilised in commercial reactors and minor actinides are destroyed in accelerator

driven systems. Significant progress has been made in the recent years, proving the scientific feasibility of the concept. However the ADS still needs substantial development. The IRT supports the approach of integrating the French national programme into the broader European initiative, to enable a future sound judgment on ADS technology and its efficiency for transmutation.

- The IRT notices that the goals of the research are all stated in terms of radiotoxicity reduction. There are two perspectives with respect to the management of the long-term hazard of the waste, namely to reduce the total radiotoxicity inventory or to reduce the long-term radiation dose to populations from any future disposal and some discussion on this point would be beneficial. P&T of actinides addresses the first point while P&T of fission products would be more directed at the second. P&T might also have a role in the efficiency of repository use through a reduction in heat loading and volume of waste to be deposited.
- The report does not try to address an integrated approach to the effects of P&T on the whole fuel cycle. For example, it looks neither at the implications of minor actinide recycling on fuel fabrication nor at the consequences of P&T implementation on final disposal repository performance. It will be necessary to produce this more comprehensive overview at some point in the near future.

Overview

The IRT was impressed with the technical progress made by the CEA on its P&T programme since 1991. The level of development of the various technical areas is however different. The chemical partitioning studies, by liquid-liquid extraction, of PWR spent fuel is very well developed, with some excellent innovative work especially into the liquid-liquid extraction of minor actinides, which places the CEA at the forefront of international efforts. The research on transmutation fuels and targets (fabrication, performance testing and subsequent chemical processing) is still at an exploratory stage. The IRT felt that more strategic thinking could have been applied to advantage during the course of the research, though this was not specifically required under the 1991 law. There has to be a concern that progress in transmutation is endangered by the shrinking availability of R&D infrastructures, especially fast reactor irradiation facilities.

1. INTRODUCTION

1.1 Background

The handling of spent nuclear fuel in France involves chemical reprocessing of the irradiated nuclear fuel to extract the plutonium and unused uranium so as to allow their reuse as required. The waste from this process contains the fission products together with various minor actinides produced from uranium and plutonium under neutron irradiation whilst in the reactor. The first stage of chemical reprocessing by liquid-liquid extraction separates the bulk of the fission products together with the minor actinides as a highly radioactive liquid waste stream. Present practice is to convert this liquid stream into a solid glass form suitable for long-term storage and possible disposal.

There has been, and is still, some public concern about the disposal of radioactive waste and the fact that the radioactivity can persist for a very long time. The integrity of any storage, or disposal, facility cannot be guaranteed absolutely over a period of many thousands of years. There is a possibility that many years in the future, there may be some release of radiotoxic material which, in the public mind, could represent an unacceptable risk for future generations.

In 1991, the *Assemblée nationale* and the *Sénat* adopted a law which stipulated that the storage of high-level and long-lived radioactive wastes has to be ensured in respect of the protection of nature, the environment and health, taking into account the rights of future generations. This law, Law 91-1381 of 30 December 1991, also became known as the Bataille Law after its instigator *député Christian Bataille*.

The law stipulated that research had to be carried out in the following topic areas:

- Area 1 – to search for solutions to the partitioning and transmutation of long-lived radioactive elements present in radioactive waste.
- Area 2 – a study of the possibilities of reversible or irreversible storage in underground geological formations.

- Area 3 – a study of the conditions for the conditioning and long-term surface storage of radioactive wastes.

After a period not exceeding fifteen years, that is by the end of 2006, the Government shall submit an overall evaluation report to the Parliament.

This 1991 Law also established a National Evaluation Commission (*Commission nationale d'évaluation*, CNE) which is required to make regular reports to the Government and the Parliament on the progress in these study areas. To fulfil its role, the CNE periodically organises hearings of reports from various experts on subjects of CNE's choice.

The responsibility for carrying out the studies was given to the French Atomic Energy Commission (CEA) for Area 1 and Area 3 whilst the French Waste Management Agency (*Agence pour la gestion des déchets radioactifs*, Andra) has been given responsibility for the Area 2.

As an input to the 2006 reporting deadline, the CEA has produced a report (Report 2005: Partitioning and Transmutation) which compiles the findings of the R&D programme appropriate to the first study area under the 1991 Law and gives the conclusions of the CEA on the feasibility of the partitioning and transmutation of minor actinides and certain fission products found in spent nuclear fuel.

It is the wish of the French Government that the “Report 2005: Partitioning and Transmutation” should be widely read and discussed with the general aim of triggering the waste management debate and building confidence among stakeholders. Therefore, the French Government considered it essential to submit this report to peer review by an independent team of international experts and the French authorities asked the NEA to carry out this Peer Review.

1.2 The French nuclear programme

1.2.1 Overview

France is heavily committed to nuclear energy; during the 1950s and 1960s six first generation gas-graphite nuclear power reactors were built and commissioned together with France's first irradiated fuel reprocessing plant. All these facilities are now no longer in use and are being decommissioned, however from 1977 onwards, fifty-eight pressurised water reactors (PWR) were built and operated together with uranium enrichment, fuel manufacturing, irradiated fuel reprocessing and waste management facilities. In 1973, the 250 MWe fast neutron reactor Phénix was commissioned at the Marcoule site

followed in 1985 by the commercial sized 1 200 MWe fast reactor Superphénix at Creys-Malville. Nuclear power accounts for 78% of electricity production in France.

1.2.2 The nuclear fuel cycle

The nuclear fuel used in a reactor must be replaced periodically as the uranium (and plutonium) nuclei undergo fission to yield energy. Once discharged from the reactor the used (spent) fuel can either be reprocessed to extract and recycle the unused uranium and the plutonium content, or can be considered as waste; this latter option, the open fuel cycle, is followed in some other countries. The open fuel cycle does not include reprocessing and the associated waste management but consists of keeping the spent fuel assemblies, unloaded from the reactor and containing the entire radionuclide inventory, in safe and secure storage awaiting final disposal.

France, and for example the United Kingdom and Russia, implement a spent fuel recycling process. A reprocessing-recycling programme requires a range of industrial facilities to allow for the transformation and use of radioactive material contained in the fuel. This recycling generates a highly active liquid waste stream (raffinate), containing the fission products and the minor actinides, which remains after the reusable uranium and plutonium have been extracted. Less active (intermediate level) waste streams, such as used fuel cans, are also produced. These reprocessing-recycling facilities represent a sizeable investment and have a long lifetime; given this industrial reality, any significant changes to the fuel cycle are only foreseeable over several decades.

Since 1977, the CEA has developed the technology to produce mixed uranium-plutonium oxide fuel (MOX). This allows for the recycling of reusable material present in spent fuel while reducing the radiotoxicity of final waste by 80% over 300 years and 90% over 500 years. Plutonium was recycled into MOX fuel which was loaded into a power reactor for the first time in the Saint-Laurent reactor in 1987. Fifteen years later, twenty French 900 MWe PWRs are consuming this fuel, thus contributing to a reduction in plutonium stocks. These twenty reactors use MOX fuel for 30% of their fuel load with two of these reactors also using uranium from spent fuel reprocessing.

Plutonium recycling, however, implies an approximate 30% increase in the quantity of minor actinides present in spent MOX fuel. In France, around 1 150 tonnes of spent UOX and MOX fuel are discharged annually from the 58 reactors which make up the EDF nuclear fleet, which has an electrical production of approximately 400 TWh per year. This spent fuel is stored in cooling ponds on the power plant sites for one or two years before being sent to

La Hague for future reprocessing. The partitioning of uranium and plutonium from the spent fuel will only take place after a minimum of five years of cooling in a pond.

Today, only the quantity of UOX spent fuel necessary to produce the required amount of MOX fuel is reprocessed; therefore 850 of the 1 050 tonnes per year of discharged UOX spent fuel are reprocessed each year in La Hague, which allows for around 100 tonnes of MOX fuels to be produced in the Melox plant in Marcoule. The remaining 200 tonnes of UOX spent fuel and the MOX spent fuel are stored while waiting to be reprocessed in the future.

The CEA developed conditioning technologies designed to stabilise the different waste products while awaiting a final disposal solution. Vitrification was the option chosen for conditioning the liquid high-level waste produced from the reprocessing of spent fuel and the first nuclear glass was cast at Marcoule in 1963, with industrial scale casting becoming operational fifteen years later. Similar developments were made for long-lived intermediate level waste and the CEA teams designed conditioning processes, employing bitumen and cement, which were implemented on the industrial sites of Marcoule and La Hague.

Following its obligations under the Bataille Law, the CEA continued to adapt the facilities needed for its study programme and significant financial investment was made to carry out the necessary experiments. The Atalante facility for example, in service from 1992, was adapted to host partitioning and conditioning experiments on highly radioactive materials.

In 1998, the government ordered the shutdown of the Superphénix fast neutron reactor, which meant that the reactor in which researchers had planned to carry out transmutation experiments was no longer available. Phénix is now the sole fast neutron reactor available in France to undertake these experiments and necessary changes to accommodate these experiments had to be undertaken. In June 2003, the Phénix reactor, shutdown since 1999 for extensive periodic maintenance and safety related renovation work, was returned to service, albeit for a limited period.

1.2.3 Fuel irradiation

The fresh nuclear reactor fuel consists of UOX or MOX pellets contained in fuel pins, which are then held as a multi-pin cluster in a fuel assembly which is introduced into the reactor. In-reactor irradiation of this fuel generates a great deal of heat and forms a large range of radionuclides within the fuel and in the metallic fuel can and fuel assembly. There are typically no fewer than

300 radionuclides spread over approximately forty chemical elements of the periodic table.

CEA report that a fuel assembly containing around 500 kg of spent UOX fuel from an existing PWR contains in mass:

- 94% uranium and 1% plutonium – elements with a high energy potential (equivalent to around 10 000 tonnes of oil for current reactors), which are not considered as waste;
- other radionuclides – which currently represent energy production waste.

A large part of these other radionuclides are short-lived fission products which are mainly responsible for the spent fuel's radioactivity and thermal energy over a few dozen years after leaving the reactor. As the radioactive decay period of these radionuclides is below thirty years, their radioactivity drops quickly (divided by a thousand after three hundred years) as does the resulting heat release. This is not the case for minor actinides (0.1% of spent fuel) or long-lived fission products (0.3% of spent fuel), which continue to cause residual radioactivity, though lower than that caused by short-lived fission products, for several thousand or even several million years. Two radionuclides in particular (^{241}Am and ^{238}Pu) are responsible for thermal release which lasts for around a thousand years.

1.2.4 Waste considered in the Law of 1991

Radioactive waste in France is listed under different categories depending on its radioactivity and the radioactive half-lives of the radionuclides it contains. Radionuclides are called long-lived when their half-life exceeds thirty years; otherwise they are referred to as short-lived. French classification comprises the following categories:

- Very low-level waste – contains a very small quantity of radionuclides (10 to 100 Bq/g) which bars them from being considered as conventional waste.
- Short-lived low- and intermediate-level waste – the radioactive level of this waste is between a few hundred and one million Bq/g of which there are fewer than ten thousand Bq/g of long-lived radionuclides. Its radioactivity will be comparable to natural radioactivity in less than three hundred years.
- Long-lived low-level waste – this category comprises “radium-bearing” waste which comes from the extraction of rare earths in

radioactive minerals and “graphite” waste from the first generation of reactors.

- Long-lived intermediate-level waste – which varies greatly due to its origin. This arises mainly from spent fuel structures (cladding tubes and end-pieces) and the operating and maintenance of nuclear facilities.
- High-level waste – which contains the fission products and the minor actinides separated during spent fuel reprocessing and then incorporated into a glass matrix. Around 120 m³ of nuclear glass is cast each year. This waste contains most of the radioactivity and therefore releases a great amount of heat which remains at a high level over several centuries.

Overall, radioactive waste conditioned in France represents less than 1 kg per year per inhabitant. This kilogram can be broken down as follows:

- over 90% is short-lived low- and intermediate-level waste containing only 5% of the total radioactivity;
- practically no long-lived low-level waste;
- 9% is intermediate-level waste;
- less than 1% is high-level waste.

Andra provides the National Inventory [see reference AND-04 in the CEA Axe 1 Report Bibliography] of radioactive waste which gives a geographical picture of waste disposal on French territory together with the grouping of this waste into categories so as to provide an overview and characterisation statistics and a forward projection for French waste arising in 2010 and 2020 and a prediction of spent fuels produced after 2020 by the current fleet. It also provides an estimate for the volume of waste as a result of the disassembly and decommissioning of existing facilities.

1.2.5 Current waste management principles

The aim of long-term radioactive waste management in France is to protect humankind and the environment from the effects of radioactive material and radiological risks in particular. Any emission or spreading of radioactive materials must therefore be avoided by isolating the waste from the environment. In brief, this management is based on the following principles:

- producing as little waste as possible;
- reducing the hazardous nature of the waste as much as possible;
- taking into account the specific nature of each waste category;

- opting for measures which minimise the responsibilities (for monitoring, maintenance) of future generations.

Intermediate- and high-level wastes, which contain radionuclides with very long radioactive half-lives (sometimes greater than several hundred thousand years), are currently kept in storage facilities which are regulated by the Nuclear Safety Authority. Their long-term future, beyond the storage period, is the subject of the Law of 30 December 1991.

The purpose of the research, started by the 1991 Law, is to provide scientific and technical information which will contribute to determining the most appropriate long-term management methods to control and minimise the risk posed by intermediate and high-level waste.

1.2.6 The role of the CEA

The management of Area 1, partitioning and transmutation (P&T) and Area 3, conditioning and long-term surface storage, was entrusted to the CEA.

This research has mainly been carried out by CEA teams; however an important partnership with the CNRS (*Centre national de la recherche scientifique*) was put in place for aspects of Area 1, for example transmutation technology and pyrochemistry. Furthermore, the CEA and Andra have worked closely so as to ensure the full technical consistency in the area of waste package management, from storage to disposal. Cogéma, EDF and Framatome-ANP have also contributed to this work by making their industrial experience available to the research. The CEA analysed the aims of Area 1 of the 1991 Act and structured their research programmes to answer the following questions:

- What long-lived radioactive elements can be partitioned, from what waste and how?
- What can be done with these elements once they have been partitioned?
- Which of the partitioned elements are transmutable into stable or short-lived elements and how?

To study these various questions, the CEA allocated significant human, technical and financial resources and set up new cooperation with national, European and international centres of expertise. Since 1992, several hundred people have worked in the different areas of the 1991 Act's three research areas. This review is, however, concerned only with the work carried out on partitioning and transmutation.

The research necessary for Area 1 posed significant scientific challenges. In order to carry out the partitioning of certain radionuclides from others with similar chemical properties, more than a hundred chemical extractants had to be designed, synthesised and tested. For the transmutation irradiation experiments in the Phénix reactor, more than five years are necessary from experiment design to obtaining the first irradiation results.

1.2.7 Report 2005: Partitioning and transmutation synopsis

The *Report 2005: Partitioning and Transmutation* compiles all acquired data and knowledge leading up to the CEA's conclusions on the feasibility, under specific conditions, of the partitioning and the transmutation of the minor actinides neptunium, americium and curium into short-lived or stable radionuclides. The report details the experimental and theoretical results obtained in the areas of enhanced liquid-liquid extraction and pyrochemistry for specific radionuclide partitioning and gives the results of transmutation work using both nuclear reactors and accelerator driven systems (ADS) as neutron sources. Possible P&T scenarios are then discussed.

In this context, the Report has the status of a report providing conclusions for the decision-making process. After a general introduction (Chapter A) and a partitioning and transmutation introduction (Chapter B), the report is organised in the following order:

- Chapters C.1 to C.12 concern the results related to the partitioning of spent fuel and describe namely:
 - the possible retrieval from existing waste packages (Chapter C.3);
 - results of the aqueous partitioning of minor actinides and long life fission products (Chapters C.4 to C.8);
 - assessment results of the intermediate storage of separated minor actinides (Chapter C.9);
 - results of the pyrochemical separation advanced process (Chapter C.10);
 - assessment of research results on partitioning and the future outlook, in Chapters C.11 and C.12, respectively.
- Chapters D.1 to D.7 concern the results of studies on transmutation and look particularly at:
 - transmutation possibilities in thermal or fast critical or sub critical reactors (Chapter D.4);
 - the fabrication of fuel and targets and the transmutation experiments (Chapter D.5);

- the assessment of research results on transmutation and the future outlook in connection with the sustainable development of nuclear energy in Chapters D.6 and D.7, respectively.
- Finally, Chapter E looks at possible separation-transmutation scenarios in the future making it possible to use new type reactors, especially those with a fast neutron core operating in a critical or sub-critical mode.

1.3 Peer review objective

The objective of the Peer Review is to inform the French authorities (*ministère de l'Industrie and ministère de la Recherche*) whether the “Report 2005: Partitioning and Transmutation” is soundly based and competently implemented in terms of scientific and technical approach, methodology, results and strategy. The French authorities are particularly interested in the provision of detailed recommendations for specific improvements which could be brought in to that effect, notably if the decision-making process leads to a P&T application phase.

The reviewers were expected to pay particular attention to:

- the technical feasibility of retrieval of long-life radio nuclides from existing vitrified waste;
- the scientific and technical aspects of the partitioning processes;
- the scientific basis for the transmutation processes and their efficiency as a function of neutron irradiation conditions;
- the ADS efficiency for transmutation, and the level of development of such systems.

The full terms of reference for the international review team are given in Appendix 1 and details of the Team members are given in Appendix 2.

2. REVIEW OF SPECIFIC ASPECTS: PARTITIONING

2.1 Introduction

The development of enhanced partitioning methods for the treatment of PWR spent fuel has been carried out with great skill and considerable success by the CEA over the past 15 years and innovative work has been carried out on the separation of americium and curium.

Ambitious recovery goals were established for americium, curium, neptunium, iodine, technetium and caesium. The value of setting recovery goals is acknowledged, but the technical basis for setting the goals is not discussed.

Pyrochemical separation of minor actinides from the PUREX raffinate was initially considered but the focus for such techniques is now, correctly in the IRT's view, on possible treatment of innovative fuels and transmutation targets. Considerable development is still required before industrial application can be assured.

This section refers to the research undertaken in respect of the partitioning studies for minor actinides and selected fission products as mentioned in Chapter C of the Report and includes pyrochemistry and recovery from vitrified waste.

Many years of successful commercial operation of a large aqueous reprocessing plant in France at La Hague, for recovery of uranium and plutonium from light water reactor spent fuel, is testimony to the technological maturity of the PUREX process. Much of the success of that operation can be attributed to the development work done with the UP1 plant by the CEA and to the subsequent technical interactions between the CEA and the Cogéma professional staff. The extensive commercial infrastructure built up at the La Hague plant, and related facilities throughout France, represents an enormous investment and the realisation of the full benefits of that investment imposes a certain bias on the development of a programme for enhanced partitioning in response to the 1991 Law.

Optimisation of the PUREX process over the past years has resulted in the attainment of a very high recovery efficiency for plutonium and in the gradual reduction in the amount of radioactive waste generated in the course of PUREX operations. This achievement has given CEA scientists and engineers a high degree of confidence in their ability to adapt aqueous solvent extraction technology to enhanced partitioning methods that are at once both practical and environmentally sound.

Enhanced partitioning involves the extraction of all significant actinide elements present in spent nuclear fuel; this includes, in addition to the uranium and plutonium recovered by the PUREX process, the recovery of the minor actinides neptunium, americium and curium. Certain fission products were also selected for consideration, that is iodine, technetium and caesium.

The enhanced partitioning of spent nuclear fuel was studied by the CEA with a view to reducing the radiotoxic inventory of high-level waste and a number of ambitious recovery goals were established for americium, curium, neptunium, iodine, technetium and caesium. The value of setting recovery goals is acknowledged, but the technical basis for setting the goals is not discussed in the report.

The CEA initially also considered the application of pyrochemical separation techniques for the extraction of minor actinides from the PUREX raffinate, but the project focus has now evolved into the use of pyrochemistry as an alternative to hydrometallurgy for treatment of innovative fuels and transmutation targets. It is recognised, correctly in the IRT's view, that pyrochemistry is not a competitor to hydrometallurgy; the application fields are different and the best suited process should be used.

The enhanced partitioning studied in the frame of the 1991 French law was mainly focused on the treatment of spent LWR fuel. This is appropriate, but it is clear that the eventual recycling of transmutation fuels and targets is inevitable in order to achieve a high transmutation rate. Recycling technology for transmutation fuels and targets should be developed in close contact with the fuels and targets development programme; this does not appear to have been done or could not be found in the report.

2.2 Enhanced aqueous partitioning

Aqueous processes for separation of minor actinides (neptunium, americium and curium) from the PUREX raffinate have been brought to a point where there is reasonable assurance that industrial deployment can be successful. A key experiment will be the kilogram scale trials in the *chaîne blindée procédé* (CBP) facility.

The separation of americium from curium is perhaps the most challenging of the partitioning steps considered and some truly groundbreaking work has been done by the CEA in furthering the development of a process to do this separation, but the decontamination of the separated americium in this process has not been fully demonstrated. The purity requirements will depend strongly on the intended use of the americium, which has not been defined.

Certain recovery goals were set for minor actinides and selected fission products, apparently based on a reduction in radiotoxicity of the residual wastes to a target level that was not defined in the CEA report. Consideration of alternative criteria is recommended, such as a reduction in heat load imposed on a geological repository or a reduction in waste volume.

Processes developed for the extraction of important fission products (specifically iodine and caesium) seem to be reasonable, although the report provides little in the way of process details. No detail is provided of the technetium extraction process. Of greater concern is that the approaches for the immobilisation and ultimate dispositioning of these materials are only vaguely defined. This is particularly important in the case of caesium with its substantial decay heat generation rate.

Both the CEA and its partner organisations in European Commission projects (NEWPART, PARTNEW, EUROPART) have done work of historic proportions in the development of methods for the separation of americium and curium from the lanthanide fission products and from one another. For the partitioning of americium and curium from the PUREX raffinate by liquid-liquid extraction, the progress made is notable and the achievement of the separation of americium from curium is impressive. The first step is to extract the minor actinides, americium and curium, together with lanthanides from the PUREX raffinate. The second step is the selective extraction of americium and curium from the lanthanides with the third step being the separation of americium and curium from each other. Although the similarity in the chemical properties of americium, curium and lanthanides causes their partitioning to be complex, the scientific feasibility of the partitioning of americium and curium was demonstrated in innovative laboratory scale experiments.

The demonstration that, at a laboratory scale, these elements can be separated from actual fuels with the same efficiency as the separation of uranium and plutonium in the PUREX process, represents an essential step in the implementation of a P&T fuel cycle strategy. Even if the technical feasibility has still to be proven conclusively, it seems now possible to have a practical extended PUREX process available in the next decade.

To demonstrate the feasibility for scale-up of the process further experiments are proceeding. A key experiment will be the kilogram scale trials in the *chaîne blindée procédé* (CBP) facility at Marcoule to test, under realistic conditions using spent fuel, the stability of the diamides and various process flowsheets. The fact that technical and economic evaluations in close collaboration with SGN and Cogéma are included gives a considerable added value to this large scale test.

A number of ambitious recovery targets have been established by the CEA:

- 99.9% of the americium and curium present in the PUREX raffinate.
- More than 99% of the neptunium and iodine present in the original spent fuel.
- More than 99% of the technetium present in the PUREX raffinate.
- 99.9% of the caesium present in the PUREX raffinate.

The basis for these recovery targets appears to be a reduction in radiotoxicity of the high-level waste that will ultimately be sent to disposal in a geological repository. This may not be the best criterion on which to base process performance targets; if the waste is efficiently immobilised and retained in the repository then the cancer risk to humans is, in any case, greatly diminished. More meaningful criteria, such as reduced cost, reduced heat loading, or reduced waste volume should be investigated.

The IRT notes that there is no consensus among experts in the field on the need to develop a process for the further separation of already segregated americium with curium, and the value of other options should be considered. It appears that information is available among fuels and separations experts upon which to reach a definitive position on americium/curium separation and a decision should be taken in the near future.

For the partitioning of neptunium, the method is based on a modification of the PUREX process. The neptunium extraction yield is essentially determined by the kinetics of neptunium (V) oxidation in the aqueous phase. The feasibility of the partitioning of neptunium with a modification of the PUREX process was

demonstrated both by experiments at the Atalante facility and by development of computer modelling simulations. The recovery of 99% of the neptunium inventory should be attainable.

As regards technetium, more than 95% of the soluble technetium is currently recovered in a specific output stream from the PUREX process. The target of recovery of soluble technetium is set at 99%, though the basis of the decision is again unclear, especially considering the presence of 20% to 50% of technetium as insoluble metallic inclusions in the spent fuel. No plan of how to treat or dispose of the soluble technetium is described. The insoluble constituent is presently directed to high-level waste glass with other fission products.

For the partitioning of iodine, around 97% of iodine is presently recovered in a liquid solution before being discharged to sea and about 2% is immobilised in the filters of the existing PUREX process plant. The processes developed of the selective trapping of iodine in solution and filter decontamination would permit the recovery of at least 99% of the iodine, meaning that the target for the recovery should be attainable. Any subsequent transmutation of iodine however seems rather difficult because no really suitable matrix has been found up to now which would allow safe and efficient irradiation in a reactor. Conditioning in a stable storage matrix should be considered as a better option; no indication was given in the report as to plans in this regard.

For the partitioning of caesium, an assessment of new extractant molecules capable of selectively extracting caesium was made and a process, based on these new extractants, was demonstrated at laboratory scale. The feasibility of the partitioning of 99.9% of caesium has been proven. The recovered caesium can be immobilised in a mineral form such as hollandite, as the CEA experiments have shown. The long-lived nuclide ^{135}Cs accounts for about 17% of the recovered caesium but the transmutation of ^{135}Cs without prior isotopic separation will not be feasible from a neutronic viewpoint. No plan for the ultimate disposition of the recovered caesium has been presented.

Within the frame of the CEA/CNRS reported studies, the purpose of P&T is the reduction of the radiotoxic inventory of the waste, but in some parts of the report the merit of reduction of the heat content of the waste by P&T was mentioned. The question of whether the heat emitters caesium and strontium should be separated depends very much on the waste storage strategy. The reduction of the heat source within specific wastes will contribute to the effective use of any repository. For this purpose then, the partitioning of strontium as well as caesium should be considered for inclusion in the scope, as the decay heat generation from ^{90}Sr and its daughter ^{90}Y are comparable to that from ^{137}Cs and its daughter ^{137}Ba . If very long-interim storage times of several

hundred years are to be considered either for the spent fuel before reprocessing or for the separated waste then the separation of caesium and strontium might not be relevant.

2.2.1 Americium and curium recovery

The CEA staff has been extremely diligent in their evaluation of candidate processes for accomplishing this separation. If the transmutation scenario is to proceed, it is extremely important that a practical process for recovery of americium and curium, including adequate decontamination from lanthanide fission products, be developed.

The extraction of americium and curium from the PUREX raffinate with high efficiency and high degrees of decontamination is a challenging proposition. The CEA staff has been extremely diligent in their evaluation of candidate processes for accomplishing this separation. The difficulty arises from the chemical similarity of americium and curium, their affinity for the lanthanide fission products (also similar in many respects) and the comparative fragility of those organic extractant molecules that exhibit good selectivity for americium or curium.

A two-step approach for americium/curium recovery has been adopted by the CEA with the first step being the DIAMEX process, which operates on the PUREX raffinate to co-extract americium and curium together with the lanthanide fission products. A number of tests of the DIAMEX process, with both stimulant and actual feed solution and with different extractants, were carried out by the CEA in the period 1993-2000. Acceptable results were obtained with the dimethyldioctyl hexylethoxy malonamide (DMDOHEMA) extractant; in the last test in this series, the incorporation of a scrub step with oxalic acid and HEDTA (hydroxyethylene diaminetriacetic acid) was successful in promoting the decontamination of the product from the transition metal fission products (specifically zirconium, molybdenum, iron and palladium) to reasonable values, although there was significant contamination from yttrium.

The second step chosen by the CEA for recovery of americium and curium is the SANEX process. In this step, a bis-triazinylpyridine (BTP) extractant is used to separate americium and curium from lanthanide fission products in the product stream from the DIAMEX process. The family of BTP molecules was selected by the CEA after exhaustive study of a number of different possibilities. Initial tests showed significant degradation of the solvent, and more stable variants were sought by the CEA workers. This has not been very successful to date, and the CEA has developed two alternative processes, the SANEX “low acidity method” and the SANEX “single cycle method”.

These process variants have been tested with model solutions with encouraging results but they are, however, quite complex and perhaps not suited for industrial implementation. Clearly, much more development work must be done with the DIAMEX-SANEX process; an important feasibility demonstration was conducted in November and December 2005 and the International Review Team awaits the results with interest.

If the transmutation scenario is to proceed then it is extremely important that a practical process for recovery of americium and curium, including adequate decontamination from lanthanide fission products, be developed. This is because the transmutation of americium and curium, whether in a fast reactor or a thermal reactor, requires a lanthanide decontamination factor in excess of 50 (as dictated by neutronics considerations) and perhaps in excess of 200 (if it proves necessary to limit chemical interaction between the fuel and the cladding involving lanthanides).

2.2.2 Separation of americium from curium

The CEA has done excellent work in arriving at what may prove to be a practical method for separation of americium from curium and their accomplishment is noteworthy. An evaluation study is necessary to resolve the issue of whether the programme should seek to concentrate curium.

The separations criteria adopted by the CEA for the separation of americium from curium are for a recovery of 99.9% of each actinide, with no more than 1% of americium in the curium product and no more than 1% of curium in the americium product. The separation process would operate with a feed that is the product stream from the DIAMEX-SANEX process. After limited success with an electrolysis-based process, in which the americium was oxidised electrolytically to the extractable americium (VI) state and then extracted with tributyl phosphate, the CEA conceived a DIAMEX-like process (that it has named DIAMEX 2) for americium separation from curium. The extraction/scrub section of the process requires 48 stages, and the process is very sensitive to variations in temperature, flow rate, and acidity. A carefully controlled test with a model solution in 2002 produced satisfactory results.

Technical staff members at the CEA have done excellent work in arriving at what may prove to be a practical method for separation of americium from curium and their accomplishment is noteworthy. It is not clear however, that there is a technical consensus on the need for such a separation. Curium could be stored for 200 years until it has decayed into usable products, but it poses a severe storage problem due to decay heat generation and to the potential for an

accidental criticality event. The question is whether any programme should seek to concentrate curium. It can be transmuted rather easily in a fast reactor neutron energy spectrum, and its remote fabrication into fuel, together with americium, is probably technically feasible. An evaluation study is necessary to resolve this.

2.2.3 Neptunium recovery

Neptunium extraction can be promoted by increasing the acidity of the first cycle PUREX feed solution and the modifications can be accommodated in the current La Hague plants, so it should be possible to achieve the 99% recovery target.

For the recovery of minor actinides, the CEA has focused on americium and curium, assuming the neptunium to be recovered under the umbrella of the PUREX process. Historically, the behaviour of neptunium in the PUREX process has been somewhat unpredictable. Neptunium tends to co-extract with both uranium and plutonium, but one-third to one-quarter of the original neptunium content tends to appear in the PUREX waste stream. This problem is being addressed by the CEA and it seems that neptunium extraction can be promoted by increasing the acidity of the first cycle PUREX feed solution (possibly with nitrous acid additions). These modifications can be accommodated readily in the current La Hague plants, so it should be possible to achieve the 99% recovery target without major changes.

It is not clear, however, just what the distribution of neptunium between the uranium and plutonium streams will be. This could be important if, for example, neptunium partitions to plutonium which is intended for thermal reactor multi-recycle. In this case, neutron absorption by contaminant neptunium will produce ^{238}Pu , which has a high rate of decay heating that can complicate subsequent fuel fabrication operations. Consideration should be given to the distribution of neptunium, its consequences and its control.

2.2.4 Separation of technetium

The CEA programme plan does not include a description of the means that will be explored for recovery of the technetium and the main issue of its disposition is not discussed.

Technetium, a long-lived fission product, can be a problem in the geological disposal of high-level waste because under oxidising conditions,

such as Yucca Mountain in the United States, it can become highly mobile in groundwater; in a reducing environment however, such as in many possible European sites, there is insignificant mobility.

In the head-end process of dissolution, some of the technetium will dissolve and appear in the clarified dissolver solution, while some resists dissolution and remains in the dissolver solid residues. During the first-cycle PUREX extraction, much of the soluble technetium is co-extracted with uranium and plutonium. As one of their stated recovery targets, the CEA proposes to recover 99% of the technetium in the PUREX raffinate. It is not clear if this refers to the amount that is not co-extracted with uranium and plutonium, or to the total amount of technetium in the dissolver solution fed to the PUREX process.

The CEA programme plan does not include a description of the means that will be explored for recovery of the technetium; this could include ion exchange methods, precipitation reactions, or other processes. There have been studies of methods for purifying the technetium product and converting the nitrate form to a solid carbide or metal form, but the main issue of its disposition seems to have been passed over.

2.2.5 Separation of iodine

Industrial experience with the recovery of iodine from PUREX plants has been quite successful. The approach identified by the CEA and capitalising on this experience, seems to be the appropriate one and it is likely that the recovery goal of 99% is readily attainable. The method for efficiently immobilising and disposing of the recovered iodine is not presented in the report.

2.2.6 Separation of caesium

It is proposed by the CEA to extract caesium from the DIAMEX process raffinate stream. At this point, all actinides and lanthanide fission products will have been removed previously. A crown calixarene extractant is proposed for the recovery of caesium and laboratory tests have shown the efficacy of this approach. Such a process has also been selected for caesium removal from tank wastes at the Savannah River Site in the United States and its prospects for success are quite high.

The only deficiency in the CEA programme plan is the absence of an identified path forward for the disposal of the recovered caesium. Conversion to a mineral form is certainly feasible and has been done elsewhere, but the question remains as to its ultimate disposition.

2.3 Pyrochemical partitioning

Pyrochemical processes incorporating molten salt techniques have great promise for specialised nuclear fuel cycle tasks. Of the three techniques studied by the CEA, two (pool-cathode electrowinning and salt/metal reductive extraction) are more selective than fractionated precipitation techniques. Much work remains to be done, in particular:

- Partitioning performance at the 99.9% actinide recovery goal remains to be demonstrated.
- The stripping of actinides from the Al-Cu reductive solvent in the salt/metal reductive extraction process and the behaviour of fission products (Zr, Cs, etc.) other than noble metals and lanthanides is not developed.
- The development of main and auxiliary process equipment is at a very early stage.

A number of uncertainties associated with the partitioning performance, the technological difficulties of implementing high-temperature processes and the corrosive nature of the media must still be overcome before considering the deployment of these methods.

The pyrochemical investigations fulfilled during the 1999-2005 period were based on four lines:

- consolidation of knowledge on pyrochemical concepts and processes;
- search for new paths;
- carrying out of demonstration experiments on representative materials;
- pre-selection of processes adapted to targets and fuels to be reprocessed and studies on associated systems.

The principal application for pyrochemical separation techniques as envisioned by the CEA was initially in the extraction of minor actinides from the PUREX raffinate. Although that may still be a valid application, the project focus has now evolved into the use of pyrochemistry as an alternative to hydrometallurgy for treatment of transmutation targets and fuels. Two distinct chemical forms are most likely for this treatment method:

- oxide fuel dispersion in an inert matrix, for minor actinide transmutation;
- carbide fuel in an inert matrix (probably silicon carbide) for use in the gas-cooled fast reactor.

Pyrochemistry has a number of potential advantages that make it attractive for future applications:

- rapid reaction kinetics due to the high operating temperatures;
- radiation resistant reagents;
- reduced concerns with criticality (as long as the fissile materials are retained in the salt phase);
- favourable economics when operated at very small scale (for example a few tonnes of spent fuel per year).

The CEA investigation of pyrochemical processing of spent fuel was advanced by the creation of a well-equipped pyrochemical laboratory in the Atalante facility at Marcoule. The initial direction of the programme was the study of fundamental phenomena associated with pyrochemistry; this resulted in some important findings regarding the behaviour of actinides in molten salt media and the effect of oxoacidity of the electrolyte salt on control of actinide speciation. Recently, there has been more work with specifically developed applications, such as salt/metal reductive extraction. The work that is being done is of excellent quality, but it must be emphasised that is only exploratory and should not be construed as nearing the technical feasibility demonstration stage.

Pyrochemistry should not be regarded as a competing concept to aqueous techniques for reprocessing; as correctly stated in the report, the application fields are different. Wherever reprocessing is necessary, the most suited process should be chosen. Pyrochemical technologies should be developed, not to replace aqueous processes, but to be used where they seem to be advantageous in giving the required result, for example for short-cooled fuels, for fuels which are difficult to dissolve in nitric acid, or for integrated reactor-reprocessing-recycle fuel fabrication units.

It is important to note that a grouped actinide recycling might be easier to realise for the pyrochemical process in comparison to an aqueous technique; however, it remains to be seen whether the goal recovery rates and adequate decontamination levels are achievable. This could hinge on the development of a multistage extraction process that can be realised at full scale.

A drawback of the molten salt technology is the high temperature required for the process. The CEA, in collaboration with the CNRS, has conducted research programmes to investigate the use of low temperature or room temperature ionic liquids for pyro-reprocessing purposes; continuation of these studies may yield technologically useful results.

The salt-metal extraction process is an excellent option because it allows an efficient separation from lanthanides. This issue might be less important if the separated materials are conditioned and not recycled but of high importance if partitioning is followed by transmutation.

The use of a liquid cadmium cathode in molten salt electro-refining might be an interesting option but the poor separation of lanthanides, already found for Pu, would be even worse in the case of americium and curium. In addition to the difficulty of obtaining an adequate salt-metal contact surface, the handling problems of strongly volatile cadmium add complications. The IRT is doubtful that a full grouped recycling of actinides would be possible with electro-refining on a liquid cadmium cathode.

It should be noted that within the framework of the EUROPART programme, where many of the results presented in this report were also obtained, the waste treatment issue is a major subject of investigation. The treatment of the used molten salts and metals and of other secondary wastes is to be developed together with the process itself, because it is believed important to treat the process from the beginning as a whole, thus avoiding later criticism for an unsolved waste problem. The report does not contain information on any current CEA studies related to immobilisation of pyrochemical salt wastes, although it is understood that there has been a limited collaboration with the US programme on this matter.

The pyrochemical studies carried out during the last seven years have shown the growth of experience for complex investigations of actinides. One of the key results of this work is the development of an experimental capability for high quality pyrochemical investigations in France.

2.4 Product conversion

The choice of the oxalate precipitation process seems appropriate, particularly in light of the commercial experience with plutonium, but the co-precipitation of curium with uranium has not yet been done in the laboratory.

The concepts for curium storage seem to be sound, and the cost may be minor compared to the additional cost of shielded and remotely operated fuel fabrication facilities that would be required for curium recycle.

The CEA plan is to convert plutonium, neptunium and americium to their oxides and store these materials in powder form until they are due to be fabricated into fuel or targets. It is noted that the storage period could be a number of years. Curium is to be converted to the oxide and stored, with a

uranium oxide diluent, for the nearly two hundred years required for the decay of the ^{244}Cm isotope. Conversion to the oxide would be by means of the oxalate precipitation process, whereby the nitrate solutions of the transuramics are contacted with oxalic acid to form precipitates of the transuranic elements. It appears that co-precipitation of neptunium with plutonium is possible and this process requires little development because oxalate precipitation of plutonium is already in commercial practice at the La Hague plant. Americium would also be converted by the oxalate precipitation process and stored as americium dioxide (AmO_2) powder. Curium would be co-precipitated with uranium in the proper proportions. There have been small-scale experiments on the precipitation of americium, but the co-precipitation of curium with uranium has not yet been done in the laboratory. Transuranic losses in the precipitation and filtration steps are not known, but apparently the plutonium experience is satisfactory. The choice of oxalate precipitation seems appropriate, particularly in light of the commercial experience with plutonium.

The CEA has undertaken a conceptual study of the storage of mixed uranium/curium oxide powders, whereby the powders would be doubly encapsulated in stainless steel canisters with the internal canister having a diameter of 25 mm and a length of 250 mm. Four canisters would be placed in a stainless steel casing that is backfilled with helium and welded shut. The design basis maximum internal pressure of the casing is 45 bars, accommodating helium build-up due to alpha decay of ^{244}Cm . A vented design might be preferred, unless there is no intent of opening the casing at any time in the future.

The determination has been made by the CEA that americium oxide and neptunium oxide powders can be stored in existing facilities used for plutonium oxide storage. It may be necessary to dilute the americium oxide powder with uranium oxide or plutonium oxide to accommodate the higher decay heat generation, but the proposal seems sound. A great deal of thought has gone into the design of a storage facility for the separated uranium/curium oxide powder. The encapsulated material could be stored in a spent fuel storage basin or in floor silos such as those used at La Hague for storage of vitrified waste. Both concepts seem to be sound, and the cost may be minor compared to the additional cost of shielded and remotely operated fuel fabrication facilities that would be required for curium recycle.

One of the goals for enhanced partitioning stated by the CEA is the recovery of more than 99.9% of the caesium present in the PUREX raffinate. However, the CEA plan does not indicate any plans for the disposition of the separated caesium; if sent to the vitrification stage then there would have been no reason to separate it. It must be assumed that the intention is to store the

caesium and allow the ^{137}Cs to decay. This is a reasonable approach, but the decay heat rate of ^{137}Cs (together with its daughter $^{137\text{m}}\text{Ba}$) is not much less than that of ^{244}Cm . This means that the storage requirements for caesium are much more significant than those for curium, and planning for this storage should take place.

2.5 Recovery from glass

The conclusion not to continue with the investigations for recovery of minor actinides and fission products from a vitrified matrix or to store the calcines seems entirely reasonable.

The idea to recover minor actinides and fission products from a vitrified matrix seems to be problematic and not easily realisable. Both routes suggested, that is either dissolution after mechanical crushing or quenching of molten glass, are certainly very difficult to carry out, especially at large scale. The first option involves very high costs and the safety hazards of dealing with hydrofluoric acid, the second the addition of less aggressive sodium oxide. In both cases the recovery rate for the long-lived fission products and minor actinides is not known and losses could be considerable. If one considers furthermore that the industrialisation of such a process will certainly be extremely difficult, then the recommendation can only be to refrain from implementing such a process; extensive further R&D work would be required but with great uncertainty on the final result.

The alternative option, to store the waste constituents separated in the PUREX process in the form of calcines, seems to be equally complex and difficult to realise; thus the conclusion in the report not to continue with the investigations for any of the two options seems entirely reasonable.

3. REVIEW OF SPECIFIC ASPECTS: TRANSMUTATION

3.1 Introduction

The transmutation studies looked at using existing reactors as irradiation sources but with some reference to new reactor technology. Although the various reactor scenarios were excluded from the terms of reference, it seemed to the IRT that some cognisance had to be taken, since they all influenced the P&T programme in some way.

The development work was recognised as being carried out to a very high standard. The IRT agreed that a range of irradiation facilities, including systems with a fast neutron spectrum, would be required for full management of plutonium and minor actinides. Much work remains to be done on actinide fuels and targets, especially fabrication aspects; fabrication of fuels containing curium will pose particular problems.

The conclusions of the impracticability of transmutation of the selected fission products were accepted by the IRT.

This section covers Chapter D of the report and considers the results of studies on transmutation looking particularly at:

- transmutation possibilities in thermal or fast critical or sub-critical reactors;
- the validation of nuclear data and calculation methods;
- actinide fuels and targets as well as fission product targets;
- ADS development with a view to the spallation target, the accelerator, the sub-critical reactor, and design studies.

3.2 Transmutation systems

The principal goal of the research carried out under Area 1 of the Law of 1991 is to reduce the long-term radiotoxic inventory of the high-level waste. Both homogeneous and heterogeneous recycling of minor actinides in either PWRs or fast reactors are considered. The transmutation of separated fission products (^{99}Tc and possibly ^{129}I) in the form of targets is also studied.

On the whole, the CEA scenarios underlying the Area 1 research take into account the existing installations (the large fleet of PWRs and associated fuel cycle facilities which cannot quickly be replaced by other types of installations) and their respective knowledge base. At the same time, France is a partner of the Generation IV International Forum (GIF), which now focuses much of its R&D on innovative reactor systems with associated fuel cycle technologies.

3.2.1 General observations regarding the global scenarios

The scenarios reflect a preference for managing the transuranium elements, as far as possible, in PWRs, accounting for the fact that the French nuclear fleet is essentially made up of PWRs. Heterogeneous recycling of americium and curium is preferred to avoid contamination of the commercial fuel cycle.

An assessment of the reported achievements requires an understanding of the priorities assigned to the different Area 1 research areas. These priorities are linked to “global” fuel cycle scenarios which reflect the strategy of the CEA in implementing the Law of 1991.

The features of the scenarios requiring special attention are discussed in Chapter E of the report and are summarised in Table 1. In general, the P&T scenarios studied by the CEA are equivalent to those studied in other countries.

Table 1. Summary of the scenarios considered
[RF = radiotoxicity reduction factor relative to open cycle]

Pu burning in PWR RF: Low (~5)	Pu is multi-recycled in PWRs alone. Different fuel concepts: MOX-UE, APA, CORAIL, MIX. Increased demand for ^{235}U enrichment.
TRU burning in PWR RF: Modest for Pu-Am recycling	Fuel cycle is closed for all TRU. Np and Cm recycling leads to (undesirable) build up of ^{238}Pu and Cf. Consequently, only Pu and Am can be recycled.
Heterogeneous mono recycling RF: Modest (~60)	Am (and Cm) are recycled once as targets in FRs. Np is multi-recycled homogeneously in MOX fuel. Option: Cm is stored until it is decayed to Pu.
Double strata fuel cycle RF: High (>100)	Fuel cycle in the 2 nd stratum fully closed. Requires innovative technology in the 2 nd stratum but the LWR/ADS support ratio is high.
All FR transmutation strategy RF: High (>100)	Fuel cycle is closed for all TRU. U is not recycled. MAs are diluted in the whole fuel cycle.

It seemed relevant to the IRT to make some general observations on these global scenarios which had bearing on the P&T programme:

- The scenarios are based mainly on Generation III reactors (EPR-type PWRs and EFR-type sodium-cooled fast reactors). Generation IV fast reactors are considered as long-term alternatives.
- The scenarios reflect a preference for managing the transuranium elements, as far as possible, in PWRs, accounting for the fact that the French nuclear park is essentially made up of PWRs. Symbiotic PWR-FR systems are considered only when an actinide (for example curium) cannot be transmuted in PWRs.
- The scenarios are basically those with partially (or semi-) closed fuel cycles where minor actinides are separated and recycled either homogeneously or heterogeneously. Heterogeneous recycling of americium and curium is preferred to avoid contamination of the commercial fuel cycle. Uranium is not recycled.
- The scenarios were devised such that the fuels can be reprocessed with advanced aqueous reprocessing methods. Pyroprocesses are regarded as alternatives. For instance, the ADS fuel in the Double Strata scenario may require pyrochemical reprocessing.

3.2.2 Transmutation in thermal reactors

The CEA has studied a broad spectrum of possibilities for managing transuranic elements in PWRs. It appears that the incorporation of small amounts of minor actinides in the fuel can have a serious impact on the fuel cycle. The IRT agrees that the concepts are useful for managing plutonium but not worthwhile for managing the minor actinides.

The CEA has studied a range of innovative schemes for actinide recycling in PWRs. The principal challenge of the R&D is to develop a PWR fuel concept which maximises the minor actinide consumption while respecting the authorised operation limits (reactivity coefficients, safety parameters, etc.). An interesting feature of the transmutation in PWRs is that the core may be designed to make the net minor actinide production, while not negative, minimally small. This means that the systems can stabilise the minor actinide inventory, but are not true minor actinide burners. It should, however, be noted that the americium consumption is balanced by a similarly large curium production. It should also be noted that the incorporation of small amounts of minor actinides in the fuel could have a major impact on the fuel from the viewpoint of its fabrication, its transport and its irradiation behaviour.

While the neutronic calculations confirm the feasibility of the thermal americium recycling for several cycles, it is not proven that the fuel composition would ever reach equilibrium. Pending this proof, the option of a later transfer of the americium to a fast reactor fuel cycle must be kept open. Moreover, even if the number of possible recycles could be shown to be unlimited, the PWRs would not have the necessary neutronic potential for “burning” their own minor actinide inventories. This means that the strategy could not be applied in a shrinking reactor park, for example in a phase-out situation.

Considering these difficulties as well as the relatively modest radiotoxicity reduction potential of a thermal plutonium-americium burning strategy, the IRT supports the conclusion of the CEA that although the multi-recycling of americium in PWR fuels is possible in principle, it is not an attractive option, even in the most favourable case of MOX-UE fuels.

3.2.3 Transmutation in critical fast reactors

The IRT agrees that fast neutron spectra are necessary for a successful transmutation programme. The IRT fully supports the long-term perspective to manage minor actinides in a nuclear park which contains a significant number of fast reactors, but would like to emphasise the need for short and medium-term development and demonstrations necessary to achieve the long-term goal.

As regards transmutation in critical fast reactors, three scenarios were investigated by the CEA:

- the all FR reactor park where the transuranium elements are homogeneously recycled in the fuel;
- the heterogeneous mono-recycling of americium and curium as moderated target assemblies with direct disposal of the irradiated targets;
- the heterogeneous multi-recycling of americium and curium as specially designed fuel pins or assemblies.

The first and the second are global scenarios as discussed in Chapter E of the report.

The principal R&D challenges for the heterogeneous mono-recycling scenario are:

- the neutronic design of a moderated target assembly which achieves a high transmutation rate while avoiding undesired power peaking in the core;
- the selection of suitable compounds/materials for the “fuel”, the support matrix, the moderator and the cladding with regard to the goal of fissioning at least 90% of the actinides without excessive damage to the materials.

Whereas the neutronic feasibility of the heterogeneous mono-recycling scenario can be assumed to be proven, this is not yet the case for the technical feasibility, for example ensuring fuel pin integrity to such high burn-up.

The all fast reactor transmutation strategy, where fast reactors replace the existing PWR fleet, is unique in that it manages all minor actinides while requiring no enriched uranium at all. As the minor actinides are diluted in the whole fuel cycle, their concentration in the fuel is small. The feasibility of this fuel has been experimentally demonstrated. Because the path to equilibrium of an all fast reactor park will be very long, the IRT recommends that the CEA considers the scenarios of the symbiosis of PWR and FR, which will be the inevitable situation in deploying fast reactors. There is no way to go from all PWRs to all FRs without taking the symbiotic route. The IRT has to express a concern that the short- and medium-term development programmes of a Generation IV fast reactor and its associated fuel cycle are neither mentioned nor considered as a related part of the Area 1 study.

3.2.4 Transmutation in accelerator driven systems

The IRT agrees that the ADS has a role to play in the double strata system where all plutonium is utilised in commercial power reactors and minor actinides are destroyed in the ADS. However, the ADS still requires substantial development.

One way to handle minor actinides is to concentrate them in a specific “stratum” using systems which are dedicated to transmutation. The accelerator driven system (ADS) is well known as a possible means to transmute large amounts of minor actinides. In 2001, the CEA and the CNRS prepared and presented a dossier [see reference CEA-01 in the CEA Axe 1 Report’s Bibliography] outlining the need for a hybrid demonstrator. The report’s conclusions confirmed the interest of ADS in actinide transmutation. The spallation target and the accelerator are main components of an ADS and as

such are an integral part in the demonstration of the ADS concept. The ADS activities of the CEA, as all French activities in this field, are highly integrated into the European activities and follow the European Roadmap.

The fact that the neutron multiplication factor of the core of an ADS is smaller than 1 and that the neutron flux in the core is controlled by adjusting the accelerator beam current has important consequences for the static and dynamic behaviour of the core. In particular, a continuous measurement of the sub-criticality level is a new requirement which is not known in critical reactors.

In agreement with other economic studies, the CEA Report concludes that the ADS is not a competitive electricity producer. This conclusion is also supported by the CNRS. The reasons are the additional cost of the target and the accelerator and the reduced overall electrical efficiency of the system since a fraction of the generated electricity is used by the accelerator. This means that the role of the ADS in nuclear energy scenarios is restricted to applications where a small number of ADS facilities perform a special function which cannot be performed by critical reactors. The predestined application of the ADS is, therefore, that of the minor actinide burner in a double strata (see Table 1) scenario, where the sub-critical state compensates for the degraded characteristics of a fast-spectrum core which is heavily loaded with minor actinides. In this scenario, the fraction of ADS facilities is so small that the high capital cost of the ADS does not have a major consequence on the cost of electricity. This is confirmed by the OECD/NEA Expert Group study [see reference NEA-1 in the CEA Axe 1 Report's Bibliography] and other economic studies.

3.3 Supporting R&D

3.3.1 Nuclear data and calculation methods

It is the evaluation of the IRT that the CEA has done an outstanding job in creating and validating the neutronic codes. The IRT found that the database is extensive but in the future will need more data that is relevant to cores with significant minor actinide loading. Additional work will be needed to obtain more accurate predictions of situations involving minor actinide loadings in thermal reactors, fast reactors, and accelerator driven systems.

The analyses of various transmutation concepts rely heavily on neutronics codes that calculate parameters of importance such as criticality, flux distributions and isotopic compositions. In turn, these parameters are used to evaluate the transmutation performance of the various systems proposed.

Heavy reliance on codes puts a special importance on the validation of these tools. It is the evaluation of the IRT that CEA has done an outstanding job in creating and validating these codes. Throughout their work, the CEA has used a consistent set of tools for their evaluation: the JEF2 nuclear data files and the APPOLLO and ERANOS codes. Consistency in analytical tools is a strong guarantee for the quality of the results. These codes include state-of-the-art algorithms for evaluating key neutronics parameters, in particular for spatial heterogeneities and energy related treatments. The JEF2 library has been very extensively validated based on both French and European experiments. In general, this library behaves very well, and its weaknesses are well defined; of particular importance is the need to obtain better nuclear data for minor actinides.

The CEA has used a solid approach for validating their codes. A first step was to obtain numerical validation, based on comparisons with reference codes. A second crucial step was to compare calculated values to experimental results and the CEA has used a well developed experimental database that covers many of the situations of interest. The IRT found that the database is extensive but in the future will need more data which is relevant to cores with significant minor actinide loading. The CEA has used systematic approaches (slightly different for thermal and fast spectra) to analyse these experimental requirements. The IRT concurs with this approach, but would like to suggest that a more systematic understanding of numerical biases and statistical experimental variances be developed.

The IRT concurs that the uncertainty estimates produced by that process are correct. The IRT would also like to point out that there remain significant areas where improvement should be sought, foremost for minor actinide related cases. In most cases, these uncertainties do not have a significant effect on the technical conclusions drawn by the CEA. In particular, the comparisons of various fuel cycles they have performed are valid. Additional work will be needed in the future to obtain more accurate predictions of situations involving minor actinide loadings in thermal reactors, fast reactors, and accelerator driven systems.

3.3.2 Actinide fuels and targets

The quality of the research programme on the transmutation fuels is generally of a high standard. The CEA research has addressed various scientific problems of these fuels and has produced important data for the fuel selection.

The report does not explain why the work concentrated on the so-called heterogeneous transmutation using an inert support matrix rather than follow up the homogeneous transmutation work of the Phénix and Superphénix fuel development.

An analysis of the impact of minor actinides recycling is missing in Chapter D of the report.

There is no detailed discussion of how the CEA will perform its fuel development programme after 2009 in relation to the Generation IV reactor development, although this appears a crucial issue to the IRT.

The R&D programme described in the report focused on the fabrication of the minor actinide fuels and targets and the tests to investigate the irradiation behaviour. The minor actinide transmutation schemes that are addressed are various, but broadly classify into homogeneous and heterogeneous recycle schemes. The system using an ADS for transmutation may be regarded as the extreme case of the heterogeneous recycling.

The overall rationale behind this part of the programme is not very clear from the report. Contrary to the partitioning part of the programme, in which the technological developments are based on extending the existing industrial process (PUREX), the fuel and targets research programme seems to address mainly highly innovative fuel and target concepts, while (European) industrial experience is almost limited to uranium dioxide and MOX in a metal clad fuel pin. The so-called homogeneous transmutation in fast reactors using oxide fuels would have been the logical follow-up of the Phénix and Superphénix fuel development, compatible with aqueous partitioning, but no activity in this field has been initiated since 1991, except for TRABANT1 test. This is surprising since the SUPERFACT experiment on oxide fuels with significant minor actinide content was very informative and the CEA and ITU successfully demonstrated the complete cycle of fabrication, irradiation and reprocessing of this type of fuel. The report does not explain why this route was not followed further and why the work concentrated on the so-called heterogeneous transmutation using an inert support matrix.

Concerning the heterogeneous recycling scenario with either a fast reactor or an ADS, extensive studies have been made to identify the proper matrix for the uranium free composite fuels and targets. The results narrowed the candidates, but further extensive studies are necessary before really viable fuel and target materials can be selected. The design and development of such composite fuels and targets are, by definition, much more difficult due to the lack of an existing database.

Nevertheless, the quality of the research programme on the transmutation fuels is generally of a high standard. The CEA research has addressed various scientific problems of these fuels and has produced important data for the fuel selection. The emphasis of the work has been mainly on irradiation studies, which involve time-consuming and complicated research activities. The CEA has unique facilities for this type of work, with of course Phénix and Atalante as key tools. It is good to see that this reactor is used intensely for the P&T programme until proposed final closure in 2009. It is also good to see that use is being made of the other irradiation facilities still available in Europe (HFR) and that many other European research institutions have been involved in the programme. The EFTTRA and THERMET experiments have contributed significantly to the understanding of composite fuels in areas such as the importance of the size of the included phase and the role of irradiation damage to the matrix. However, the work described mainly addresses the macroscopic aspects of the transmutation fuels, less so the microscopic ones which are probably the key to the design. Moreover, from the report one gets the impression that the work is not sufficiently supported by fundamental physico-chemical studies. The fabrication of fuels with such complex chemical compositions needs better understanding of the phase relationships and interactions.

The technical implications of the alpha decay heat, the fast neutron emissions and increased gamma doses associated with the handling of minor actinides, such as americium and curium, need to be discussed for the public to grasp the real technical obstacles. However, the analysis of the impact of minor actinides recycling on the other process steps is missing in Chapter D of the report. There is only limited experience with the fabrication of americium fuels, and almost none for curium, but a discussion of the implications would have been useful, especially since the fuel fabrication seems to be a key issue for feasibility of transmutation. A discussion of alternatives to solid fuel (for example molten salts as proposed in the TASSE reactor design of the CEA and AMSTER of EDF) would have been useful in this context.

Advances have also been made in fabrication technologies which are suited to remote handling and which show economic benefit. However, the

experimental capability of handling substantial amounts (kilograms rather than grams) of minor actinides is lacking anywhere in the world. There is limited capacity of existing fast neutron fields and the available R&D infrastructure is deteriorating. After the end of operation of Phénix in 2009, an important tool for the transmutation research programme will be lost.

It seems to be premature that the fuel programme has proceeded so far that the next phase will be the testing of fuel pins, for example in MONJU as suggested in the report, without any prior experimental irradiation programme. The IRT considers that much work on fuel design and development will still be needed before that phase can be entered, especially when the composite design is pursued. In case of the mixed oxide route this may be feasible, however, the report does not address in detail how the CEA will perform its fuel development programme after 2009 in relation to the Generation IV reactor development, although this appears a crucial issue to the IRT.

The GEN IV programme is only briefly mentioned in the section on mixed fleet scenarios in Chapter E of the report. It would be useful if the report would make clear that the homogeneous transmutation scenario in fast reactors is approaching the GEN IV concepts and therefore a statement on the French GEN IV strategy would be welcomed.

3.3.3 Fission product targets

The impracticability of transmutation of fission products is evident from the arguments presented, if however, radiological risks and/or heat production were to be considered, then more prominence ought to be given to alternative routes for disposal of specific long-lived fission products.

Relatively little attention is given to fission product transmutation, though the fission nuclides dominate the radiological risks of geological storage. The choice to focus the work on iodine, technetium and caesium has not been motivated by the probable conditions of a possible French repository. The geochemical mobility of an element, and thus the risk of it reaching the geosphere depends strongly on the redox conditions of the host rock and engineered barriers of the repository. Technetium, for example, is only mobile under (strongly) oxidising conditions, and its potential mobility thus only relevant to very specific conditions. How relevant technetium is in the probability assessment of French repository designs is unclear.

The conclusions on the feasibility of fission products are very definite in view of the limited work performed, especially for iodine, the transmutation of

which is stated as impossible. The main text, however, does not present strong arguments why sodium iodide (NaI) cannot be used as target material. In spite of that, the conclusions on fission product transmutation may be right in general, but it is a pity that reference to alternative solutions such as conditioning in ceramics or glasses (immobilisation) after partitioning, are not mentioned.

3.3.4 ADS development

The CEA and its partners have a well-focused R&D programme for spallation target development (lead-bismuth target with window). In view of the difficulties, the IRT believes parallel development of a simpler target should be considered.

The IRT agrees that modular linear accelerators are most appropriate for industrial ADS systems.

The IRT concurs with the collaborative approach to ADS development and considers that the EUROTRANS project will be key to deciding on the future development of ADS systems.

3.3.4.1 Spallation target

The spallation target is the most challenging component of the ADS. The CEA accounted for this by launching, together with its partners, a very comprehensive and well-focused R&D programme for the development of a lead-bismuth cooled target. A target with a window was chosen as the reference. The programme, ranging from small, special effects experiments to large, integral experiments started some time ago and some encouraging results have already become available. However, the present results do not yet allow definite conclusions to be drawn on the viability of such a target. In view of the open issues (corrosion potential of the lead-bismuth, behaviour of the window under the complex stress and irradiation conditions prevailing in an ADS, the need for instrumentation, difficult handling and replacement of the target and impact on cost), it would be sensible to develop an alternative, “simpler” target concept in parallel.

As to the integral experiments, the MEGAPIE experiment is the most important. The MEGAPIE target, a complete spallation target designed for a beam power of 1 MW and 6 Ah of accumulated current, was successfully manufactured in France and will be tested in the spallation neutron source at the Paul Scherrer Institute in 2006. The experiment will provide a full feasibility demonstration, including the in-pile and post-irradiation testing of all components, as well as the demonstration of the decommissioning.

3.3.4.2 Accelerator

The report claims that, at a power level required for an industrial ADS, modular linear accelerators are the favoured option. This claim is justified and is based on the outcome of the PDS-XADS project within the 5th framework programme of the EC, where the potentialities of LINACs and cyclotrons were compared with each other. In particular, the PDS-XADS study concluded the following for the superconducting LINAC:

- no limitation in energy and in intensity;
- highly modular and upgradeable design, thus applicable to the industrial transmuter;
- excellent potential for reliability, as it can allow the fault-tolerance design approach;
- high efficiency, allowing optimisation of operating cost.

As stated in the report, a major requirement for application of the ADS is the reliability of the accelerator that is a very low number of beam interruptions or so-called beam trips. Beam trips that last longer than say a second may lead to unacceptable thermal stresses to components of the sub-critical system and their number must therefore be limited.

The accelerator comprises an injector, an intermediary energy zone (room temperature or superconducting cavities) and a high energy zone with superconducting cavities. The report mentions the need to focus on the experimental evaluation for the main modular components of the reference accelerator configuration but restricts itself to actions related to the injector and the high energy zone.

In the report, the IP EUROTRANS project under the EC 6th Framework Programme is mentioned; this is essential information needed to understand the statements made in the “accelerator” section of Chapter D4.5 of the report. It should be noted that the IP EUROTRANS accelerator work package has the following main tasks:

- experimental evaluation of the proton injector reliability;
- assessment of the reliability performance of the intermediate energy accelerating components;
- qualification of the reliability performance of a high-energy cryo-module at full power and nominal temperature;
- design and test of a prototypical radio-frequency control system for fault-tolerant operation of the linear accelerator;

- overall coherence of the accelerator design, final reliability analysis, cost estimation of XT-ADS and EFIT.

3.3.4.3 Sub-critical reactor

The objectives of the MUSE experiments in the zero-power reactor Masurca at Cadarache were to contribute to a better understanding of the neutronic phenomena in a sub-critical core, to develop new experimental techniques in support of the sub-critical operation and to contribute to the validation of nuclear data and computer codes. The experimental set-up consisted of a strong pulsed neutron generator (Genepi, developed by CNRS), a deuterium or tritium target in the centre of the core surrounded by a lead buffer zone and an annular, MOX fuelled, core. Two coolants, sodium and a lead-bismuth alloy, were simulated.

The MUSE experiments provided unique reactor physics information with regard to both code validation requirements and the development of sub-criticality measurement techniques. The prompt neutron decay method was found to be particularly suited for an on-line measurement of the sub-criticality level. It should, however, be noted that compared to the MUSE experiments, the core of an industrial minor actinide burner will be larger, use a different fuel and operate at a much higher power; moreover the burn-up reactivity prediction for minor actinide dominated cores has yet to be verified. This means that the reactor physics information from the MUSE experiments may be sufficient for the design and start-up of an experimental ADS with normal MOX fuel, but not for the operation of an industrial ADS with uranium-free transmutation fuel.

3.3.4.4 Design studies

Design studies for an experimental ADS were carried out in the PDS-XADS project of the 5th Framework Programme of the EC. Three concepts were considered in this project: an 80 MWth lead-bismuth cooled system proposed by ANSALDO, an 80 MWth gas-cooled system proposed by Framatome-ANP, and the 50 MWth lead-bismuth cooled MYRRHA system of SCK•CEN. Common features are the choice of a linear accelerator and the use of lead-bismuth eutectic (LBE) as target material (a helium-cooled solid tungsten target is an alternative option for the Framatome system). For the accelerator/target interface, concepts with a window (ANSALDO, Framatome) and without a window (MYRRHA, ANSALDO) were considered.

The engineering studies for the XADS confirmed that an ADS in the 100 MWth power range is feasible with no barriers to progress identified. However, several questions concerning the accelerator and the target remain open. The integrated EUROTRANS project of the 6th Framework Programme of

the EC was set up with the goal of answering these questions and preparing a common reference design for a European industrial ADS by 2008. If the outcome of the project is positive, a decision on the construction of a demonstrator is envisaged in the same year.

4. CONCLUSIONS

4.1 Scope and limits of the report

- The report presents many areas of excellent technical work, but it is written in a way which makes it difficult for the reader, especially one who was not well acquainted with the technical areas reported, to follow and understand easily. It would be helpful to produce a more readable version to inform the non-specialist reader for the forthcoming debate on the new nuclear waste law.
- The report does not try to address an integrated approach to the effects of P&T on the whole fuel cycle. For example it does not look at the implications of minor actinide recycling on fuel fabrication, or at the consequences of P&T implementation on final disposal repository performance. It will be necessary to produce this more comprehensive overview at some point in the near future.

4.2 Strategy

- Much of the technical work reported is of a very high standard. However the underlying strategic logic of the approach is not obvious from the presentation.
- The level of development of the various technical areas is different. Chemical partitioning of PWR spent fuel is very well developed, with some excellent work. The research on transmutation fuels and targets (fabrication, performance testing, and subsequent chemical processing) is still at an exploratory stage. More worryingly, shrinking R&D infrastructures and especially a lack of fast neutron irradiation facilities would endanger progress in this area.

4.3 Objectives

- The IRT notices that the goals of the research are all stated in terms of radiotoxicity reduction. There are two perspectives with respect to the management of the long-term hazard of the waste, namely to reduce the

total radiotoxicity inventory or to reduce the long-term radiation dose to populations from any future disposal and some discussion on this point would be beneficial. P&T of actinides addresses the first while P&T of fission products would be more directed at the second. P&T might also have a possible role in the efficiency of repository use, through a reduction in the heat loading and volume of waste to be disposed.

- The goals set for partitioning and transmutation levels have no clear basis being set by what might be achievable rather than established by what is necessary to achieve some outcome objectives (e.g. reduction of heat level in the repository, reduced dose to the public from final disposal).

4.4 Achievements and IRT agreements

- The CEA has done excellent work to demonstrate that technically feasible pathways exist for the management of plutonium in light water reactors.
- The scientific and technical aspects of aqueous partitioning are well founded. They provide a high level of confidence of the ability to deploy those processes in advanced fuel cycles.
- The IRT agrees that management of minor actinides in light water reactors is not sensibly possible and that fast neutron fields are necessary for successful transmutation approaches.
- The IRT fully supports the long-term perspective for the management of minor actinides in a reactor fleet which contains numbers of fast reactors.
- The IRT agrees that transmutation of fission products for radiotoxicity reduction is not practical.
- The IRT also agrees that retrieval of minor actinides from glass is not worth pursuing with the currently available technologies and that the intermediate storage of calcines to await future transmutation is not an attractive approach.

4.5 Further developments and alternatives

- Although the IRT supports the vision of long-term management of minor actinides via fast reactors as a practical possibility, it would like to emphasise the need for the short and medium developments and demonstrations that will be needed to make the transition and achieve the long-term goal.

- The current level of fuel development, spallation target technology and accelerator reliability means that significant progress is still required for an ADS. Such development work is underway via the IP EUROTRANS project and the IRT believes that the CEA and CNRS contributions to this programme should continue to be pursued.
- With respect to pyrochemical technology, it has been appropriately directed in the French programme to speciality applications. It is a technology which holds promise but it is at an early stage of development.

5. RECOMMENDATIONS

The IRT makes the following recommendations based on its review of the report 2005, including additional written material supplied by the CEA and discussions held with the CEA and the CNRS. The IRT is aware that considerable work has been conducted for the other two areas of research stipulated by 1991 Law. It may be that some of the further work recommended here has already been covered by the research and development conducted for Areas 2 and 3.

5.1 Scope and limits of the report

- A more readable version of the report should be produced, designed for the non-specialist audience. This would better enable the results of the work to inform the debate on the new French nuclear waste law.
- The report does not try to address an integrated approach to the effects of P&T on the whole fuel cycle. For example it looks neither at the implications of minor actinide recycling on fuel fabrication, nor at the consequences of P&T implementation on final repository performance. This more comprehensive overview should be produced in the near future.
- P&T is almost always considered in terms of reduction of radiotoxicity in the report. Other criteria, such as reduced heat loading to the repository, reduced waste volume or the impact on the full cycle cost should also be considered.

5.2 Aqueous partitioning and pyrochemistry

- The value of setting recovery goals for actinides and fission products is acknowledged, but the IRT recommends that these should be set on some clear and rational technical basis.
- Recycling technology for transmutation fuels and targets should be developed in close relationship with the fuels and target development programme itself.

- It is not clear how neptunium might distribute itself between the uranium and plutonium streams in the PUREX process. Consideration should be given to such distribution, its consequences and its control.
- It is not obvious that the separation of americium and curium is a necessary process step. An evaluation study should be made on this and other options including future use of separated material.
- If reduction of heat load from the waste is a valued objective, the separation of strontium should also be considered.
- If the promising pyrochemical processes are to be further developed and employed then:
 - the necessary waste management processes (for example the immobilisation of pyrochemical salt wastes) should be developed in parallel;
 - the partitioning performance, fission product behaviour and process equipment development must be demonstrated.

5.3 Product and fission product management

- The proposal for storage of uranium/curium oxide powders is for canisters that can accommodate up to 45-bar pressure from build up of helium. The IRT considers that a vented design to avoid pressure build up should be explored in view of the difficulties which might be experienced upon subsequent reopening.
- Plans and technologies for the management and disposition of separated fission products should be developed.
- The management of caesium may require its long-term storage. Consideration of its long-term storage arrangements (like that undertaken for curium) needs to be conducted.

5.4 Fuels and targets

- The report should address more fully the difficulty of handling of multigram quantities of minor actinides, particularly americium and curium, in the fuel cycle, caused by the large decay heat and the significantly higher neutron and gamma emissions, as well as their particular physical and chemical properties.

- The overall rationale behind the fuel and targets R&D needs to be developed or explained. It is not obvious, for example, why homogeneous transmutation in fast reactors using oxide fuels has not been followed up after its promising start.
- All fuel designs, in addition to those for the homogeneous recycling of americium and neptunium in mixed oxide fuel for fast reactors, need further validation.
- Considerable further work is required before viable fuel and target materials can be selected. The microscopic aspects of transmutation fuels and a better understanding of the phase relations will need to be addressed in this development process.
- Fuel and target development after 2009 with the closure of Phénix will be difficult. A strategy for how this work will be conducted and the fuel designs validated needs to be developed; this links to the work programme for the French Generation IV fuels work.

5.5 Strategy: transmutation

- The IRT accepts that long-term management of actinides via fast reactors is a practical possibility. With this in mind the IRT recommends:
 - development of the short- and medium-term programme necessary to achieve the longer-term goal;
 - consideration of the transition scenarios between a PWR based reactor fleet and one containing significant numbers of fast reactors;
 - integration of any French development programmes for Generation IV fast reactors and their associated fuel cycle, which are not addressed in the report.
- With respect to nuclear data and calculation methods, there will be a need to obtain better nuclear data for the minor actinides and the experimental database will need more data relevant to cores with significant minor actinide loadings. The IRT would also like to suggest that a more systematic understanding of numerical biases and statistical experimental variances be developed.
- For ADS systems, integration of the French R&D into the European programme is fully supported for the continuation of this work. A lead-bismuth target with a window has been chosen as the reference design. In view of the technical uncertainties it would be sensible to develop an alternative, simpler target concept in parallel.

Appendix 1

PEER REVIEW BY THE OECD NUCLEAR ENERGY AGENCY: TERMS OF REFERENCE OF THE INTERNATIONAL REVIEW TEAM

Background

Radioactive waste management has been a technical issue in France since the first reactors were built and operated in the 1960s. Deep geological disposal of these wastes was already considered as a potential solution, to be investigated, notably through underground facilities for in-situ geological characterisation.

Following unsuccessful siting attempts by the French Atomic Energy Commission (CEA) to start preliminary geological surveys in 4 sites, the French government decided in 1989 to involve the Parliament in the decision-making process, at first, through hearings, and then through the proposal of a Waste Act finally voted at the end of 1991.

The 1991 Waste Act defines the general frame of research and development and identifies three areas concerning the management of high-level and long-lived radioactive waste, as well as a 2006 milestone for decisions by the Parliament about the possible implementation of proposed solutions.

The CEA is in charge of two of these R&D areas foreseen by the Waste Act. Namely:

- Area 1: partitioning and transmutation (P&T);
- Area 3: waste conditioning and long-term interim storage.

Research on P&T has been conducted by CEA and CNRS (*Centre national de la recherche scientifique*) teams, together with some French Universities.

The Waste Act foresees a global assessment of all the areas of research in the year 2006. In this goal, the Act also created an Independent National Review Board (*Commission nationale d'évaluation*, CNE) to inform and advise the government on the interim progress at technical and scientific level.

In order to prepare the 2005-2006 reporting approach which includes notably the global assessment of the three areas, as required by the Waste Act, the CEA has set out to produce at the beginning of 2005 a dossier: the “Report 2005: Partitioning and Transmutation of long-lived radio nuclides of high-level and long-lived radioactive waste: research and results”. A similar dossier concerning the waste conditioning and long-term interim storage (Area 3) has also been produced by the CEA.

The Report 2005: Partitioning and Transmutation

As an input to the 2005-2006 global assessment report to be produced by the National Review Board (CNE) for the decision making bodies (government and parliament), as required by the Waste Act, the CEA has produced a report concerning the conclusions on the feasibility of partitioning and transmutation of long-lived radionuclides.

The *Report 2005: Partitioning and Transmutation* compiles all acquired data and knowledge leading up to the CEA’s conclusions on the feasibility, under some specific conditions, of the partitioning and the transmutation of the minor actinides neptunium, americium and curium into short-lived or stable radio nuclides. This report takes also into account results acquired by CNRS in the case of programmes developed in co-operation with the CEA.

In this context, the *Report 2005: Partitioning and Transmutation* has the status of a report providing conclusions for the decision making process. After a general introduction (Chapter A) and a “Partitioning and Transmutation” introduction (Chapter B), the report is organised in the following order:

- Chapters C.1 to C.12 concern the results related to the partitioning of spent fuel and describe namely:
 - the possible retrieval of existing waste packages (Chapter C.3);
 - results of the aqueous partitioning of minor actinides and long-life fission products (Chapters C.4 to C.8);
 - assessment results of the intermediate storage of separated minor actinides (Chapter C.9);
 - results of the pyrochemical separation advanced process (Chapter C.10);
 - assessment of research results on partitioning and the future outlook, in chapters C.11 and C.12, respectively.
- Chapters D.1 to D.7 concern the results of studies on transmutation and look particularly at:
 - transmutation possibilities in thermal or fast critical or sub-critical reactors (Chapter D.4);

- the fabrication of fuel and targets and the transmutation experiments (Chapter D.5);
 - the assessment of research results on transmutation and the future outlook in connection with the sustainable development of nuclear energy in chapters D.6 and D.7, respectively.
- Finally, Chapter E looks at possible separation-transmutation scenarios in the future making it possible to use new type reactors, especially those with a fast neutron core operating in a critical or sub-critical mode.

The *Report 2005: Partitioning and Transmutation* is technically conclusive and is an essential input to the future political decision-making process.

It must be observed, however, that while it does claim technical feasibility of partitioning and transmutation and, as such, paves the way to the license application process for the corresponding future nuclear facilities, the *Report 2005: Partitioning and Transmutation* does not consider:

- optimisation, for instance, in terms of cost and safety;
- some scientific issues, for which a complete assessment has not yet been carried out but of which an overall evaluation is provided as a whole; this includes, for instance, accurate knowledge of some very specific transmutation nuclear data, or possible high power operation feasibility of sub critical systems still to be demonstrated.

Moreover, the nuclear cycle scenario studies, combining fuel production and processing aspects, which are Chapter E of the report, are considered out of the scope of the review since they are only specific to the possible French situation for the technological developments of the industrial tool to be made in relation with the relevant waste management scenario.

Peer Review of the NEA

General Context

Long-life radionucleides contained in spent fuel assemblies are responsible for radioactivity which lasts several thousand, even several million, years. Area 1 of the 1991 Waste Act requests that solutions be found to separate and transmute these long-life radioactive elements which are present in waste. The *Report 2005: Partitioning and Transmutation* is the conclusive report delivered by the CEA, presenting the results of the research programmes conducted in France from 1992 to 2004 both by the CEA and its main research partners, especially the CNRS.

It is the wish of the French government that the *Report 2005: Partitioning and Transmutation* should be a widely read and discussed document with the general aim of triggering the debate and building confidence.

Therefore, the French government considers it essential to submit this important report to a review by an independent team of international experts. The useful contribution provided to national programmes by earlier NEA reviews has led the French authorities naturally to ask the Agency to carry out a peer review of the CEA's *Report 2005: Partitioning and Transmutation*.

The scientific and technical different issues of the report to be reviewed are shortly presented below.

General objectives of partitioning and transmutation studies

Plutonium is the largest contributor to the radiotoxic inventory of spent fuel. In order to implement a long-life radio nuclide separation-transmutation strategy, a plutonium management strategy has first to be implemented. Plutonium recycling in reactors is the first stage to reach, so that the separation-transmutation of other elements which contribute to waste toxicity makes sense.

Once the plutonium has been separated, the minor actinides, first americium and then curium and neptunium, are the biggest contributors to the spent fuel radiotoxic inventory. They therefore appear as radioelements which must be managed as a priority in separation-transmutation to usefully and effectively reduce the waste radiotoxic inventory in the long term. Due to this, they are central to the research carried out as part of Area 1.

Beyond the first hundred years, fission products only contribute slightly to the radiotoxicity of spent fuel. Nevertheless, various geological storage mock-up studies have shown that before minor actinides, the first radio nuclides which return to the biosphere after several hundreds of thousands of years are fission products, especially iodine-129, caesium-135 and technetium-99: this is due to their particular physical and chemical properties, such as high water solubility. These fission products must therefore be considered within a separation-transmutation strategy. Chlorine-36 is also mentioned as potentially mobile. However, as its contribution to spent fuel is around a thousand times less than the previously mentioned fission products, it has not been considered in the separation-transmutation studies.

On the basis of the points made above, the following six radio nuclides were therefore considered to be of interest to Area 1 research: americium, curium, neptunium, iodine, caesium and technetium.

Retrieval of existing waste

In France, the processing-recycling of spent fuel started several decades ago: many high activity waste packages, produced by this processing operation, have already been made. The objective of the study was therefore to determine whether it is technically and financially possible or not to implement specific processing solutions which would allow the most radioactive elements of a package be extracted, so as to reduce their life span or their radiotoxicity.

High-level waste from the processing of spent fuel is suspended in a stable glass matrix, thus forming vitrified waste packages. So as to imprison high activity waste over long periods of time, the vitreous matrix has outstanding physico-chemical properties which are stable when subject to irradiation and are resistant to leaching. The report concludes that the retrieval of long-life radionuclides from this existing vitrified waste would require the implementation of complex nuclear operations and would be financially unrealistic given the volume which would need to be processed.

Partitioning of the radionuclides contained in spent fuel

Separation research has been very active since 1991 as part of the French Actinex programme. In line with current fuel processing, the Actinex separation research programme focused especially on hydrometallurgical partitioning for which an industrial knowledge of several decades has been acquired with the Puretex process implemented in Cogéma La Hague plant. In this light, enhanced separation was considered as a complementary operation to the current processing of spent fuel which would be implemented on the basis of the solution, today meant for vitrification, which imprisons highly radioactive elements.

The current Puretex process separates uranium and plutonium and could potentially separate radio nuclides at even degrees of oxidation. Due to the extremely diverse chemical properties of the elements to be separated, the research programmes were elaborated to design individual separation methods. The separation of some of these elements required the elaboration of specific extractants. The objectives of the partitioning studies have been to demonstrate that extraction of more than 99% of the neptunium and 99.9% of americium and curium of the spent fuel is possible.

Pyrochemical processes, which were more investigative, were also assessed in Axe 1 research, especially by the CNRS. This was particularly based on international results in the area through collaboration with the US, Japan and Russia.

The industrial implementation of minor actinide transmutation shall probably not be possible before 2035 at best, whilst their enhanced separation at a significant scale could occur around 2020. In light of this, it was necessary to study the design of storage facilities to house separated minor actinides over a few decades. The objective of the study was to evaluate the feasibility of such a storage and namely for curium.

Transmutation of radioelements

Science had already proven the feasibility of transmutation through neutron irradiation (neutron capture and fission reaction) of a certain number of radioelements before the 1991 Waste Act Law. This was based on the outstanding potential of fast neutron spectrums in this area.

The research aimed to provide information to clarify the technical feasibility of transmutation by specifying the technological conditions (existing or planned reactors) in which the transmutation could actually occur and by assessing the net gain achieved with regard to the radiotoxic outcome.

For these studies, the following reactor types were considered:

- as existing reactors, those of the French current and future park (PWR type) and sodium fast reactors (SFR type), whose technology is mastered today;
- as planned systems, the fast neutron nuclear reactors developed under the GEN IV international initiative to produce energy around 2035, and the systems specifically meant for transmutation (hybrid system composed of a sub-critical core coupled to an accelerator) which are notably studied under the framework programmes funded by the EC.

Various transmutation methods for separated elements, which can be diluted in nuclear fuel (homogeneous recycling) or concentrated in specific targets (heterogeneous recycling) were also considered. Research was particularly based on:

- basic knowledge and simulation: gathering of basic nuclear data, neutron study of various reactor cores loaded with minor actinides;
- the behaviour of fuel materials and new technological components based on reactor irradiation experiments;
- technological aspects related to hybrid systems (ADS) specific to transmutation, which were assessed with CNRS' teams.

Furthermore, the sustainable development of nuclear energy has to look not only at the short-term and medium-term situation but must also investigate what could be possible in the longer term, around a hundred years from now. In this light, the thorium-uranium cycle, which would require sizeable changes in the existing nuclear industrial structure, was assessed.

Peer review objectives

The Peer Review should inform the French Authorities (*ministère de l'Industrie and ministère de la Recherche*) whether the *Report 2005: Partitioning and Transmutation* is soundly based and competently implemented in terms of scientific and technical approach, methodology, results and strategy. The French Authorities are particularly interested in the provision of detailed recommendations for specific improvements which could be brought in to that effect, notably if the decision-making process leads to a P&T application phase.

It is expected that the reviewers will pay particular attention that the objectives assigned to the P&T studies have been achieved in terms of:

- the technical feasibility of retrieval of long-life radio nuclides from existing vitrified waste;
- the scientific and technical aspects of the partitioning processes;
- the scientific basis for the transmutation processes and their efficiency as a function of neutron irradiation conditions;
- the ADS efficiency for transmutation, and the level of development of such systems.

It must be observed, however, that while it does claim technical feasibility of partitioning and transmutation and, as such, paves the way to the license application process for the corresponding future nuclear facilities, the *Report 2005: Partitioning and Transmutation* does not consider:

- optimisation, for instance, in terms of cost and safety,
- some scientific issues, for which a complete assessment has not yet been carried out but of which an overall evaluation is provided as a whole ; this includes, for instance, accurate knowledge of some very specific transmutation nuclear data, or possible high power operation feasibility of sub critical systems still to be demonstrated.

Moreover, the nuclear park scenario studies, combining fuel production and processing aspects, which are Chapter E of the report, are considered out of the scope of the review since they are only specific to the possible French situation for the technological developments of the industrial tool to be made in relation with the relevant waste management scenario.

Peer review documentation

The peer review concerns the basic document, being the synthesis report *Report 2005: Partitioning and Transmutation*. This report is available in an English version.

The second level of documentation corresponds to 26 documents which are the bibliography of the report. It is proposed that the executive summaries of the main (among the 26) documents will be available in an English version for the review. Moreover, translation in English will be completed for some specific parts of these documents, if considered important and asked for by the reviewers.

The well-foundedness in terms of rationale of the conclusions of the studies and the clarity and traceability of the documentation, through its structure and its synthesis, are also part of the review.

Reference may be made, when pertinent, to the conclusions of some recent P&T related studies carried out under the aegis of the OECD/NEA.

The international review team (IRT)

The IRT is assembled independently by the NEA, and it may include experts from the NEA staff.

In order to preserve independence and avoid conflict of interest, the chosen experts must not be, and must not have been, involved (e.g., as consultants, experts or contractors) in the CEA or the CNRS activities directly contributing to the “Dossier 2005: Partitioning and Transmutation”. The CEA will be available to the NEA in order to confirm that the chosen experts are, indeed, independent of previous important commitments to the CEA or the CNRS.

The peer review team should have a broad international composition. The possibility for some of the members to be able to read French technical documents in function of the special points of interest mentioned under Chapter 3 would be of interest.

One or two experts should be “reprocessing” experts. At least, one team member should have a large experience in neutronics and transmutation science, one or two team members should be transmutation fuel expert and one or two team members should be “critical or sub-critical reactors” experts.

Tentative schedule and conduct of the Peer Review

July-September 2005

The CEA is ready to organise, between July and early September 2005, an orientation seminar for the members of the IRT, aiming at providing general information on the P&T programme and a first overview of the report in relation with the objectives of the review.

The seminar will have mainly an information role. Oral presentations by the CEA and the CNRS experts could be given on:

- the general framework and current situation of the programme on partitioning and transmutation;
- the most relevant chapters of the *Report 2005: Partitioning and Transmutation* as indicated in the specific objectives of the review.

A visit of the nuclear laboratories and facilities used in the framework of the partitioning and transmutation research (such as the Phénix reactor and the Atalante laboratory) could also be organised.

The *Report 2005: Partitioning and Transmutation* documents, including French specific bibliographic documents, will be made available on CD-ROM for the NEA in July 2005. Translations in English of parts of the bibliographic documents will be provided upon specific request of the IRT.

September-October 2005

The NEA would communicate to the CEA a first list of written questions by mid-September to mid-October 2005. Written replies will be provided by the CEA within three weeks of receipt of those questions.

A second list of questions could be made in advance of the review workshop.

November-December 2005

The main review workshop will be organised in November. The agenda of this workshop will be defined by the IRT. It will last several days and it will be highly interactive, based on face-to-face discussions between the IRT and the CEA's and the CNRS's experts.

After the workshop, the IRT will provide an oral presentation on the preliminary findings of the review. A written record will be made available by

the IRT directly within a week thereafter the workshop, with the understanding that some of the reported findings may be rectified during the later stages of the review.

A first draft of the IRT conclusions will be submitted to the CEA for factual check at the beginning of December 2005.

January 2006

The review team will provide its final report, in English version, to the French authorities (French Ministry of Industry and to the French Ministry of Research) at the very beginning of January 2006 and will publish it thereafter as a regular Agency publication in English and French versions.

Follow-on activities

Two oral presentations on behalf of the international team of experts and dealing with the findings of the review are probably to be foreseen: one to the National Review Board members; possibly a second one to a public audience, in the framework of the French national debate on nuclear wastes management. Both oral reports shall take place before the end of 2006.

Contacts

Contacts on the NEA side

Stan Godelier, Head of Nuclear Development Division
Claes Nordborg, Head of Nuclear Science Section

Contacts on the French side

Florence Fouquet (Head of the Nuclear Industry Division, Ministry of Industry – General Directorate of Energy and Raw Materials (DGEMP))
Philippe Pierrard (Staff of the Nuclear Industry Division, Ministry of Industry – General Directorate of Energy and Raw Materials (DGEMP))
Dominique Goutte (Head of the Energy, Environment and Natural Resources Division, Ministry of Research – General Directorate of Technology)
Philippe Pradel (Director of Nuclear Energy Division, CEA)
Charles Courtois (Director for Waste Management Research Programmes, CEA)

ANNEX

DOCUMENTS AVAILABLE TO THE PEER REVIEW

The “Report 2005: Partitioning and Transmutation” consists of the document (the synthesis report) making up the “Report 2005: Partitioning and Transmutation” and of an extensive set of documents.

The relevance of each document to the peer review is indicated as follows:

- * The higher level document, being the synthesis report. This document is available in an English version.
- ** The Bibliography documents (26) of the synthesis report, which only exist in a French version. Executive summaries of the main (among the 26) documents will be available in an English version, and some important specific parts of these documents will also be translated if asked for by the IRT.

Appendix 2

MEMBERS OF THE INTERNATIONAL REVIEW TEAM

International members

Alexandre BYCHKOV

Dr. Alexandre Bychkov graduated in Chemistry at the Moscow State University in 1982. Since 1982 he has worked at the Research Institute of Atomic Reactors (RIAR), Dimitrovgrad, Russian Federation (Now “State Scientific Centre – Research Institute of Atomic Reactors”). Alexandre Bychkov received his PhD in May 1998. Recent positions of A. Bychkov are as Deputy of RIAR, General Director on Science (Nuclear Fuel Cycle Direction) and Director of Chemical Technology Division of RIAR.

Dr. Bychkov is one of Russia’s leading specialists in the field of non-aqueous methods for reprocessing and recycling of nuclear fuel cycle. He was one of the active developers of pyroelectrochemical technology for the fast reactor oxide fuel reprocessing and production.

In period between 1997 and 2002 he participated in studies and developments on the technology of weapon plutonium conversion into MOX fuel. Experimental batches of fuel were tested in the BOR-60 and BN-600 reactors. The technology could be used in the frame of the Russian-USA Agreement on military plutonium disposition.

In the beginning of the 1990s, Dr. Bychkov initiated the investigations on the introduction of minor actinides into the fast reactor closed fuel cycle. The complex investigations on the chemistry of neptunium and americium in molten chlorides were completed and became the basis of the development of technology for minor actinides recycling.

Dr. Bychkov participated in the other new RIAR projects related to non-aqueous processes: production of molybdenum-99, recycling of boron-10 and development of matrices for immobilisation of pyrochemical wastes.

He has active collaboration with nuclear institutes of Japan, Korea, France and some other countries. He also provides expert advice to IAEA, NEA/OECD and Minatom Projects related to advanced fuel cycle or nuclear weapon materials disposition.

Pierre D'HONDT (Co-Chair)

Dr. Pierre J. D'hondt graduated in Physics at the University of Ghent in 1974 where he continued as a scientific researcher in the area of Nuclear Physics. He obtained his PhD in 1981 at the same university.

Since 1984, Dr. Pierre J. D'hondt has worked at the Belgian Nuclear Research Centre first in the position of scientific researcher, then as Head of the Reactor Physics Department, in 1992 he became responsible for the Fuel Research Unit, now he is director of the Reactor Safety Division.

In conjunction with his professional responsibilities, Dr. Pierre J. D'hondt is vice-chairman of the NEA Nuclear Science Committee, chairman of the NEA Nuclear Science Committee Executive Group, chairman of the NEA Task Force on Reactor based Pu-disposition, chairman of the NEA Expert Group on Needs of Research and Test Facilities in Nuclear Science.

Dr. Pierre J. D'hondt is also chairman of the European Working Group on Reactor Dosimetry (EWGRD). He plays an active role within the EWGRD since 1984 and has been nominated chairman since 1994.

Dr. Pierre J. D'hondt was the coordinator of the thematic network of the 5th Framework Programme of the EC called ADOPT (Advanced Options for Partitioning and Transmutation).

Phillip FINCK

Dr. Phillip J. Finck, Deputy Associate Laboratory Director, Applied Science and Technology and National Security, Argonne National Laboratory. Phillip Finck received his Ph.D. in Nuclear Engineering from MIT in 1982, and a MBA in 2001 from The University of Chicago. He was a mechanical engineer at NOVATOME, France from 1983 to 1986, and was involved in the safety and design of fast reactors, including Superphénix. In 1986, he joined Argonne National Laboratory and was involved in neutronics methods development for the Integral Fast Reactor concept, and later for the New Production Reactor. In 1991, he became the lead for EBR-II neutronics analyses at ANL-E. In 1993, he joined the French Atomic Energy Commission where he became the head of the Reactor Physics Laboratory at the Cadarache Centre, with activities in LWR

and LMR physics, criticality safety, fuel cycle physics, and nuclear data. In 1995, he was elected to chair the European nuclear data project (JEF). Dr. Finck rejoined ANL in 1997, where he became the Associate Director of the Technology Development Division. He has led the ANL activities in the Advanced Accelerator Applications programme since 2000, and has been heavily involved in transforming the programme from accelerator-based to reactor-based transmutation. In 2003, he was named Deputy Associate Laboratory Director, Engineering Research, where he was responsible for coordination of all nuclear energy related activities at ANL, including AFCI and Gen IV programmes, and development of new initiatives. Since 2004, Dr. Finck is the Deputy Associate Laboratory Director for Applied Science and Technology and National Security; in this position, he coordinates all energy-related activities at ANL.

Dr. Finck is a Fellow of the American Nuclear Society.

Jean-Paul GLATZ

Jean-Paul Glatz is a senior scientist at the European Commission Institute DG-JRC, Institute for Transuranium where he has worked since 1981 in the Nuclear Chemistry department on partitioning studies of minor actinides from spent nuclear fuel and on spent fuel corrosion projects related to long-term intermediate and final storage.

In 1976, Jean-Paul Glatz received a chemical engineering diploma and in 1980 a PhD at the Institute for Analytical and Radiochemistry, University of Saarbrücken.

In 1992, Jean-Paul Glatz became responsible for the chemical hot cell facility of JRC Karlsruhe undertaking the following projects:

- spent fuel characterisation in relation to direct disposal;
- partitioning of actinides in the frame of an international P&T programme (collaboration with Beijing University, China, JAERI, Japan and CEA, France);
- dissolution studies of high burn-up nuclear fuels (contract work for CRIEPI, Japan);
- participation in the PHEBUS PF experiment (nuclear reactor simulation);
- preparation of ^{248}Cm target material for the production of ^{106}Sg at GSI Darmstadt.

In 1996, he became deputy head of the “Nuclear Chemistry Unit” with the following research programmes:

- Safeguards research and development.
- Metrology and quality assurance for the Euratom safeguards directorate support to the IAEA Vienna.
- Measurement of radioactivity in the environment.

Since 1998, Jean-Paul Glatz has been head of the “Hot Cell Technology Unit” at ITU, responsible for all post irradiation examination work on irradiated fuel and other highly active materials. The main projects are related to the

- Safety of nuclear fuel.
- Spent fuel characterisation for storage.
- Partitioning and transmutation (P&T).

Rudy KONINGS

Rudy Konings is a senior scientist at the Institute for Transuranium Elements of The Joint Research Centre of The European Commission, where he has worked since 1999 on various aspects of nuclear fuel and nuclear waste forms. He has been responsible for the P&T programme at ITU from 2003 to 2005 and is head of the Materials Research unit since the beginning of 2006. Rudy Konings graduated in Geochemistry at the Utrecht University (Netherlands) in 1985, after which he joined the Netherlands Energy Research Foundation ECN, where he first completed a PhD on Thermochemistry of Fission Products (University of Amsterdam, 1990). Since then has been involved in miscellaneous material research related to nuclear fuel cycle issues and in 1998 became manager of the Fuel, Actinides and isotopes unit of NRG.

James LAIDLER (Co-Chair)

James Laidler is a Senior Technical Advisor in the Chemical Engineering Division at Argonne National Laboratory in the United States. He has been associated with Argonne National Laboratory since 1988 and has held a number of management positions in the Laboratory, including a stint as Director of the Chemical Engineering Division from 1994 to 1999. He presently serves as the National Technical Director for Separations Technology Development in the U.S. Department of Energy’s Advanced Fuel Cycle Initiative, where he directs the work of national laboratories and universities on development of advanced spent fuel chemical separations methods. Prior to his assignment at Argonne National Laboratory, he worked for thirty years in a variety of assignments at the Hanford site of the Department of Energy, including the metallurgy of plutonium, irradiated fuel reprocessing, the study of fundamental radiation

effects in metals and alloys, the development of fast reactor fuels and materials, and safety upgrades to a plutonium production reactor. He received the E. Met. degree from Colorado School of Mines in 1958, the M.S. degree from the University of Washington in 1964, and the D.Sc. Degree from the University of Virginia in 1968. He is a Fellow of the American Nuclear Society and a recipient of the Mishima Award from that Society. He received the Eichner Medal from the French Metallurgical Society in 1987 for his contributions to the development of fast reactor fuels and materials. He has served on a number of expert groups convened by the OECD Nuclear Energy Agency.

Kazuo MINATO

Kazuo Minato is Director of Fuels and Materials Engineering Division at the Japan Atomic Energy Agency (JAEA), where he is responsible for research and development of minor actinides-bearing fuels, pyrochemical and aqueous separation processes for reprocessing of spent fuels. He graduated from the University of Tokyo in nuclear engineering in 1979, and received his Doctors Degree in nuclear engineering from the University of Tokyo in 1992. He joined the Japan Atomic Energy Research Institute (JAERI) in 1979, where he has worked in the field of research and development of fuels and fuel cycle technologies. He developed the fabrication and characterisation technologies for the coated particle fuels for high temperature gas-cooled reactors and the irradiation behaviour analysis including fission product behaviour of the coated particle fuels. From 1989 to 1991, he was involved in the research programme at Kernforschungszentrum Karlsruhe on fuel behaviour in severe fuel damage accidents of light water reactors. Partitioning and transmutation of minor actinides and long-lived fission products are his current research items, which include the fabrication, properties measurements, irradiation tests and pyrochemical process of minor actinides-bearing fuels, and the fabrication and properties measurements of Tc and I targets. Kazuo Minato is currently a member of the Japan delegation to the NEA/NSC Working Party on Scientific Issues of the Fuel Cycle and its sub-working groups. He is also a consultant for the IAEA workings on the Development of a Database on Minor Actinides used for advanced Nuclear Fuel Cycles and on the Processing and Properties of Minor Actinide Fuels and Targets for Transmutation in Fission Reactors.

Toru OGAWA

Toru Ogawa is the Deputy Director General, Nuclear Science and Engineering Directorate, JAEA (the Japan Atomic Energy Agency). JAEA was founded on 1st October 2005, by merging JAERI (the Japan Atomic Energy Research Institute) and JNC (the Japan Nuclear Cycle Development Institute). He has worked in JAERI since 1975 mainly on the fuel engineering and the

related basic research. His major contributions have been the development of advanced coated particle fuel for VHTR (very high-temperature gas-cooled reactor) and the study of fuel cycle concepts for dedicated actinide transmutation systems.

Toru Ogawa received his MS in Nuclear Technology from the Tohoku University and joined JAERI (the Japan Atomic Energy Research Institute) in 1975. After a half-year of training in decommissioning work in a plutonium facility at the Tokai Research Establishment, he worked on R&D of HTGR fuel. He was in charge of developing ZrC coated particle fuel, which is now regarded as a strong alternative to the current Triso coated particle fuel to be used in a Generation IV reactor, VHTR. He received his PhD from Osaka University in 1983 on the study of the fabrication process and the out-of-pile examination of ZrC coated particle fuel. After returning from his stay in 1985-1986 in Chalk River Nuclear Laboratories, Canada, where he studied the fundamental diffusion mechanisms of fission-product gases and iodine in the oxide fuels, he took a responsibility to examine the feasibility of actinide recycling in dedicated transmutation systems in a special task team on innovative reactors in JAERI. The study formed a small part of the Japanese OMEGA research programme by the Atomic Energy Commission, which was launched in October 1988 and marked the beginning of so-called “second era” of international Partitioning and Transmutation research activities. His investigation further led to fundamental studies on the high-temperature chemistry of transuranium elements such as the constitution of their alloys and nitrides.

He has edited an OECD/NEA report *Fuels and Materials for Transmutation* (2005), a state of the art report prepared within the activities of the Working Party on Scientific Issues in Partitioning and Transmutation.

Kemal PASAMEHMETOGLU

Kemal Pasamehmetoglu is the AFCI and GEN IV National Technical Director for fuel development. The fuel development activities include development, fabrication, characterisation and testing of various fuel types: transuranic bearing mixed oxide fuels, inert matrix fuels and TRISO fuels for thermal reactors, and transuranic bearing advanced ceramic, metal and composite fuels for fast-spectrum systems. Previously, also under the AFCI programme and under its predecessor programmes (AAA and ATW), Kemal worked as the project leader for transmutation science dealing with the transmuter research and development needs. Kemal joined LANL as a post-doctoral fellow in 1986 and since then has worked on projects related to nuclear systems design and analyses. Prior to joining the ATW Programme, Kemal worked on the development of the Transient Reactor Analysis Code (TRAC)

with emphasis on phenomenological modelling of fast transients, and on the safety analyses for the K-Reactor restart project. He also served as the project lead for the LANL work in support of the flammable gas mitigation tasks for high-level waste storage tanks located at the Hanford site in Washington. Most recently, Kemal worked as the team leader in charge of the thermal hydraulic design and safety analyses for the tungsten neutron source designed for the APT Project. Kemal, who has authored or co-authored more than 100 technical papers and reports, received his BSE from the Bogazici University (Istanbul, Turkey), and his MSE and Ph.D. in Mechanical Engineering from the University of Central Florida. His Ph.D. dissertation was sponsored by the U.S. Nuclear Regulatory Commission (NRC).

Peter WYDLER

Peter Wydler graduated as a physicist in 1961 at the Swiss Federal Institute of Technology, Zürich (ETHZ). From 1961 to 2000 he was employed by the Paul Scherrer Institute (PSI), Villigen, formerly the Swiss Federal Institute for Reactor Research (EIR), Würenlingen. Since 2000, he is working as a private consultant.

From 1961 to 1966, P. Wydler was engaged in the development of neutron time-of-flight measurement techniques and performed neutron cross-section and spectrum measurements at the DIORIT reactor at EIR, at the Harwell linear electron accelerator, and at the LIDO reactor at Harwell, UK. The experimental and theoretical work performed at the Atomic Energy Research Establishment Harwell, in 1968, was elaborated as a doctoral thesis which was awarded the silver medal of ETHZ. In the following year, Peter Wydler joined the reactor physics team at the zero-power reactor PROTEUS at EIR where he was responsible for the neutronic code development, the planning and interpretation of integral experiments for the validation of nuclear data and calculation methods, and the development of neutron spectrum measurement techniques, including software development for on-line data acquisition and analysis. In the framework of the International Fuel Cycle Evaluation (INFCE) of the IAEA, he performed neutronic studies for alternative fuel cycles in fast reactors.

From 1980 to 1993, Peter Wydler was leader, first, of the Fast Reactor Project and, later, of the Reactor Physics and Numerical Methods Section at PSI. In these functions, he was responsible for analytical and experimental activities in the areas of fast reactor safety and reactor physics, including transmutation studies and studies for accelerator-driven systems. From 1993, he held the position of the Delegate for the Safety at the Nuclear Installations in the Nuclear Energy and Safety Research Department of PSI and co-ordinated scientific activities at the department level.

Peter Wydler has a long association with OECD/NEA. From 1979 to 2000, he was the Swiss representative, first, in the NEA Committee on Reactor Physics (NEACRP) and, later, in the NEA Nuclear Science Committee and its Executive Group for the NEA Data Bank. As the last Chairman of the NEACRP, he was involved in the transformation of the old scientific committees into the new Nuclear Science Committee. From 1989, he was the Swiss Liaison Officer for the NEA Information Exchange on Actinide and Fission Product Partitioning and Transmutation, and from 1999 to 2002, he chaired the NEANDC Expert Group on the comparative study “Accelerator-driven Systems and Fast Reactors in Advanced Nuclear Fuel Cycles”.

OECD/NEA Secretariat

Stan GORDELIER

Stan Gordelier is the Head of the Nuclear Development Division in the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development. He runs a team of experts assisting member countries with strategy, policy and economic analyses of nuclear energy and its fuel cycle. He received his BSc in mechanical engineering from the University of Sussex, UK, in 1969 and is a Fellow of The Institute on Mechanical Engineers and a Fellow of The Institute of Nuclear Engineers.

After graduating Stan Gordelier began his professional career working in nuclear research and development in the UK electrical power industry. He then moved to several roles in scientific and technical support for the operating power plants in the UK, before becoming Director of Liabilities Management Division for Magnox Electric plc, where he was responsible for all radioactive waste management, decommissioning and spent fuel management issues. After a short period with British Nuclear Fuels Limited he joined the Board of The United Kingdom Atomic Energy Authority, where he served two terms of three years each as the Director of the Harwell, Winfrith and Windscale sites.

Claes NORDBORG

Claes Nordborg is, since 1993, Head of the Nuclear Science Section in the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD), a division that assists member countries in developing and disseminating basic scientific knowledge required for the safe and reliable operation of current and next generation technologies. He is also coordinating the close collaboration between the Nuclear Science Section and the NEA Data Bank, an international centre of reference with respect to basic

nuclear tools, such as computer codes as well as nuclear and chemical thermodynamic data.

Claes Nordborg obtained a M.Sc. in mathematics and physics at the University of Lund, Sweden in 1969. He then continued with an Engineer exam in physics at the University of Uppsala, Sweden, before starting his Ph.D. studies in neutron physics at the same university, supported by the Swedish National Defence Research Institute. In 1979, he moved to Paris, France, to work for the OECD Nuclear Energy Agency (NEA), where his initial work at the NEA was mainly devoted to coordinating international efforts in nuclear data measurements and evaluations, before taking on the post as Head of the Nuclear Science Section.

Consultant

Peter THOMPSON

Dr. Peter Thompson graduated in chemistry from the University of Oxford and received his D.Phil. from Oxford in 1970. He joined UKAEA at Dounreay and where he specialised in liquid-liquid extraction, mass transfer and chemical reprocessing flowsheet development. He worked on the Dounreay enriched uranium recovery process, the PFR reprocessing flowsheet, development of the proposed UK commercial fast reactor reprocessing flowsheet and the proposed European Development Reprocessing Plant. This work developed into full technical assessment and feasibility studies of the UKAEA fuels manufacturing and processing business, with definition and execution of new technical projects. In 1993, he was elected a Fellow of the Institution of Chemical Engineers.

As the Dounreay site moved into a decommissioning phase Peter became responsible for aspects of decommissioning strategy and then became International Relations Manager for UKAEA.

On leaving UKAEA in 2005 Peter Thompson now runs his own consultancy business.

GLOSSARY

ADS	Accelerator-driven system. This is a nuclear reactor operating in a sub-critical configuration, in which part of the neutrons necessary for the chain reaction is provided by bombardment of a heavy metal source by a beam of accelerated protons.
AMSTER	AMSTER is a concept for a continuously reloaded, graphite-moderated molten salt critical reactor, burning transuranic elements on a uranium-238 or thorium-232 support, slightly enriched with ^{235}U if necessary.
Andra	French Waste Management Agency: Agence pour la gestion des déchets radioactifs.
ANSALDO	Gas cooled 80 MW reactor system for ADS proposed by Framatome-ANP.
APA	Assemblage plutonium avancé : future PWR fuel assembly to improve plutonium combustion while increasing neutron moderation containing uranium oxide pins and plutonium oxide (not MOX) pins. Significant redesign of present assemblies is required to increase coolant channel cross-section.
APPOLO	Neutron simulation computer code for thermal reactors.
ATALANTE	Atelier alpha et laboratoires pour analyses, transuraniens et études de retraitement : A suite of laboratories and active cells at CEA Marcoule dedicated to studies on spent fuel treatment including high-level waste conditioning.
BTP	Bis-triazinyl-pyridine: family of extractants for the separation of americium and curium from lanthanides.
CBP	Chaîne blindée procédé – Chain of shielded process cells: a suite of shielded cells, which are part of the Atalante facility of the CEA at Marcoule, in which process experiments on radioactive materials are possible and which permit the testing of significant quantities (up to 80 kg) of spent fuel repro-cessing flowsheets over long periods of time.

CEA	Commissariat à l'énergie atomique : the CEA is a public body charged with R&D primarily in the nuclear field.
CNRS	Centre national de la recherche scientifique : French national centre for scientific research.
Cogéma	Compagnie générale des matières nucléaires : a part of the Areva Group.
CORAIL	PWR fuel assembly with a mixture of uranium oxide pins and MOX pins.
DIAMEX	DIAMide EXtraction: Liquid-liquid extraction procedure for separation of fission products from a mixture of lanthanides and minor actinides.
DMDOHEMA	N,N dimethyl N,N-diethyl hexylethoxymalonamide: extractant for americium, curium and lanthanides from PUREX raffinate.
EC	European Commission.
EDF	Electricité de France : The major French electricity utility which has responsibility for the commercial power generating reactors (the PWR fleet).
EFIT	Conceptual design of industrial ADS for transmutation.
EFR	European Fast Reactor.
EFTTRA	European Feasibility of Target for Transmutation: European group consisting of the CEA, EDF, FZK, ITU, HFR and NRG to study and develop the targets for transmutation.
EPR	European Pressurised water Reactor: a new generation of pressurised water reactor developed by the Areva subsidiary company Framatome-ANP in conjunction with electricity utilities. Designed to have improved safety, better use of fuel and improved economics of operation compared to present reactors.
ERANOS	Neutron simulation computer code for fast neutron reactors.
EUROPART	European Framework 6 project to study separation of minor actinides.
FR	Fast reactor.
GEN IV	Generation IV. A class of advanced reactors for deployment from 2035 which should be able to destroy some of the spent fuel waste.

Genepi	Generateur de neutrons pulsé intense : a high-intensity pulsed neutron generator, constructed by CNRS/ISN/Grenoble, used to accelerate a 250 keV deuteron beam towards either a deuterium target or a tritium target, producing well-characterised neutron sources via fusion reactions.
HEDTA	n-(2 -hydroxyethyl)-ethylenediamine triacetic acid: scrub reagent for fission product removal from americium, curium and lanthanide product liquors.
HFR	High flux reactor: European experimental reactor with a high neutron flux; situated at Petten in the Netherlands.
IP EUROTRANS	EUROpean Research Programme for the TRANSmutation of High-level Nuclear Waste in an Accelerator-driven System: European Framework 6 project for ADS research.
IRT	International review team for the OECD/NEA Peer Review.
ITU	Institute for TransUranium Elements: located at Karlsruhe, one of seven institutes of the Joint Research Centre that functions as a reference centre of science and technology for the European Union.
JEF2	Continuous energy cross section neutron/gamma data library.
LINAC	Linear particle accelerator.
LWR	Light water reactor.
MA	Minor actinides (Np Am, Cm).
Masurca	Zero energy experimental reactor at Cadarache.
MEGAPIE	An international experiment to be carried out in the SINQ target location at the Paul Scherrer Institute which aims at demonstrating the safe operation of a liquid metal target at a proton beam power in the region of 1 MW.
Melox	The Cogéma plant at Marcoule for the manufacture of mixed uranium plutonium oxide fuel assemblies.
MIX	A MOX fuel containing enriched uranium.
MONJU	Prototype fast reactor located in Fukui Prefecture, Japan, rated at 280MW electrical; presently shutdown but restart planned.

MOX	Mixed Oxide Fuel: mixture of uranium oxides (natural or depleted) and plutonium dioxide.
MOX-UE	Mixed Oxide Fuel containing enriched uranium with a plutonium level of around 9%.
MUSE	Multiplication avec Source Externe : programme, started in 1995, conceived to validate the physics of the subcritical part of an ADS.
MWe	Mega-Watts electrical: electrical power rating; 1 million watts.
MWth	Mega-Watts thermal: thermal power rating; 1 million watts.
Myrrha	Multi-purpose Hybrid Research Reactor for High-Tech Applications: Research project at SCKCEN Mol for ADS development. Consists of a proton accelerator delivering a 350 MeV, 5 mA proton beam to a liquid Pb-Bi spallation target that in turn couples to a Pb-Bi cooled, sub-critical fast nuclear core, due to enter in service in 2014-2015.
NEWPART	European programme to develop liquid-liquid extraction partitioning processes of minor actinides, mainly americium and curium, which are contained in the high active raffinate generated during spent nuclear fuel reprocessing by the PUREX process.
NEA	Nuclear Energy Agency.
OECD	Organisation for Economic Co-operation and Development.
P&T	Partitioning and Transmutation.
PARTNEW	Follow-on of NEWPART: further European programme to develop multi-cycle liquid-liquid extraction processes to separate both americium and curium from acidic raffinates or concentrates.
PDS-XADS	Preliminary design studies of an experimental accelerator-driven system: European research funded by Euratom.
Phénix	French fast reactor at CEA Marcoule. Authorised for operation only until 2009.
PUREX	Plutonium Uranium Refining by Extraction: Liquid-liquid extraction process for separation of uranium and plutonium from spent fuel.
PWR	Pressurised water reactor.

PYROREP	An integrated R&D programme funded by the European Commission. The project, which aims to study basic pyroprocessing methods, is coordinated by CEA with six direct partners and four associated partners involved.
SANEX	Séparation des actinides par extraction or Selective ActiNides Extraction: process for separation of actinides and lantha-nides.
SCK•CEN	Studiecentrum voor Kernenergie – Centre d'étude de l'énergie nucléaire : Belgian nuclear research centre.
SGN	Specialist nuclear engineering company which is a subsidiary of Cogéma and a part of the AREVA group.
SUPERFACT	The SUPERFACT programme in Phénix confirmed the feasibility of transmutation of neptunium in homogeneous fuels.
TASSE	Thorium-based accelerator driven system with simplified fuel cycle for long-term energy production; proposed molten salt core.
THERMHET	Irradiation experiments to select inert matrices for actinide fuels; irradiations performed in the Siloé reactor at Grenoble.
TRABANT 1	TRAnsmutation and Burning of ActiNides in Triox carrier: Irradiation experiments in the High Flux Reactor of pins with high actinide content.
TRU	TransUranic elements: those elements with atomic number greater than that of uranium.
TWh	TeraWatt-hour: unit of energy consumed, equivalent to 1 million million watt-hours. One watt hour is equivalent to one watt of power consumed for one hour. This is equivalent to 3 600 joules.
UOX	Uranium oxide fuel at the required enrichment.
UP1	Usine d'extraction du plutonium – Reprocessing plant built at Marcoule to reprocess fuel from the G1, G2, and G3 reactors; shutdown in 1997.
XT-ADS	Experimental demonstration of transmutation in ADS.

OECD PUBLICATIONS, 2 rue André-Pascal, 75775 PARIS CEDEX 16
Printed in France.