Nuclear Development
and Nuclear Science

ISBN 92-64-02125-6
EUR 20618 EN

Actinide and Fission Product Partitioning and Transmutation

Seventh Information Exchange Meeting
Jeju, Republic of Korea
14-16 October 2002

In co-operation with the
European Commission
and the
International Atomic Energy Agency

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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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, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, 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.

FOREWORD

The objective of the OECD/NEA Information Exchange Programme on Actinide and Fission Product Partitioning and Transmutation, established in 1989, is to enhance the value of basic research in this area by facilitating the exchange of information and discussions of programmes, experimental procedures and results. This Programme was established under the auspices of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) and is jointly co-ordinated by the NEA Nuclear Development Division and the NEA Nuclear Science Section.

The scope of the Programme includes information on all current and past research related to the following areas:

1. Physical and chemical properties of elements generated in the nuclear fuel cycle:
    a. Chemical properties and behaviour of the actinide species in aqueous and organic solutions.
    b. Analytical techniques and methods.
    c. Physical and chemical properties of various actinide compounds.
    d. Collection and evaluation of nuclear and thermodynamic data of relevant elements.

2. Partitioning technology:
    e. Partitioning of high-level liquid waste with wet and dry processes.
    f. Platinum-group metals-recovery technology.
    g. Fabrication technology of the fuel and target materials.
    h. Partitioning in the reprocessing process.

3. Transmutation:
    i. Transmutation with fast reactors.
    j. Transmutation with TRU burner reactors.
    k. Transmutation with proton accelerators.
    l. Transmutation with electron accelerators.

4. Applications.

Other activities related to nuclear data, benchmark exercises and more basic science studies in relation to this Programme are conducted by the NEA Nuclear Science Section and the NEA Data Bank.

The Programme is open to all interested NEA member countries contributing to the information exchange activities and the European Commission. All participants designated a liaison officer who is a member of the Liaison Group (see Annex 1).

The information exchange meetings form an integral part of the Programme and are intended to provide a biennial review of the state of the art of partitioning and transmutation. They are co-organised by the NEA Secretariat and major laboratories in member countries.

An overview of NEA activities on partitioning and transmutation and relevant publications are available at http://www.nea.fr.html/pt/welcome.html.

These proceedings include the papers presented at the 7th Information Exchange Meeting on P&T in Jeju, Republic of Korea on 14-16 October 2002, held in co-operation with the European Commission (EC) and the International Atomic Energy Agency (IAEA). The opinions expressed are those of the authors only, and do not necessarily reflect the views of any national authority or international organisation. These proceedings are published on the responsibility of the Secretary-General of the OECD.

Acknowledgements

The OECD Nuclear Energy Agency (NEA) gratefully acknowledges the Korea Atomic Energy Research Institute (KAERI), the Korea Electric Power Research Institute (KEPRI) and the Korean Nuclear Society (KNS) for hosting the 7th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation. The Agency also extends its gratitude to the European Commission (EC) and the International Atomic Energy Agency (IAEA) for their co-operation. Special thanks are conveyed to Ms. Brigitte Ziegler for having prepared the proceedings for publication.

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EXECUTIVE SUMMARY

Partitioning and transmutation (P&T) has gained interest during the past decade and the OECD Nuclear Energy Agency (NEA), in response to the interest from member countries, has included P&T in its programme of work since 1989. The information exchange meetings are one of the key components of this international project, providing experts with a forum to present and discuss current developments in the field.

Seven information exchange meetings have so far been organised (Mito, Japan in 1990; ANL, USA in 1992; Cadarache, France in 1994; Mito, Japan in 1996; Mol, Belgium in 1998; Madrid, Spain in 2000 and Jeju, Korea in 2002). This 7th meeting was generously hosted by the Korea Atomic Energy Research Institute (KAERI), the Korea Electric Power Research Institute (KEPRI) and the Korean Nuclear Society (KNS), and was held in co-operation with the European Commission and the International Atomic Energy Agency.

In keeping in mind the main objectives and roles of P&T in nuclear energy, the 7th meeting focused on the current state of developments and progress made, and future work to undertake in the P&T field.

The 7th meeting was opened with a general session in which nine national and international programmes on P&T were addressed. As major national programmes, current P&T programmes in Japan, the United States, the Republic of Korea, France, the Russian Federation and China were presented. International programmes led by the European Commission (EC), the International Atomic Energy Agency (IAEA) and the OECD Nuclear Energy Agency (NEA) were then addressed.

Six technical sessions followed on the main scientific and technical issues in the P&T field.

- Session I: Fuel Cycle Strategy and Future Reactors.
- Session II: Progress in Partitioning and Waste Forms.
- Session III: Progress in Fuels and Targets.
- Session IV: Progress in Materials: Spallation Targets and Advanced Coolants.
- Session V: Progress in Physics and Nuclear Data.
- Session VI: Transmutation Systems (Critical and Sub-critical): Design and Safety.

During Session I on Fuel Cycle Strategy and Future Reactors, 15 papers were presented dealing inter alia with national and international policy, overviews of R&D programmes at NRI Rez, in the Czech Republic and at FZK in Germany, multi-recycling issues and various fuel cycle schemes studies such as ORIENT, Double Strata, CORAIL, PEACER and a phase-out scenario based on fast neutron ADS systems, core design and optimisation for TRU burners, new concepts of transmuters including critical and sub-critical molten-salt reactors, long-lived fission product transmutation studies, thorium-based plutonium and minor actinides transmutation in PWRs.

Nineteen papers were presented during Session II on Progress in Partitioning and Waste Forms. As for minor actinide partitioning, major progress made in Japan, the Russian Federation and the United States was reported. In Japan, a simplified PUREX process was proposed with co-extraction of U, Pu and Np. In Russia, the DOVITA process was extended to MAs although the reprocessing of MA fuels still seems to be problematic. In the United States, a dual tier strategy was proposed. In the first tier, Np/Pu are recycled in LWRs, in the second tier remaining Np/Pu and other MAs are burned in a fast spectrum combined with ADS. For the problematic An/Ln separation, the progress made in both aqueous and pyro-techniques was addressed. The problem of long-lived fission products was also addressed in several papers.

During Session III on Progress in Fuels and Targets, 12 papers were presented covering research areas from fuel preparation and basic properties, fabrication processes and irradiation programmes to design and modelling calculations. Regarding chemical forms, papers addressed alloys, inter-metallic dispersion, oxides (pellets, VIPAC), nitrides, molten salt and fission product targets (Tc and I). Since the last meeting, several post-irradiation experiments such as T4, MATINA1, THERMET and RIAR programmes have been completed, and new irradiation tests for transmutation such as T5, CAMIX-COCHIX and FUTURIX are being carried out or planned. Experimental studies on Am-bearing fuels have been undertaken, although still at laboratory scale. Remaining questions include behaviour of He during irradiation, selection of inert matrices, chemical form for transmutation of ^{129}I, processing of Cm and metallic vs ceramic fuel. Its was stressed that international collaboration is essential for further development with effective use of fabrication facilities, reactors, PIE facilities and compilation of existing data.

During Session IV on Progress in Materials: Spallation Targets and Advanced Coolants, 10 papers were presented dealing with validated data and tools in the area of materials, thermal hydraulics and engineering design to enable the design of ADS components, mainly the spallation target. More specifically, fundamental experiments and physical model development, applied large-scale experiments such as CIRCE at ENEA (Italy) and KALLA at FZK (Germany), and design validation of spallation targets including next generation spallation source projects such as ESS, SNS, JSNS, and the international MEGAPIE initiative were addressed. With regard to target design options, technical issues on closed/open spallation target systems, the windowless option and the solid window option were discussed.

Session V on Progress in Physics and Nuclear Data addressed, through the 16 papers presented, mainly recent studies of basic physics processes on ADS, reactor-based and differential accelerator-based integral experiments for cross-section and basic nuclear data validation and measurements, development of specific measurement techniques, new simulation tools for ADS and transmutation systems, and studies of transmutation scenarios and devices. The experiments on basic physics processes in mock-ups of transmuter/ADS and associated simulation benchmarks enable one to develop the correct concepts to understand these systems and to identify the needs and deficiencies of the currently available nuclear data. A combination of reactor-based and differential accelerator-based experiments using new specific measurements, should provide basic nuclear data required as well as models needed to predict non-measured data. The results of these efforts will be incorporated into new simulation tools for ADS and transmutation systems (models and data) to optimise concepts of transmutation scenarios and devices.

During Session VI on Transmutation Systems (Critical and Sub-critical): Design and Safety, 19 papers were presented. A great number of options are still under evaluation for transmutation facilities. For both critical and sub-critical systems, a fast spectrum is the most favourable option. Regarding primary coolants, Pb-Bi is in general considered as the reference option, but Na, gas and molten salt are being studied as possible alternatives. Well-proven MOX fuel is proposed for demonstration plants. Investigations into more advanced fuels such as metallic fuels, nitride fuels, metallic thorium-based fuels, mixed uranium-transuranics carbide, molten-salt bearing plutonium and minor actinides are being made. As for the targets, solid tungsten targets cooled by sodium or liquid Pb-Bi targets are under consideration. Concerning target design options, the solid window configuration is considered worldwide as the reference, while the windowless option is being studied for two Pb-Bi cooled target systems in Europe. For the ADS power range, it varies from 40 MW for the Belgian MYRRHA, 80 MW for the European PDS-XADS, 100 MW for the US ADTF to 1 000 MW for the Korean HYPER system. Based on the current design of the 80 MW European PDS-XADS cooled by Pb-Bi, a comparative safety analysis between Na and Pb-Bi shows an advantage of Pb-Bi coolant in case of an unprotected loss-of-flow scenario. A proper design will provide sufficiently higher cooling capability of the reactor core preventing from cladding and fuel overheating. Two experimental facilities – SAD and TRADE – were presented.

A panel discussion was organised at the end of the meeting. The main theme of the discussion was perspectives for the future development of P&T. Seven panellists presented their thoughts on the issue, followed by an open discussion involving all participants. The following points were emphasised during the panel discussion:

- The role of P&T must be considered in a global future nuclear power context, including the economic aspects, for example in the form of a cost/benefit analysis.
- An international consensus on performance criteria for P&T should be established.
- The R&D needs to be prioritised, due to the limited resources available.
- The nuclear waste form, following P&T, must be fully understood in order for the performance of P&T to be clearly and efficiently evaluated.
- It is absolutely essential to have closer collaboration between P&T specialists and the radioactive waste management community responsible for the development of geological repositories. In addition, good measures for repository performance must be developed to better connect the two communities.
- International co-operation is crucial, not at the micro scale, but at the macro scale. A kind of burden-sharing collaboration is preferable.

The meeting was closed by the scientific chairman, Dr. Dave Hill. The 8th information exchange meeting is provisionally scheduled to be held in Las Vegas, New Mexico, USA in autumn 2004.

WELCOME ADDRESSES

In-Soon Chang
President of the Korea Atomic Energy Research Institute (KAERI)

Good morning Ladies and Gentlemen,

We are here in beautiful Jeju Island in the most beautiful season.

It is a great pleasure and honour for me to welcome all of you to “The 7th OECD/NEA Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation”. I would like to express my sincere thanks to all participants who are willing to share their invaluable experience and information with us. I also would like to express my wholehearted appreciation to the organising and scientific advisory committee of this meeting.

Korea has been known as the hermit country or the Land of Morning Calm. However, our country is no longer the Land of Morning Calm, but is now known as the Land of the Morning Rush due to its recent economic development. Korea is a country blessed with natural beauty. However, this country has not been blessed with natural energy resources. In this reason, Korea industry has been dependent on the turnkey-based trade, and we had to find a solution for the electric power supply.

Recognising the benefits of nuclear energy, Korea, with poor natural resources, has been an active promoter of its nuclear power programmes ever since it introduced nuclear power as a new source of electricity generation in 1978. Nuclear power is the most reliable and sustainable means of generating electricity, improving human life and ensuring the nation's economic growth. Since the commercial operation of the Gori nuclear power plant in 1978, 17 nuclear power plants are currently in commercial operation. Nuclear power generation in 2001 provided more than 40% or the country's total electrical generation. I am sure that nuclear energy is the power to drive Korean economic engine in the past, present and furthermore in the future.

Last summer, we experienced floods the most terrible in last half a century in this country. Property damage due to floods were estimated to be about 4 billion US dollars. And these days, in various corners of the world we see the abnormalities of climate. In Europe, there was a flood which was the worst in the last 100 years. And we know the catastrophe which Australia has never experienced. All these things remind us that global warming due to greenhouse effect is imminent to all of us. We all know that reduction of carbon-dioxide(CO_2) emission is an urgent and important task we must solve. And we all know that present nuclear power generation systems have also various issues to be solved, which I do not need to mention today. Some people say that we have to exploit alternative energy sources like solar, wind, geo-thermal or even biomass. However, most of us understand that there is no definitive solution to the worldwide energy and environmental problems in near future.

Nowadays, we start to understand again the great potential of nuclear power. During last decade, P&T people have insisted lonely the full recycle of actinide to reduce long-term radio toxicity and improve the resource efficiency. I firmly believe that this information exchange meeting has contributed to the boost-up of the R&D on P&T in a number of countries. Thanks to the P&T people and this information exchange meeting, full recycle of actinide is being considered seriously in advanced nuclear system such as Generation IV and “International Project on Innovative Nuclear Reactors and Fuel Cycles” so call INPRO which is initiated by IAEA.

The P&T technology may not be a perfect solution but can be a big jump in the improvement of nuclear energy system. I expect that, if P&T technology is successfully developed, some relevant issues overshadowing nuclear industry will be greatly alleviated and nuclear power will play a major role in supplying energy for hundreds of years to come.

Ladies and Gentlemen,

We are here together from all around of the world to complete P&T technology. There will be various ingredients necessary for the success of P&T technology, including supports and co-operation on international basis and advice from senior scientists who have gained valuable experience. I believe this meeting will be a good opportunity for all of you to exchange mutual interests and to enhance mutual communication and co-operation. Our efforts in this meeting will contribute not only to nuclear industry but also to the prevention of the catastrophe we are facing with, due to the climate change.

While US President Eisenhower proposed the “Atoms for Peace” speech before the UN General assembly in 1953 to control and develop the peaceful use of atomic energy, I would like to propose “Atoms for Next generation” to promote the peaceful uses of nuclear science and technology.

As you see, the fall of Jeju is really wonderful and there are many places where you can experience new things. Such as world cup stadium, golfing, fishing, mountain climbing etc. I hope that you will remember this meeting as a joyful occasion and enjoy your stay in Jeju.

Thank you very much.

Peter Wilmer
OECD Nuclear Energy Agency

I have two very pleasant tasks to perform at the outset of this 7th Information Exchange Meeting on Partitioning and Transmutation.

Firstly, Mr. Chang and Mr. Yoon, on my own behalf and that of everyone present, I would like to thank you for your welcome to Korea and to this wonderful island of Jeju for our meeting. The surroundings are superb and very stimulating for all our discussions. We are all very appreciative of the generous hospitality of our hosts, Korea Atomic Energy Research Institute (KAERI), Korea Electric Power Research Institute (KEPRI), Korean Nuclear Society (KNS) and Ministry of Science and Technology (MOST) and their support for the work of the OECD Nuclear Energy Agency in this area.

I have to say that it was the intention of my Director-General, Luis Echávarri, to participate in this meeting and to make these welcoming remarks himself. However, other business commitments and developments in Paris have resulted in him being unable to be present in person and he sends his apologies for absence and his best wishes for the success of this meeting. His loss is my gain! I am delighted to join you.

Jeju, Korea joins the illustrious list of hosts of the OECD/NEA Information Exchange Meeting which forms part of the broader Information Exchange Programme on Actinide and Fission Product Partitioning and Transmutation. The first meeting was held in Mito City, Japan in 1990 and it has been followed at two-year intervals by further meetings at Argonne National Laboratory (USA), Cadarache (France), Mito City again, Mol (Belgium) and most recently in Madrid (Spain) in 2000.

My second task is to express a welcome to all delegates on behalf of the Nuclear Energy Agency. It is very encouraging to see the support that you all represent for this most interesting and challenging aspect of the development of nuclear energy and for international collaboration.

We are very pleased to have co-operation with the European Commission, continuing a collaboration of previous years. It is also a pleasure to acknowledge the co-operation of the International Atomic Energy Agency for the first time. I am particularly pleased to welcome Mr. Ved Bhatnagar and Mr. Alexander Stanculescu who represent the European Commission and the IAEA, respectively.

I would also like to particularly acknowledge the participation in this OECD Nuclear Energy Agency meeting of countries which are not members of my organisation. We are pleased to welcome them here to enhance co-operation between all countries with an interest in partitioning and transmutation with a view to best serving the interest of us all.

The objective of the OECD/NEA Information Exchange Programme on Actinide and Fission Product Partitioning and Transmutation, established in 1989, is to enhance the value of basic research in this area by facilitating the exchange of information and discussions of programmes, experimental procedures and results. This Programme was established under the auspices of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle and is jointly co-ordinated by the NEA Nuclear Development Division and the NEA Nuclear Science Division.

The Information Exchange Meetings form an integral part of the Programme and are intended to provide a biennial review of the state of the art of partitioning and transmutation. They are co-organised by the NEA Secretariat and major laboratories in member countries.

Within the framework of the NEA programme of work, there are two centres of activity focussing on partitioning and transmutation. The first of these is the Working Party in Partitioning and Transmutation (WPPT) working under the auspices of the Nuclear Science Committee. General objectives of the working party are to provide the NEA member countries with up-to-date information on the feasibility and development status of P&T and to provide advice to the P&T community on the required R&D. It addresses the status and trends of scientific issues comprising different disciplines, such as accelerators, chemistry, material science, nuclear data and reactor physics. It comprises four active subgroups on accelerator utilisation and reliability, chemical partitioning, fuels and materials and physics and safety of transmutation systems. Contributions from this work will be brought forward within the technical sessions, as appropriate, over the next three days.

The second centre of activity arises from the work of the Nuclear Development Committee. I would like to dwell for a moment on the most recent of their publications *Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles*. Most of you all will already be aware of this study; at this stage of our meeting, I wish to highlight some of the high-level, policy level conclusions. These were:

- More R&D is needed to prove that the technology can be pursued on an industrial scale.
- High technical performance would be needed of a commercial plant in order to benefit the waste disposal activities.
- A system would need to be deployed for a long term, at least 100 years, to bring about a worthwhile benefit in terms of the composition of waste for disposal.
- Additional costs would be involved.

The context within which these conclusions will be judged will be dominated by two international strategic policy objectives, the pursuit of sustainable development and the increasing introduction of competition into markets, including the electricity markets, together with the globalisation of capital.

Will partitioning and transmutation bring value to the world in a detailed analysis of the economic, environmental and social dimensions of sustainable development? I do not have time allocated to me to address this topic but we all need to reflect on the implications of sustainable development goals when developing new technology. Within NEA, we have found the framework of sustainable development to be very suitable for introducing nuclear issues to general policy making and we would advocate such an approach for partitioning and transmutation specifically.

Will partitioning and transmutation aid or suppress the ability of nuclear energy to compete in electricity markets? I do not have time to address this in detail either. However we all recognise the imperative of short-term considerations in today's markets. The practical development and deployment of partitioning and transmutation currently depends on government action and interest and this seems to me to be likely to continue for some considerable time. However, government action is advancing now and I personally believe that it is time to consider the potential role of partitioning and transmutation an important option in the advanced nuclear fuel cycle, which could complement other options being studied within the future nuclear waste management strategy.

For a more thorough investigation into the nuclear waste management options, we will be working on a new study which will examine the implications of reactor fuel cycle choices on the options for waste disposal. Our member countries assign great importance to understanding the changes which can be brought about in the management of irradiated fuel – and in particular waste disposal – by actions taken earlier in the fuel cycle. We intend to make a contribution to this subject and I hope to be able to report some of the outcome to you at your next meeting to be held in two years time.

That all being said, there have been very positive development in the deployment of nuclear energy this year in which NEA has been involved with active participation of many member countries. Generation IV is an active project directed towards research and development of nuclear technology to meet both market and societal needs. Advanced fuel cycles are associated with advanced nuclear technologies and the opportunity for consideration and inclusion of partitioning and transmutation within the framework of future options is high. We need to seriously consider the issues raised within the framework of Generation IV and other initiatives.

Ladies and Gentlemen, I am looking forward to the presentations and discussions of our meeting. I wish you a stimulating and rewarding three days.

Thank you for your kind attention.

Se-Jun Yoon
Ministry of Science and Technology
Korea

Ladies and Gentlemen

It is my great pleasure to make the opening remarks on this 7th Information Exchange Meeting on Partitioning and Transmutation.

The world's population is expanding most rapidly. It is 60 billion now, but is expected to reach 10 billion by the year of 2050. As the population grows, so will the demand for energy and resources. Simply supplying energy will, however, have adverse environmental impacts and potential long-term damage to the global climate alteration. We need to supply the energy that is clean; safe, and cost-effective.

People in nuclear industry believe that the nuclear energy is what we will have to rely on for the future, and I also am a firm believer of this. The public reality, however, is somewhat different from what we give credit to. I think that the difference comes from the anxiety about safety, especially problems concerning the nuclear waste.

Intensive R&D has been performed to improve the safety since the beginning of nuclear era. The technical solutions for the safety problem are expected to be within acceptable range in near future, although it may not be in terms of mass psychology. A deep geologic repository is suggested as a solution to the nuclear waste management. This requires isolation of that site for thousands of years. It is not easy for the public to accept the idea of "permanent isolation".

R&D on various technologies is being performed to provide a better solution to the waste issues, around the world. In this regard, I believe Partitioning and Transmutation combined with a deep geologic repository is promising technologies. However, Partitioning and Transmutation technology still has a long way to go. Much more R&D on Partitioning has to be done to separate the long-lasting radioactive nuclide with acceptable recovery rate and non-proliferation requirements.

In this regard, we also are much concerned about pyroprocessing technology in connection with Generation IV development. I believe this technology will allow us to reduce the amount of nuclear waste.

Ladies and Gentlemen,

We are all here together this morning, some of us from the reactor field, some from the fuel process field, and some from the materials field. Nevertheless, we all have the same objective, seeking solutions for the nuclear waste problem. We will discuss and share different views on the fuel cycle strategies, partitioning process, fuel and materials, and transmutation reactors for next three days.

Jeju is a very popular place for honeymoon in Korea. A lot of couples begin their second life in Jeju. I hope our work for the next few days will help build a new basis for the bright future of nuclear energy.

In closing, I would like to express my deep appreciation again for your participation in this 7th information exchange meeting in Jeju, and I hope your stay would be a most enjoyable and valuable one.

Thank you very much.

General Session

National and International Programmes on P&T

Chairs: Chang-Kue Park (KAERI) and Peter Wilmer (OECD/NEA)

ACTIVITIES ON R&D OF PARTITIONING AND TRANSMUTATION IN JAPAN

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Abstract

In Japan, since plutonium is to be used as a nuclear fuel material under the nuclear energy policy, the objective of partitioning and transmutation (P&T) is oriented to removal and transmutation of mainly MA and long-lived fission products. Under the OMEGA (option making of extra gain from actinides and fission products transmutation) programme, on the basis of the double-strata fuel cycle concept JAERI (Japan Atomic Energy Research Institute) continues to carry out the development of partitioning processes, nitride fuel technology, and a basic study to support the ADS (Accelerator-driven system) development. JNC (Japan Nuclear Cycle Development Institute) bears the research and development of P&T technology of in the course of fast reactor cycle. In the present paper, these activities on the research and development of P&T are introduced.

Introduction

In Japan, since plutonium is to be used as a nuclear fuel material under the nuclear energy policy, the objective of P&T is oriented to removal and transmutation of mainly MA and long-lived fission products.

The progress of the OMEGA programme of JAERI, JNC and CRIEPI were reviewed in 1999 by the Atomic Energy Commission's Advisory Committee on Nuclear Fuel Cycle Back-End Policy and the report was issued in March 2000. Necessity of such R&D works was concluded as future system design and the development of the implementation scenario of P&T, basic experiments to demonstrate the feasibility of the processes, and engineering scale experiments in order to obtain safety data of these systems.

The R&D programme has been jointly stimulated by the collaborative efforts of JAERI, JNC and CRIEPI.

The R&D areas covered by the OMEGA Programme are as follows:

- Physical and chemical properties of MA and fission products.
- Partitioning of radioactive elements from HLW of reprocessing process.
- Transmutation: nuclear and fuel property data of MA, system design studies, reactor fuel and accelerator target development, development of high power accelerator for transmutation.

Under the OMEGA programme, JAERI continues to carry out the development of partitioning processes, nitride fuel technology, and a basic study to support the ADS development. The answer to this lies in the following facts: [1] ADS has flexibility for Nuclear Waste Transmutation in some scenarios of nuclear reactors considered in future: For instance, In case of RMWR and /or FBR introduction such as UO_2-LWR / MOX-LWR / RMWR / FBR, ADSs can transmute MAs from LWRs, and (Am,Cm) from RMWR / FBR and co-exists with RMWR/FBR. [2] ADS is the dedicated MA transmutation system and it is independent from Commercial Fuel Cycle. P&T with ADS reduce burden for commercial reactors in economy and safety. MAs are confined in one small P&T cycle site and not extended in commercial fuel cycle. [3] ADS consists of sub-critical system with external neutron sources using high-intensity proton accelerator, and one has control and flexibility in the design and operation to transmute large amounts of MAs in contract to critical reactors. As a result, ADS provides high efficient and safety transmutation system. The R&D for P&T technology in JAERI have been carrying out on the basis of the double-strata fuel cycle concept. The JAERI‘s activities are summarised on the recent technical achievements for analyses of mass flow and cost estimate for a double-strata fuel cycle, lead-bismuth technology, experimental facilities for ADS technology demonstration, partitioning and fuel processes.

In recent years, new attempts to seek for the better concepts of the nuclear fuel cycle have been made in Japan. Under these circumstances, JNC, whose basic policy is to conduct partitioning and transmutation of MA and FP in the course of fast reactor cycle, has tried to reconstruct the basic planning of partitioning and transmutation in view points of the development goal, the nuclides to be partitioned and to be transmuted, and the development schedule. As for the goal of partitioning and transmutation technology, step by step approach that consists of three steps, will be adopted. Nuclides to be partitioned and to be transmuted are selected in accordance with each goal in the following three view points; radio activity/radiotoxicity, improvement of repository, and effective use. The selected nuclides for the first step, for example, are U, Np, Pu, Am, Cm, Tc, Sr, Cs, Mo, I, and Pd, with the recovery rate of 99% for U, Np, Cm, Tc, and 99.9% for Pu, Am. The major subjects of partitioning and transmutation in order to accomplish the goal are listed up with the development schedule.

Activities for R&D of P&T based on ADS

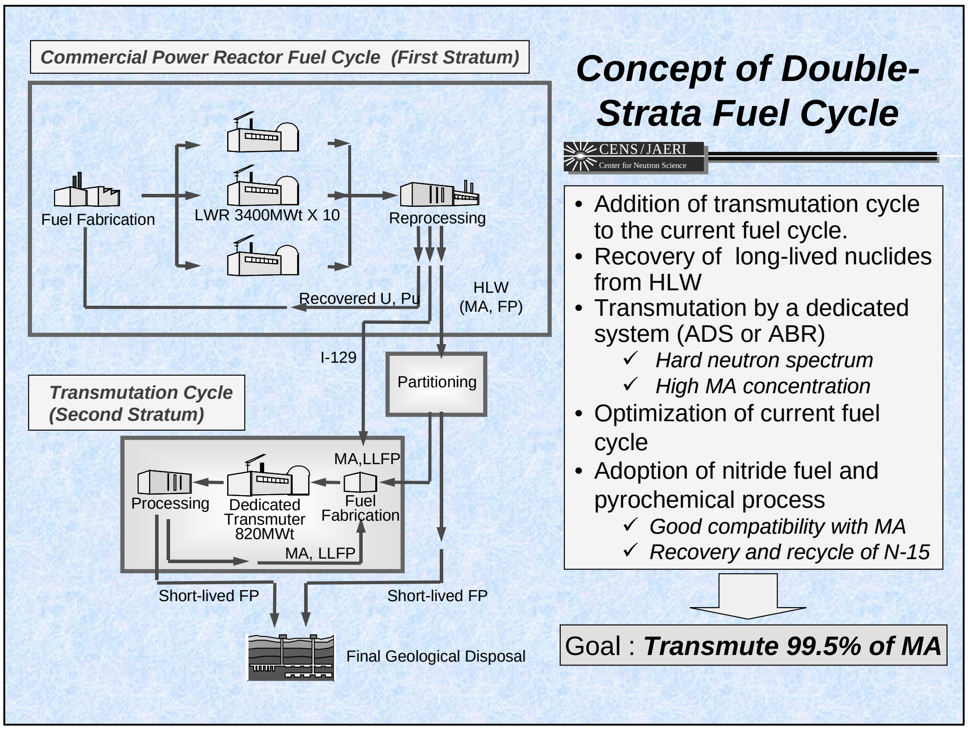
Under the OMEGA programme, JAERI continues to carry out the development of partitioning processes, nitride fuel technology, and a basic study to support the ADS development. R&D activities on ADS, recently more and more university and industry groups have got involved in this area, not only from nuclear energy community but also nuclear physics and accelerator communities.

The R&D for Partitioning and Transmutation (P&T) technology in JAERI have been carrying out on the basis of the double-strata fuel cycle concept [1,2] as shown in Figure 1. The JAERI‘s activities are summarised on the recent technical achievements for the nuclear transmutation, partitioning and fuel processes. The main R&D items for the ADS are shown in Figure 2.

Analysis of mass flow and cost for double-strata fuel cycle

As the commercial reactor fuel cycle is assumed to be sustainable in a significantly long term, the following different reactors and fuel cycles are considered: Co-existing scheme of ADS in Pu-utilisation fuel cycles with MOX-LWRs and FBRs. Furthermore, impact assessment of P&T cycle on geological disposal is studied, and the results are shown in Figure 3. The performance of the ADS considered here [3] is 800 MWt and can transmute MA and ^{129}I produced per year from about 10 PWRs of 3 400 MWt.

Figure 1. **Concept of the double strata fuel cycle based on ADS**

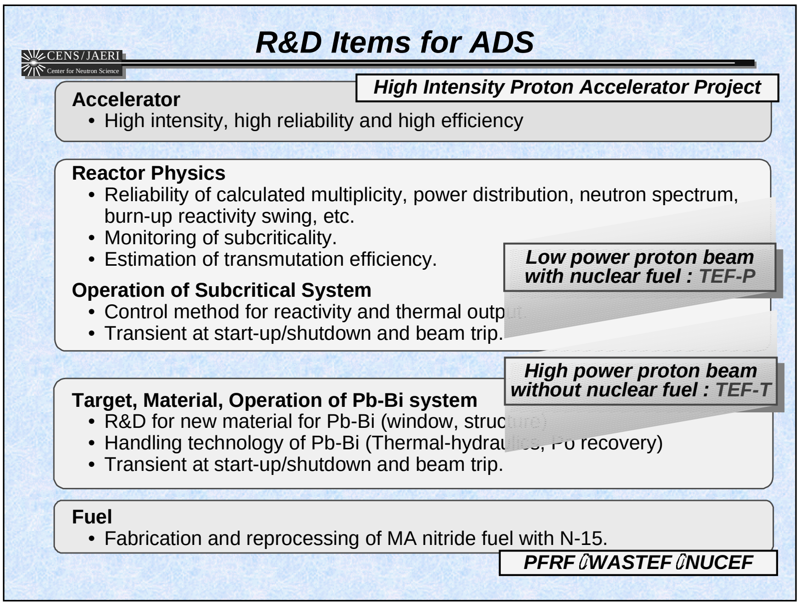


Concept of Double-Strata Fuel Cycle

- Addition of transmutation cycle to the current fuel cycle.
- Recovery of long-lived nuclides from HLW
- Transmutation by a dedicated system (ADS or ABR)
  - ✓ *Hard neutron spectrum*
  - ✓ *High MA concentration*
- Optimization of current fuel cycle
- Adoption of nitride fuel and pyrochemical process
  - ✓ *Good compatibility with MA*
  - ✓ *Recovery and recycle of N-15*

Goal : ***Transmute 99.5% of MA***

Figure 2. **Main R&D items for ADS**



R&D Items for ADS

High Intensity Proton Accelerator Project

Accelerator
- High intensity, high reliability and high efficiency

Reactor Physics
- Reliability of calculated multiplicity, power distribution, neutron spectrum, burn-up reactivity swing, etc.
- Monitoring of subcriticality.
- Estimation of transmutation efficiency.

Low power proton beam with nuclear fuel : TEF-P

Operation of Subcritical System
- Control method for reactivity and thermal output.
- Transient at start-up/shutdown and beam trip.

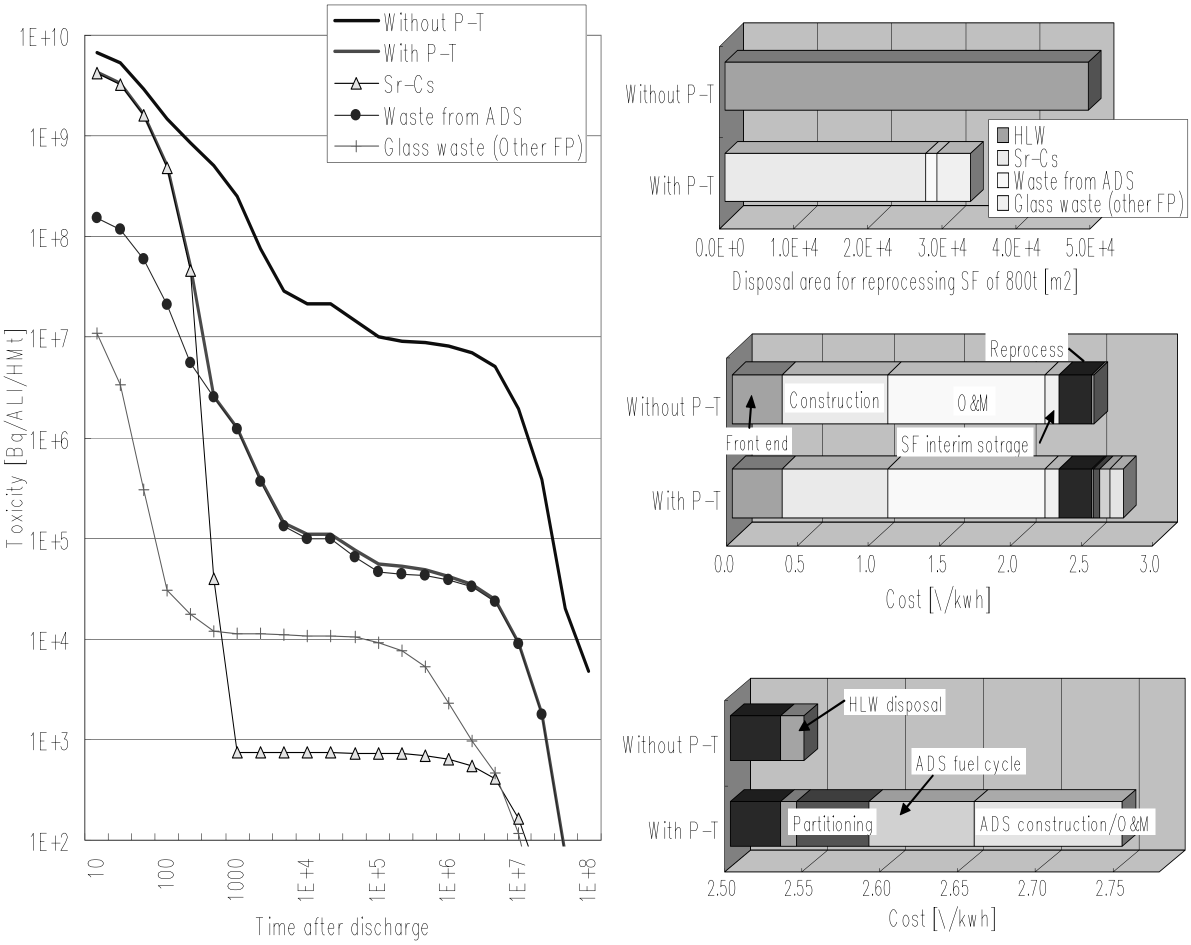
High power proton beam without nuclear fuel : TEF-T

Target, Material, Operation of Pb-Bi system
- R&D for new material for Pb-Bi (window, structure)
- Handling technology of Pb-Bi (Thermal-hydraulics, Po recovery)
- Transient at start-up/shutdown and beam trip.

Fuel
- Fabrication and reprocessing of MA nitride fuel with N-15.

PFRF 0WASTEF 0NUCEF

Figure 3. **Radiotoxicity reduction, impact on geological disposal and cost estimate by double-strata cycle scheme with ADS introduction for P&T**



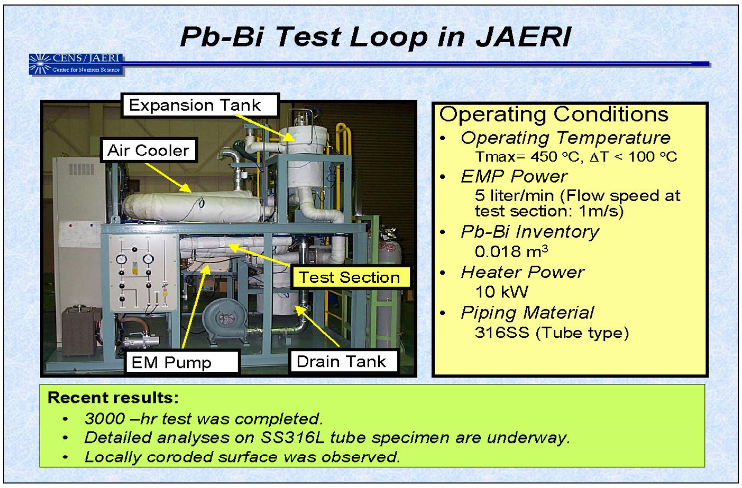
Lead-bismuth technology and material development

For target, materials and operation of Pb-Bi system, a material test loop and stagnant test devices are installed for Pb-Bi technology development and they are in operation. The statistic corrosion tests were performed after 3 000 h at 450°C. The loop corrosion test (Figure 4) was conducted under the temperature of 450°C, EMP power of 5 L/min. and velocity of 1m/s. [4] For irradiation damage, PIE is underway for samples irradiated in TIARA at JAERI/Takasaki, where triple beams combining protons with helium and iron ions were used to simulate heavy irradiation. PIE for irradiation at SINQ is also in progress

Experimental facilities for ADS technology demonstration

The experimental programme for development and demonstration of accelerator-driven transmutation technology has been carried out under the project plan of the High Intensity Proton Accelerator and the OMEGA Programme at JAERI. [5,6] Pre-conceptual design study is being made for a transmutation experimental system as shown in Figure 5. [7] The major areas of technology to be tested and demonstrated are sub-critical reactor physics, system operation and control, transmutation, thermal-hydraulics, and material irradiation.

Figure 4. **Lead-bismuth test loop at JAERI**



Pb-Bi Test Loop in JAERI

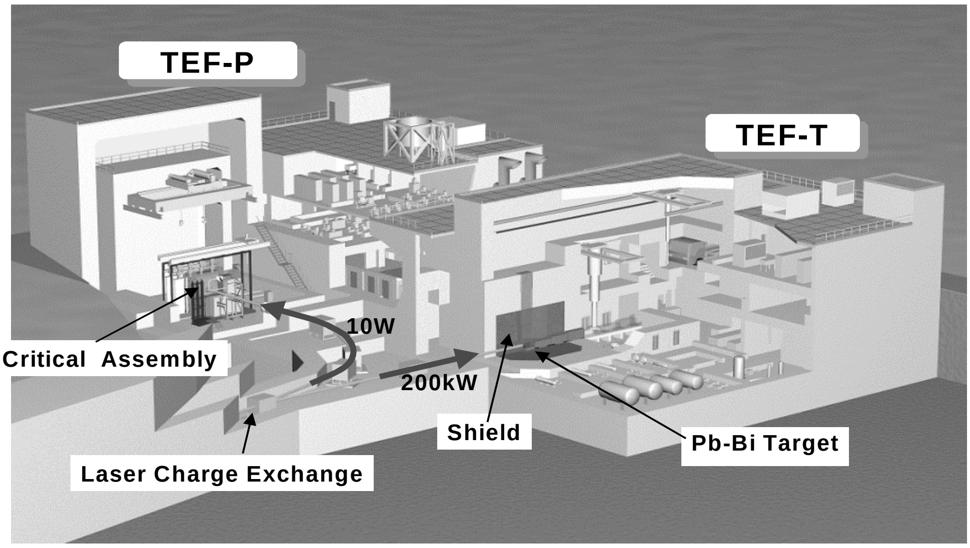
Operating Conditions

- *Operating Temperature*
  Tmax= 450 °C, ΔT < 100 °C
- *EMP Power*
  5 liter/min (Flow speed at test section: 1m/s)
- *Pb-Bi Inventory*
  0.018 m^3
- *Heater Power*
  10 kW
- *Piping Material*
  316SS (Tube type)

Recent results:

- *3000 –hr test was completed.*
- *Detailed analyses on SS316L tube specimen are underway.*
- *Locally coroded surface was observed.*

Figure 5. **Transmutation experimental facilities with sub-critical experiment and Pb-Bi target experiment**



Partitioning technology

The developed 4-Group Partitioning Process with DIDPA was tested with concentrated real HLW. Objective elements, Am, Cm were separated more than 99.98%, and Np more than 99.95%. As a modification effort of the present process, a more powerful ligand, tridentate diglycolamide (DGA), has been studied to extract actinides. From fundamental studies, TODGA [8] was selected as the most proper DGA extractant. Presently, a new extractant, TODGA, is being studied for the modification of the TRU separation step in order to make the process more effective and more economical.

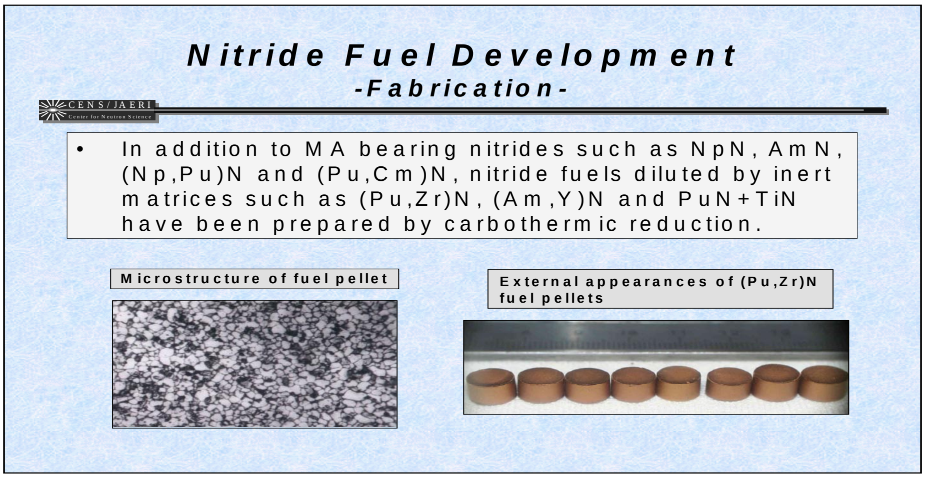
Nitride fuel and pyroprocessing

JAERI’s ADS will use (Pu, MA)N fuel diluted by inert matrices such as ZrN and TiN at the initial loading. Then, (Pu,Zr)N and PuN+TiN pellets have been fabricated and fuel pins containing the pellets are to be irradiated at JMTR as shown in Figure 6. Electrorefining of UN, NpN and PuN has been demonstrated up to now. On the other hand, that for AmN is planned from 2003 at TRUHITEC of JAERI Tokai. [9]

Road map for ADS development

P&T scenario with ADS transmutor is innovative and flexible system (coexisting with Pu fueled reactors such as MOX-LWR, RBWR and FBR) for reducing high-level wastes. After the basic R&D mentioned above, an experimental ADS with 80MW thermal power is considered to be planed in late 2010s to demonstrate the engineering feasibility of the ADS as shown in Figure 7. The experimental ADS will be operated by MOX fuel at first and gradually altered to MA nitride fuel.

Figure 6. **Nitride fuel pellets fabricated for pin irradiation at JMTR**



Nitride Fuel Development

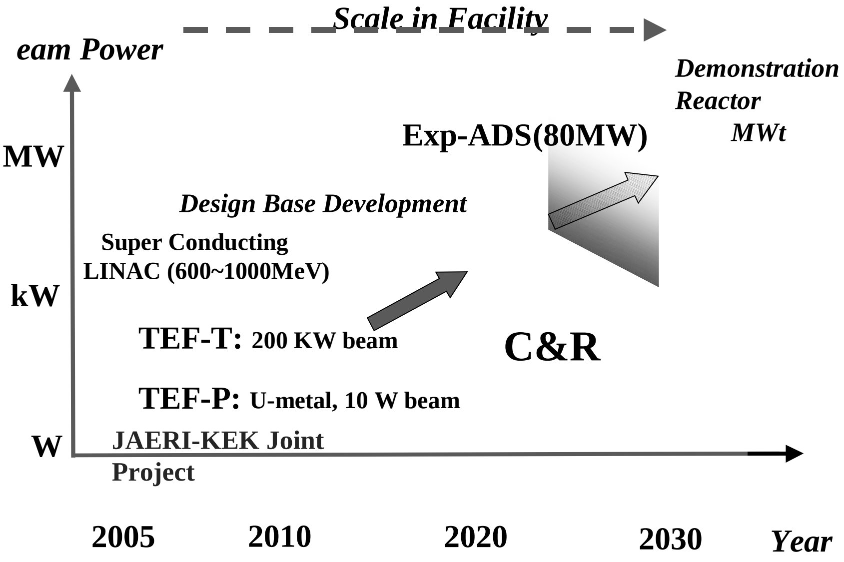
-Fabrication-

- In addition to MA bearing nitrides such as NpN, AmN, (Np,Pu)N and (Pu,Cm)N, nitride fuels diluted by inert matrices such as (Pu,Zr)N, (Am,Y)N and PuN+TiN have been prepared by carbothermic reduction.

Microstructure of fuel pellet

External appearances of (Pu,Zr)N fuel pellets

Figure 7. **Road map for ADS development at JAERI**



Activities for R&D of P&T based on FBR

JNC's basic planning of P&T

JNC, whose basic policy is to conduct partitioning and transmutation of MA and FP in the course of fast reactor cycle, [10] has tried to reconstruct the basic planning of the partitioning and transmutation studies and has tried to clarify the development goals and to clarify the nuclides to be partitioned and to be transmuted. The basic standpoints for the P&T are as following.

MA will be transmuted, but at the same time, will be recycled as a part of resources in the same manner as Pu. All TRU will be treated in the same manner without distinguishing between Pu and MA, although necessity of cooling storage of Cm will be investigated. Target fuel assembly of MA will not be studied, since there exists no necessity of heterogeneous loading of MA, from following reasons, in the case of fast reactor cycle at present.

- There exists no major problem both in core and fuel characteristics if the MA content in the core fuel of homogeneous loading is less than 5%, [11] while fast reactor, of which equilibrium MA content is around 1%, can accept and burn MA recovered from LWRs satisfactory with the MA content less than 5%.
- Target fuel assembly of MA has a lot of uncertainties to be ensured in recycling including fuel fabrication. [12]
- MA addition to the core fuel will contribute to non-proliferation.

FPs will be classified into four categories, such as the transmutation in the form of target assembly after separation (^{99}Tc, ^{129}I, ^{135}Cs, etc.), the cooling storage after separation (^{90}Sr, ^{137}Cs, etc), the waste as stable elements after separation (Mo, Nd, Ba, etc.), and. the effective utilisation after separation (Ru, Rh, Pd, etc.). Studies will be carried out based on element separation, though studies for isotope separation will be started after feasibility of isotope separation is confirmed.

Development goal

The significance of P&T is to decrease the radioactive waste itself, and in this sense P&T plays an important role together with repository technology complementary fulfilling each other. Furthermore, P&T have possibility to contribute improving the acceptability of radioactive waste through the effective utilisation of FPs represented by rare useful elements.

A step by step approach, consists of three steps, to reach the goal of partitioning and transmutation technology will be adopted as shown in Table 1. The first step is supposed to be able to attain by the present technology and on the extension of it. The second step is such a goal that is expected to be able to realise the engineering feasibility through the progress of science technology in future, although the engineering feasibility is not sufficiently foreseen at present. It will need revolutionary technology or breakthrough, since it will be difficult on the extension of the present technology, in order to attain the second step goal. The ultimate is the ideal and shows the direction to proceed.

Table 1. **Development goal of P&T technology**

Step	Goal
First Step	The radioactivity and the radiotoxicity released from the system should be decreased to 1/100 of those of LWR one-through at the time of 1 000 years later. Furthermore, the partitioning and transmutation of FPs which contribute to reduce the repository burden (1/2) and to reduce the dose risks (1/10), and the partitioning of rare elements which can be effectively utilised should be executed.
Second Step	The radioactivity and the radiotoxicity released from the system should be decreased to 1/1 000 of those of LWR one-through after 100 years. Furthermore, the partitioning and transmutation of FPs which contribute to reduce the repository burden (1/5) and to reduce the dose risks (1/100), and the partitioning of rare elements which can be effectively utilised should be executed.
Ultimate	The radioactivity and the radiotoxicity released from the system should be decreased to those of natural uranium within one generation so as not to leave the burden of the radioactive waste to the future generation. Furthermore, the partitioning and transmutation of FPs which contribute to reduce the repository burden (1/10) and to reduce the dose risks (1/1 000), and the partitioning of rare elements which has possibility of improving the acceptability of radioactive waste through the effective utilisation should be executed.

Table 2. **Nuclides to be partitioned and to be transmuted**

Step	Radioactivity and radiotoxicity view point		Repository view point		Effective utilisation view point	
	Radioactivity	Radiotoxicity	Repository capacity	Dose risk	Chemical use (Catalyst etc.)	Radio-chemical use
First step	U,Np,Cm (99%)* Pu,Am (99.9%) Tc99 (99%)	U,Np,Am,Cm (99%) Pu (99.9%)	(decrease to 1/2) Sr, Cs (90%) Mo (80%)	(decrease to 1/10) I (99%)	Pd , Tc	Heat source: Cs,Sr Radiation source: Cs
Second step	U,Np,Am,Cm (99.9%) Pu (99.99%) Se79,Pd107, Sn126 (99%) Cs135,Zr93,Tc99 Cs137,Sr90, Sm151 (99.9%)	U,Np,Cm (99.9%) Pu,Am (99.99%) Cs137,Sr90 (99%)	(decrease to 1/5) Sr, Cs, (99%) Mo, Nd, Ru, Rh, Ce, Pr, Ba, La, Te, Gd, Rb, Y, Pd	(decrease to 1/100) I (99.9%) C14, Cl36 (1/10)	Pd, Tc?Ru, Rh, Se, Te	Cs, Sr, Ru, Rh, Pd

recovery rate in the system

Ultimate	The radioactivity and the radiotoxicity released from the system should be decreased to those of natural uranium within one generation so as not to leave the radioactive waste burden to the future generation. Furthermore, the partitioning and transmutation of FPs which contribute to reduce the repository burden (1/10) and to reduce the dose risks (1/1000), and the partitioning of rare elements which has possibility of improving the acceptability of radioactive waste through the effective utilisation should be executed.

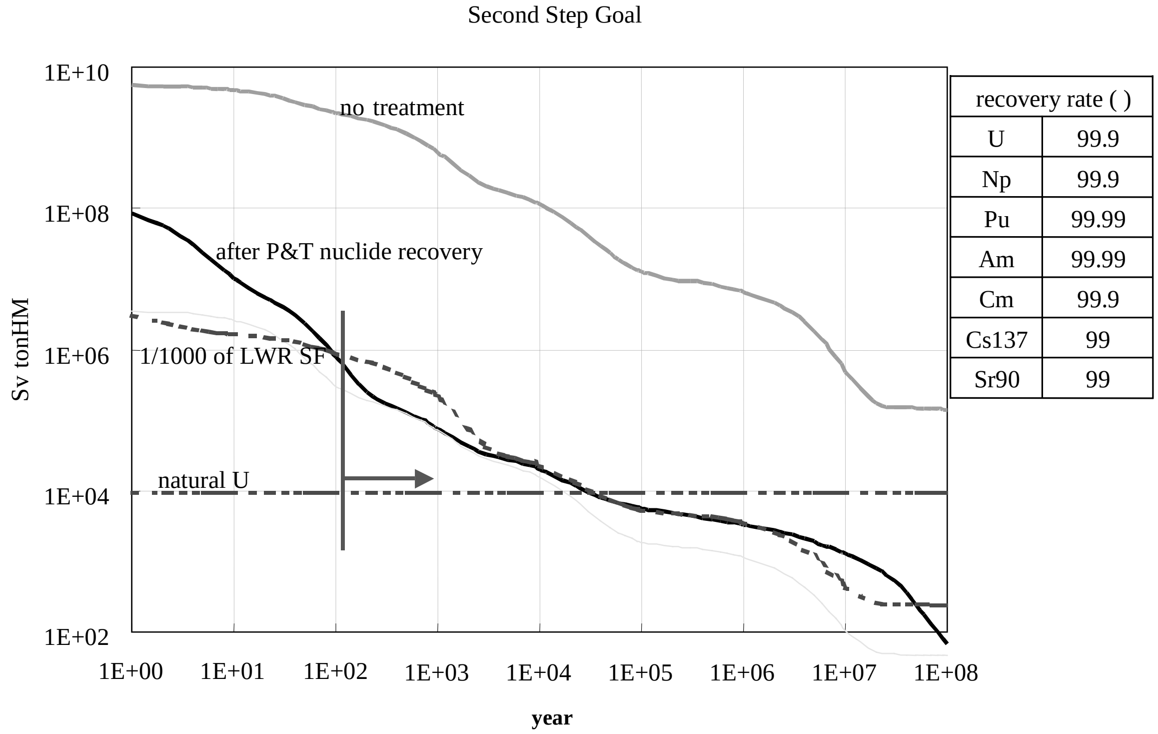
Nuclides to be partitioned and to be transmuted

Nuclides to be partitioned and to be transmuted have been selected in following three view points, “radioactivity and radiotoxicity view point”, “repository view point” and “effective utilisation view point”, corresponding to the each step of the development goal as shown in Table 2. Values in parentheses mean the expected whole recovery rate in the system.

The main nuclides to be partitioned and to be transmuted are TRU in the ratiotoxicity view point, though LLFPs are added in the radioactivity view point. The recovery rate of 99.9% for Plutonium and Americium and 99% for other TRU are necessary in the first step, while one order higher recovery rates are required in the second step.

The relationship between the radiotoxicity after P&T nuclides recovery and the aimed radiotoxicity is presented in Figure 8 as one example of selection basis for the second step goal. The curve indicated as “no treatment” presents the radiotoxicity of spent fuel from fast reactor cycle, while the curve indicated as “after P&T nuclide recovery” means the radiotoxicity of the nuclides which leak to outside the system after nuclides, listed in a table on the right hand side of Figure 8, were separated and recovered with the recovery rate shown in the table. The curve indicated as “1/1 000 of LWR SF” corresponds to the development goal of the second step, while the curve “natural U” corresponds to the ultimate development goal. The curve “after P&T nuclide recovery” should be below the curve “1/1 000 of LWR SF” after 100 years in order to satisfy the second step goal, but not necessary be below the curve “1/1 000 of LWR SF” after it cleared the natural U level. In Figure 8, the curve “after P&T nuclide recovery” satisfies the second step goal, so that the nuclides listed in a table on the right hand side have been selected as nuclides to be partitioned and to be transmuted in the second step.

Figure 8. **The radiotoxicity after P&T nuclides recovery and the aimed radiotoxicity**



recovery rate ( )	
U	99.9
Np	99.9
Pu	99.99
Am	99.99
Cm	99.9
Cs137	99
Sr90	99

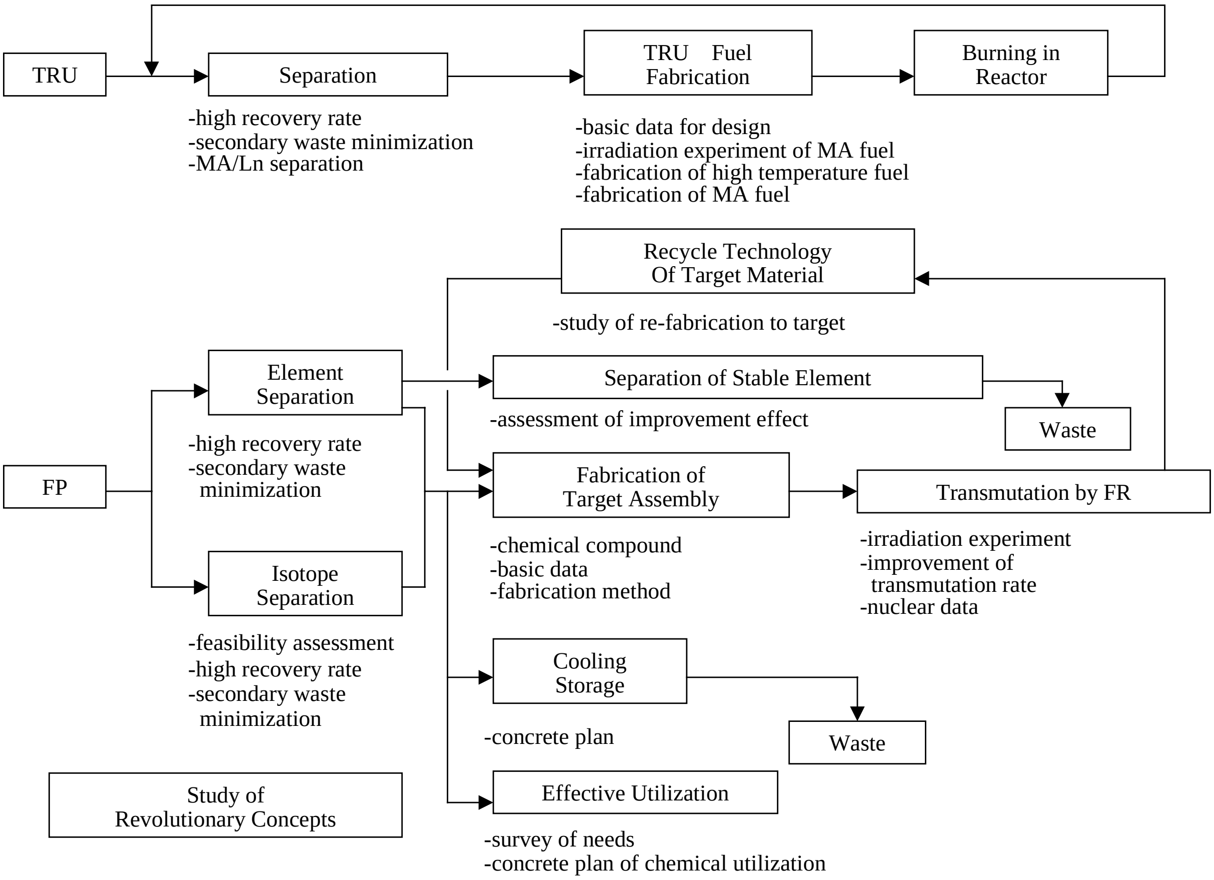
In the repository view point, Strontium and Cesium, which are heat generation nuclides, and Molybdenum, which has bad influence on the durability of vitrified HLW, have been selected in order to increase the repository capacity, while Iodine has been selected to decrease the dose risks, since Iodine has the biggest influence on the dose risks due to its high solubility and low adhesion characteristics to a geologic layer. [13] As for the second step, major stable elements, which occupy about 60% of whole fission products and may not be necessary to be included in vitrified HLW, are selected. Furthermore, Carbon-14 and Chlorine-36 are selected, since they become dominant in dose risks after the one decade reduction of Iodine. Concerning the selection basis, further discussion will be expected in future adopting new knowledge.

Such nuclides have been selected in the effective utilisation view point that Palladium, Technetium, Ruthenium, etc. in expectation for chemical use as catalyst etc., and Strontium, Cesium, etc. for utilisation as heat source and radiation source.

FP nuclides listed in the first step are supposed to be based on element separation, while part of FP nuclides listed in the second step may need isotope separation.

Research and development plan to partition and to transmute the selected nuclides has been made. Major subjects of P&T technology, together with the outline of P&T flow, can be summarised as shown in Figure 9. Residual subjects have been listed up after the present status for the major subjects in Figure 9 has been examined. The research and development plan has been produced considering the listed up residual subjects for the each nuclide in the first step. The each nuclide means TRU, Sr, Cs, I, Tc, Mo and Pd. For an instance, the development schedule of P&T technology for Iodine is presented in Figure 10. Target fabrication of Iodine, recycling technology of Iodine, and verification of analysis method will be established within ten years.

Figure 9. **Major subjects of P&T technology**

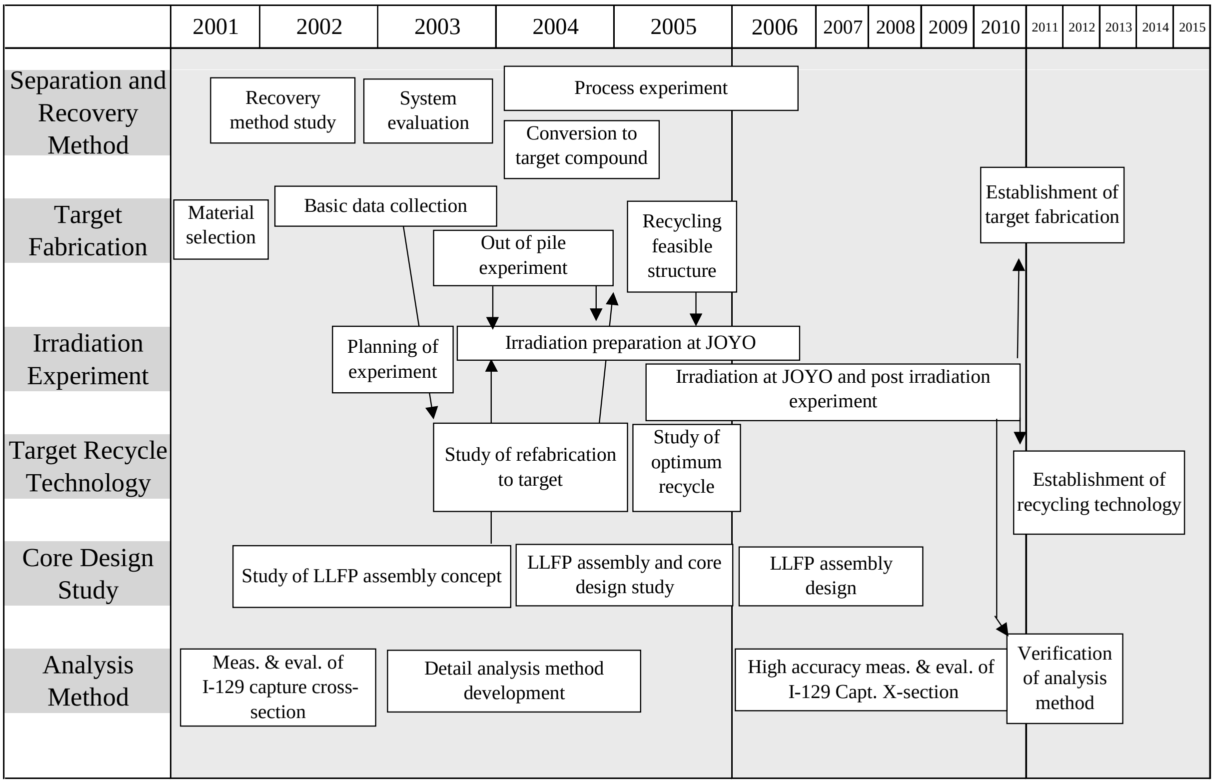


Conclusions

P&T scenario with ADS transmutor is innovative and flexible system (coexisting with Pu fueled reactors such as MOX-LWR, RBWR and FBR) for reducing high-level wastes. After the basic R&D mentioned above, an experimental ADS with 80MW thermal power is considered to be planed in late 2010s to demonstrate the engineering feasibility of the ADS. The experimental ADS will be operated by MOX fuel at first and gradually altered to MA nitride fuel.

In P&T scenario with FBR, JNC has showed the step by step approach, consists of three steps, to reach the development goal of partitioning and transmutation technology, and has clarified the nuclides to be partitioned and to be transmuted in following three view points, “radioactivity and radiotoxicity view point”, “repository view point” and “effective utilisation view point”, corresponding to the each step of the development goal. Furthermore, research and development plan to partition and to transmute the selected nuclides has been made.

Figure 10. **Development schedule of P&T technology for iodine**



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THE ADVANCED FUEL CYCLE INITIATIVE: THE FUTURE PATH FOR ADVANCED SPENT FUEL TREATMENT AND TRANSMUTATION RESEARCH IN THE UNITED STATES

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The U. S. Department of Energy (DOE) has invested over USD 100 million in transmutation research and development over the past three years. The programme has evolved from an accelerator-based transmutation programme to a multi-tier reactor and accelerator based programme. These changes have resulted in a significant re-focus of the research and development programme as well as a name change to reflect the new direction. The Advanced Accelerator Application (AAA) programme is now renamed the Advanced Fuel Cycle Initiative (AFCI).

Research completed by the AAA programme in Fiscal Year 2002 points to a multi-phased AFCI Programme consisting of two elements that would be conducted in parallel as part of an integrated research effort – an intermediate-term technology element (AFCI Series One), which emphasises advanced technical enhancements to the current commercial nuclear power infrastructure; and a long-term technology element (AFCI Series Two), which will require the introduction of next-generation nuclear energy systems to reduce the toxicity of nuclear waste.

AFCI Series One would address the intermediate-term issues associated with spent nuclear fuel disposition primarily by reducing the volume of material requiring geologic disposition through extraction of uranium. A second area of intermediate-term research and development will be development of proliferation-resistant processes and fuels to transmute significant quantities of commercially generated plutonium and other elements of concern (minor actinides) in light water reactors (LWR) or high temperature gas-cooled reactors by approximately 2015. Successful implementation of these technologies would enable the United States to reclaim the significant energy value contained in spent fuel and significantly reduce the need for a second U.S. repository.

AFCI Series Two would address the long-term issues associated with spent nuclear fuel. Specifically, this effort will develop fuel cycle technologies that could sharply reduce the long-term radiotoxicity and heat load of high-level waste sent to a geologic repository. If successful, these technologies could enable the commercial waste stored in a repository to be no more toxic than natural uranium ore after approximately 1 000 years.

In general, we have found that there is reason to believe that the following objectives are attainable:

- **Reduce High-Level Nuclear Waste Volume**: It is possible to develop and implement, by the middle of the next decade, proliferation-resistant technology to significantly reduce the volume of high-level nuclear waste from commercial spent fuel requiring repository disposal.
- **Reduce the Cost of Geologic Disposal:** Based on preliminary analysis thus far, the implementation of AFCI technologies could reduce the cost of spent nuclear fuel disposal in the first U.S. repository by several billion dollars by permitting the use of fewer drip shields and waste packages and reducing the operation and transportation costs associated with those items. AFCI could also avoid the full cost of constructing a second repository under the scenario that anticipates new plant orders during the first third of the century.
- **Reduce Inventories of Civilian Plutonium**: It is possible to develop and deploy, by the middle of the next decade, advanced nuclear fuels that will enable the proliferation-resistant consumption of plutonium in existing LWRs or advanced gas-cooled reactors that may be available in the future.
- **Reduce the Toxicity of High-Level Nuclear Waste:** It is possible to develop and deploy, by approximately 2030, advanced proliferation-resistant treatment and transmutation technologies that will both significantly reduce the volume of spent nuclear fuel and create waste forms sufficiently clean of long-lived, highly toxic species to reduce the time to reach the level of natural uranium from 300 000 years to approximately 1 000 years.

The AFCI will continue to co-ordinated technology efforts of many countries and expand as appropriate. The programme will also continue to seek advice on programme planning, technical and scientific goals, and approaches to research from the Advanced Nuclear Transformation Technology Subcommittee of the Nuclear Energy Research Advisory Committee (NERAC), which is chaired by Nobel Laureate Burton Richter.

This subcommittee has made recommendations, adopted by NERAC, which recognise the successful completion of the first phase of this research (including a significant narrowing of technical options) and urge initiation of a second phase of work to provide decision makers with sufficient information to decide which, among the remaining technology options, is most promising for enhancing the Nation’s approaches to nuclear waste, national security, and energy security.

Bringing these technologies into use would require completion of a third phase of work In the case of AFCI Series One, successful completion of the second phase would enable the United States to initiate commercial deployment of these technologies by no later than 2015. The next generation technologies of AFCI Series Two would require significantly more time and research. Deployment could come only after a demonstration phase that could require new facilities in the United States or other countries. If all research and development is completed, deployment would be possible in about 2030. A successful programme would realise the vision anticipated by the *National Energy Policy* to explore advanced technologies to deal with spent nuclear fuel in co-operation with our international partners.

R&D ACTIVITIES FOR PARTITIONING AND TRANSMUTATION IN KOREA

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Abstract

According to the long-term plan of nuclear technology development, KAERI is conducting an R&D project of transmutation with the objective of key technology development in the areas of partitioning and transmutation system. The R&D activities for partitioning and transmutation of long-lived radionuclides are introduced in this work. The studies of partitioning are focused on the electrorefining and electrowinning, which are aimed at investigating the thermodynamic properties of electrodeposition behaviours as well as the separation efficiency. As for the transmutation system, the HYPER (HYbrid Power Extraction Reactor) combined by a proton accelerator and a sub-critical reactor is being studied in KAERI as a prominent candidate facility in the future. Some conceptual studies are being conducted to develop key elemental systems of the sub-critical reactor such as the core, TRU fuel, proton target, and the cooling system. The conceptual design of the HYPER system will be completed by 2006.

Introduction

The nuclear power industry in Korea has grown dramatically since the first commercial nuclear power plant, Kori #1, started operation in 1978. Sixteen nuclear power plants (12 PWRs and 4 PHWRs) are currently in operation, supplying about 40% of total electricity demand in Korea. As of December 2001, the accumulated spent fuel accounts for 5 385 t that is stored at four reactor sites. The cumulative amount is prospected to reach 11 000 t by 2010. However, the Korean government has not decided on any definite policy yet for back-end fuel cycle, while sticking to the policy of "wait and see". In the field of R&D only, a few optional studies, such as DUPIC (Direct Use of PWR spent fuel In CANDU), transmutation, and direct disposal, are being carried out in order to find an effective solution for the long-term management of spent fuels. According to the long-term plan of nuclear technology development, KAERI is conducting an R&D project of transmutation with the objective of key technology development by 2006 in the areas of partitioning and the transmutation system. As for the transmutation system, the HYPER (HYbrid Power Extraction Reactor) system combined by a proton accelerator and a sub-critical reactor is being considered as an appropriate means for the Korean situation trying to place the priority of back-end fuel cycle on the non-proliferation of nuclear fissile materials. The sub-critical reactor is supposed to have a fast neutron flux composed of spallation neutrons that are created by the hitting of accelerated proton beams against the spallation target. This system, therefore, is anticipated to tide over a certain extent of impurities (fission products) left in the fuel at the time of transuranic element recycle. It will certainly decrease the burden of partitioning of transuranic elements and also contribute to the requirement of non-proliferation of the P&T cycle because it is not necessary to further purify the fuel material after partitioning. The long-lived fission products such as ^{99}Tc and ^{129}I can also be loaded in the system as irradiation targets and then transmuted by neutron capture, which would be achievable by local moderation of the fast neutrons. In parallel with this, the partitioning study is focused on the development of pyroprocessing technology based on the electrolysis of molten-salts. The basic study currently being conducted at KAERI includes some experimental tests of lab-scale electrorefining and electrowinning by employing only non-radioactive materials. This study is aiming at analysing its technological applicability to the P&T cycle and also its advantages in the long-term management of spent fuels in the viewpoint of disposal as well as monitoring of the environment surrounding the repositories. The experimental work employing transuranic compounds will be done in the future on the basis of international collaboration programmes.

Strategy of partitioning and transmutation

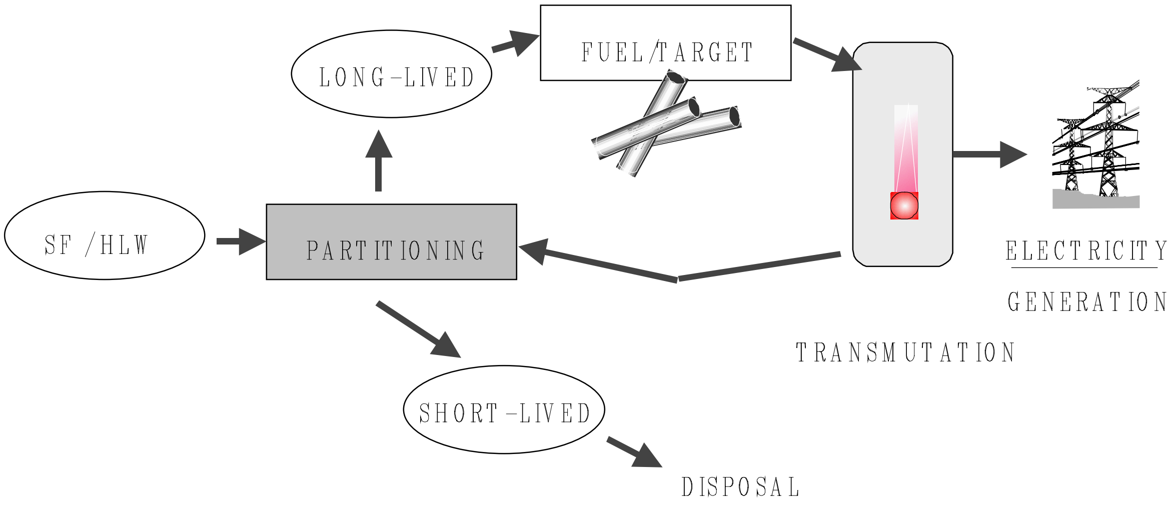
The nuclear transmutation, though it is not fully developed yet for commercialisation, is taken into account as a proper option for the solution of future spent fuel management. It may be an efficient way to relieve the risks of radiological contamination of the environment caused by probable release of long-lived radionuclides from the repositories. Since transmutation accompanies P&T (Partitioning & Transmutation) cycle where long-lived radionuclides must be partitioned and recycled, partitioning is an essential ingredient to complete the transmutation technology. Recently, pyrochemical separation method, though it is still in the R&D stage, is attracting a great interest as a prospective partitioning of long-lived radionuclides because it has noticeable advantages over wet processes, especially in terms of proliferation resistance as well as economy. According to KAERI's long-term R&D programme, we are supposed to develop transmutation technology based on a hybrid transmutation system as well as pyrochemical technology as the basis of the P&T cycle.

Conversion of oxide fuel material is being taken into account in order to reduce the oxides into metallic forms by using lithium in a lithium chloride bath. The materials of metallic forms then will be treated in the electrorefining process. [1] The concept of two step-electrorefining employing a dual cathode system is being investigated. The first step will be aimed at recovering only uranium on the solid cathode at a certain value of electrical potential, while the second step aimed at recovering all the remaining actinides together into the liquid cathode at a newly adjusted potential. The molten-salt waste from the electrorefining should be solidified as a final waste form to be disposed of. The treated waste will then be studied to solidify into ceramic form, which has very low leaching of radionuclides.

The objective materials to be transmuted are the group of transuranic elements most of which are composed of long-lived radionuclides, and the long-lived fission products such as ^{129}I and ^{99}Tc which also have long half-lives. It is necessary to separate these radionuclides from the wastes before loading them into a transmutation system because it is impossible to transmute only the long-lived radionuclides selectively.

The basic concept of recent transmutation system, is focused on the gaining of the double advantage by the use of transuranic elements as a nuclear fuel material. The advantages are the consumption of transuranic elements as well as the generation of electricity by using the transuranic elements. Based on this concept, some technological requirements are needed for the partitioning as well as for the transmutation system. The first requirement is the exclusion of uranium as a fuel source in the transmutation system because it can generate new transuranic elements by neutron capture, building up new transuranic elements in the fuel. The consumption rate of transuranic elements, however, will not reach 100% in one life-cycle, requiring another partitioning in order to separate long-lived radionuclides and then recycle them again into the transmutation system, which is called P&T cycle (see Figure 1). Another requirement for the P&T cycle is that the partitioning should be done under the condition of non-proliferation and higher economy. Transuranic elements, therefore, are required to be separated as a mixture which is directly used as a fuel material in the transmutation system without any more partitioning. This requirement may be satisfied by the introduction of the pyroelectrochemical separation even though it is not at a commercial stage yet.

Figure 1. **A concept of partitioning and transmutation cycle**



The technological requirements which are mentioned above can be summarised as follows:

- Exclusive use of uranium as a fuel source in the transmutation system.
- Partitioning based on non-proliferation.
- Higher rate of transmutation and thus less number of recycle of long-lived radionuclides.

However, a great expenditure would be needed for the partitioning and recycling of long-lived radionuclides, and also for the operation of the transmutation system, causing the economy of the P&T cycle to be negative. On the contrary, there are also some benefits that may turn the economic barometer from the negative to the positive direction. They would come from the electricity generated from the transuranic elements as well as the cost-saving in high-level waste disposal. If the economic analysis is extended to the environmental effect, it may bring additional positive effect also.

Partitioning by pyroprocessing

Recovery of uranium

Uranium is contained in spent fuels or high-level wastes from reprocessing plants as a major and a minor component, respectively. As described before, since uranium is not so desirable as a fuel source of the transmutation system, it is necessary to remove it from the spent fuels or high-level wastes in advance in the partitioning step. The fundamental studies of pyroprocessing conducted in KAERI in order to remove uranium are introduced below.

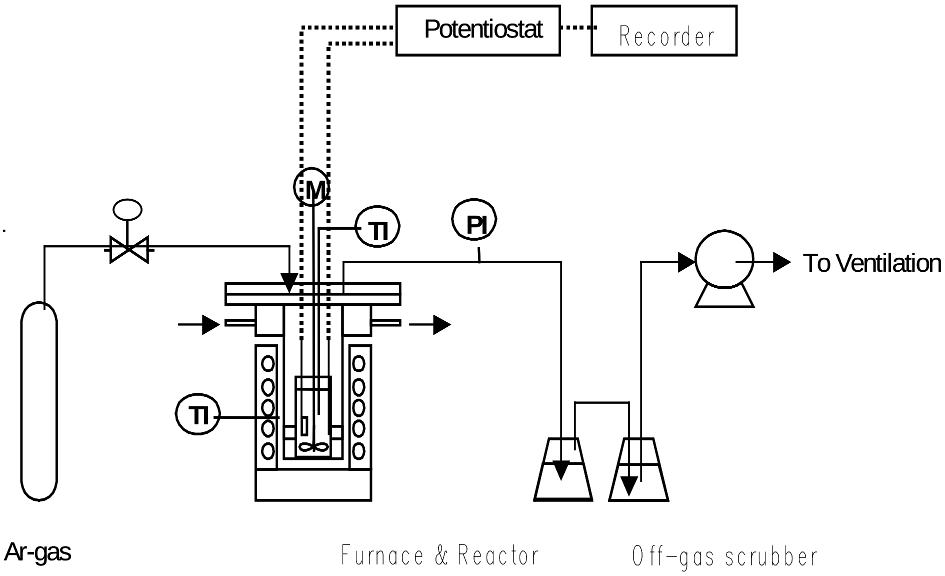
Electrorefining

Electrorefining is a key technology to recover uranium and transuranic elements from spent fuels or high-level radioactive wastes. [2,3] Since each metal chloride/fluoride has a unique value of Gibbs free energy of formation in the molten-salt electrolysis, [4] uranium can be selectively reduced and deposited on the surface of cathode by the adjustment of the electrical potential between anode and cathode. Consequently, uranium can be recovered as an electrodeposition at the cathode.

Figure 2 shows the schematic diagram of experimental electrorefining system. The electrolysis cell is installed in a furnace, which is located under the bottom of the glove box. The electrolysis cell and glove box are filled with an inert gas in order to protect the molten-salt from being reacted undesirably with oxygen or moisture. The offgas from the electrolysis cell is treated with alkali solution and water so that chlorine, hydrochloride, that could be formed in the cell, or some evaporated compounds can be trapped in the liquids before going to the ventilation system.

Figure 3 shows an experimental result of uranium deposition on the solid cathode, in which the molten-salt LiCl-KCl was used as an electrolyte at 1.3 V and 500°C.

Figure 2. **Schematic diagram of experimental electrolysis system**



Electrowinning

This is also a sort of pyroelectrochemical method to separate some selective metals in a molten-salt by electrochemical reduction and deposition on the cathode. One thing different with the electrorefining is that a sacrificing electrode is used as an anode in the electrowinning. Due to the difference in the REDOX potential for the various metal salts just like that in the electrorefining, the anode material must be appropriately chosen for the deposition of desired components. For example, if beryllium is chosen as the anode material in the electrolyte of LiF-BeF_2, then uranium, zirconium, and transition metals, having lower change of Gibbs free energy of fluoride formation, tend to deposit on the cathode.

Figure 3 shows an experimental result of uranium deposition on the solid cathode, in which the molten-salt LiCl-KCl was used as an electrolyte at 1.3 V and 500°C.

Figure 3. **Deposition of uranium on the carbon steel cathode**

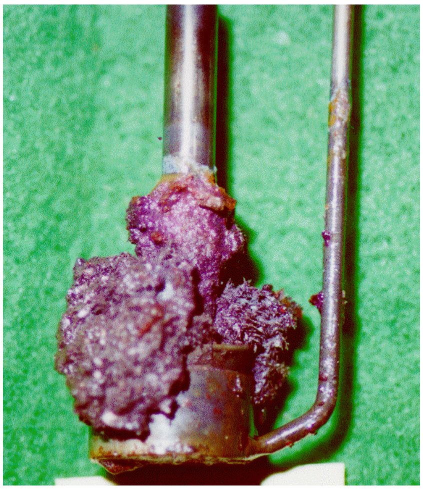
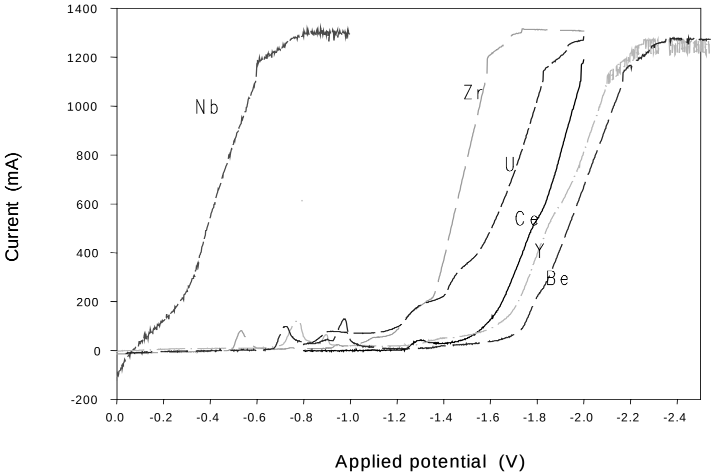


Figure 4 shows the decomposition potentials of Nb, Zr, U, and Ce in the system of LiF-BeF_2(molten-salt), Be-anode, and nickel cathode at 500°C.

Figure 4. **Decomposition potentials of various metal fluorides in the molten-salt of LiF-BeF_2**



Recovery of transuranic elements

As described above, tansuranic elements are supposed to be recovered as a mixture in the liquid cathode. This would be possible only after removing uranium from the molten-salt in advance by the first electrolysis. Since no single plutonium product is obtained in this step, and the mixture of all transuranic elements is to go to the TRU fuel fabrication process, this electro-process could be a part of the proliferation-resistive P&T cycle.

In this step, parts of rare earth tends to accompany transuranic elements into the liquid metal cathode. Therefore, the rare earths should be removed to a certain level that will allow for a transuranic fuel in the transmutation system. Since both rare earth and transuranic elements are distributed into the molten-salt and liquid metal phases with different extents, the rare earths can be removed into the salt phase by selective oxidation. At present, a feasibility study is being carried out for the removal of rare earth impurities from the molten cadmium by selective oxidation of rare earths on the basis of thermodynamic properties.

A conceptual study of transmutation system

An accelerator driven system, named HYPTrans-uranics(TRU) and some long lived fission products(FP) from LWR spent fuel will be the target materials for transmutation. The fission products that deserve the most attention are ^{99}Tc, ^{135}Cs, and ^{129}I from the viewpoint of releasing risk from a high-level waste repository. Since cesium separated from spent fuels, unlike ^{99}Tc and ^{129}I, is very hard to be transmuted, ^{99}Tc and ^{129}I are the objective fission products considered as transmutation targets in the HYPER system.

Some part of the conceptual study was already performed in Phase I (1997-2000). The study of Phase II (2001-2003) is focused on the evaluation of key unit systems of the HYPER. A conceptual design of the HYPER system will be completed at the end of Phase III (2004-2006).

HYPER core

The HYPER is being considered as one of the prominent transmutation systems to treat TRU as well as long-lived fission products at the same time. Basic core design parameters were derived as follows in Phase I:

- Neutron energy spectrum and pitch-to-diameter ratio.
- TRU fuel loading scheme and its optimisation.
- Methodology development to minimise the reactivity swing.

The HYPER will be designed as a fast neutron-irradiation system because fast neutron is much more efficient for the transmutation of TRU in terms of accelerator beam power economy, pin power peaking, and transmutation capability for all transuranics. [5] In order to keep the relative assembly power within the design target value of 1.5, the core should be divided into three different TRU enrichment zones. The fuel of low TRU fraction (26%TRU-74%Zr) will be designed to load in the innermost zone whereas the fuel of high TRU fraction(46%TRU-54%Zr) will be loaded in the outermost region. Refueling will be carried out on the basis of the scattered loading concept with multiple batches in each zone. In this case the use of burnable absorbers in the core was found to reduce the reactivity swing by 38%. [6]

Various optimisation studies on the concept of core are now underway in Phase II as follows:

- Optimisation of height-to-diameter ratio. [7]
- Optimisation of sub-criticality level.
- Optimisation of spallation source.
- Development of 3-D kinetics code, HITE (3-dimensional hexagonal finite element code for transient and steady state).

In the analysis of HYPER system, the partitioning process is assumed to achieve the rates of uranium and lanthanide eliminations from LWR spent fuel (discharged burn-up ≅ 33 000 MWD/MTU) as 99.9% and 90%, respectively. As a result, the ratio of TRU to uranium will be 9 to 1 in the HYPER. With this ratio, the HYPER core will reach a pseudo-equilibrium condition in terms of nuclide composition, approximately at the 20th cycle. The fraction of uranium in heavy metal will be about 20% at the 20th cycle. The transmutation capability of the system has been evaluated as about 313 kg of TRU for one effective full power year. About 90% of energy will be generated from the fission of TRU while the other 10% will be from the uranium at 20th Cycle. Table 1 shows the actinide burning characteristics of the HYPER at the 20th cycle.

Table 1. **Variation of actinide concentration at the 20th cycle**

Nuclide	**Inventory** (kg)		
	BOC	EOC	Variation
^{233}U	0.2144E-02	0.1902E-02	-0.0002
^{234}U	0.9166E+01	0.9215E+01	+0.039
^{235}U	0.3203E+01	0.3121E+01	-0.082
^{236}U	0.3949E+01	0.3986E+01	+0.037
^{238}U	0.9675E+03	0.9516E+03	-15.9
^{237}Np	0.7585E+02	0.6977E+02	-6.08
^{238}Pu	0.1456E+03	0.1432E+03	-2.40
^{239}Pu	0.8774E+03	0.8082E+03	-69.2
^{240}Pu	0.1299E+04	0.1270E+04	-29.0
^{241}Pu	0.2797E+03	0.2674E+03	-12.3
^{242}Pu	0.3898E+03	0.3845E+03	-5.3
^{241}Am	0.1049E+03	0.1010E+03	-3.9
^{242}Am	0.7905E-01	0.7898E-01	-0.0001
^{242m}Am	0.9818E+01	0.9773E+01	-0.045
^{243}Am	0.1191E+03	0.1182E+03	-0.9
^{242}Cm	0.8502E+01	0.8498E+01	-0.004
^{243}Cm	0.1090E+01	0.1081E+01	-0.009
^{244}Cm	0.1142E+03	0.1142E+03	0.0
^{245}Cm	0.3564E+02	0.3571E+02	+0.07
^{246}Cm	0.3084E+02	0.3072E+02	-0.12

The sub-criticality level of the core has been determined by considering the reactivity changes due to the power defect, beam tube rupture. The analysis showed that the sub-criticality of 0.97 is enough to keep the core under criticality at any anticipated condition. The HYPER system has large reactivity swing because it has very little fertile material. The reactivity swing limits the cycle length to be about 140 days. Figure 5 shows a brief description of the overall core design concept. Table 2 represents the design parameters for the HYPER system.

Figure 5. **HYPER core design concept**

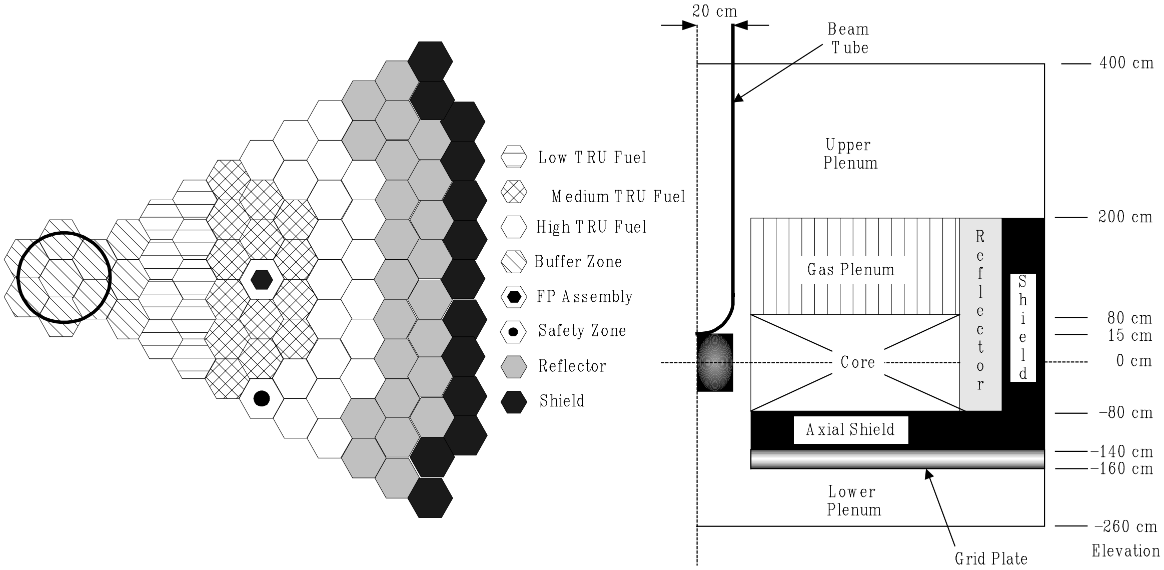


Table 2. **HYPER system design parameters**

Parameter (unit)	**Values**	**Parameter** (unit)	**Values**
System		***Assembly/Fuel***	
• Core Thermal Power (MW)	1 000	• Ass. Pitch (cm)	19.96
• Active Core Height (m)	1.2	• Flow Tube Outer Surface	
• Effective Core Diameter (m)	3.8	Flat-to-Flat Distance	19.52
• Total Fuel Mass (TRU-Kg)	2 961	(cm)	0.355
• System Multiplication Factor	0.97	• Tube Thickness (cm)	HT-9
• Accelerator Beam Power (MW)	~ 13	• Tube Material	331
• Ave. Discharge Burnup (%at)	~ 25	• Rods per Assembly	1.5
• Transmutation Capability	313	• Rod P/D	0.668
(Kg/EFPY)	183	• Rod Diameter (cm)	0.492
• Number of Fuel Assembly	13.5	• Fuel Meat Diameter (cm)	0.051
• Ave.Linear Power Density (KW/m)		• Cladding Thickness (cm)	

HYPER fuel

One of the basic requirements for the selection of HYPER fuel is a good compatibility with the partitioning process. As the loss of radioactive nuclides cannot be avoided at each recycling process, a high burn-up capability is required as a selection criterion in order to minimise the loss. A metallic fuel, among other fuel types such as oxides and nitrides, has been selected because it has relatively good comptabilities with the dry partitioning process, high burn-up requirement, and also fast neutron spectra. Either a TRU-Zr alloy or a (TRU-Zr)-Zr dispersion-type is considered as a candidate fuel for the HYPER system. In the case of the dispersion fuel, particles of 90wt%TRU-10wt%Zr metal alloy are to be dispersed in a Zr matrix.

Two computer simulation codes, MACSIS-H (alloy-type fuel analysis) and DIMAC (dispersion-type fuel analysis), were developed in Phase I. In addition, a basic fuel design and a couple of fuel performance analyses have been done using the codes. [8,9] Since there is not much knowledge on TRU-Zr type metal fuel most of the experimental result was reflected in the modification of the codes. The increment of Zr fraction decreases the deformation rate of a fuel rod (ΔD/D; D=Fuel Rod Diameter) in the alloy-type fuel as expected. The simulation predicted that more than 90% of the fission gas is released at burn-up of 5 atomic per cent for the alloy-type. The fission gas release rate is almost independent of the Zr fraction when Zr weight fraction varies from 45% to 55%. The build-up pressures due to the fission gas are 818psig and 553psig when the plenum volumes are 1.2 and 1.5 times the fuel meat volume, respectively at the burn-up of 13.6 atomic percent. Both results are acceptable. In addition to the fission gas, helium gas is produced in the TRU fuel because of the alpha decay of ^{241}Am, ^{242}Cm. Thus, larger plenum size (1.5 times) is preferred in the metal fuel bearing TRU.

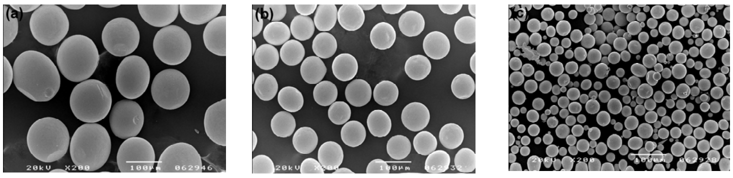
Most of the fission gas is modelled to be trapped at the inside of the fuel matrix for the dispersion-type fuel. Therefore, the dispersion fuel does not have gas plenum. The trapping of fission gas in the fuel matrix changes the fuel volume. The simulation predicts that the dispersion-type fuel has the deformation rate (ΔD/D) of 3.5% at 30at% burn-up.

In addition to the continuous update of the computer codes, simulated fuels (U-Zr) and ((U-10Zr)-Zr) have been fabricated and tested under the out-pile condition. Basic properties such as thermal conductivity, expansion, and density were obtained. Thermal stability, the reaction between fuel meat and cladding, and the redistribution of nuclides are under examination. Figure 6 and 7 show the U-10Zr powder fabricated using a centrifugal method and the measured thermal conductivity/expansion coefficients, respectively.

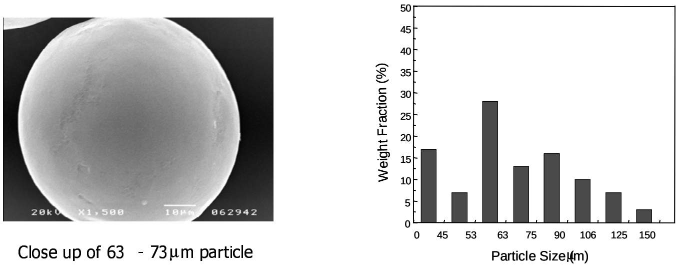
Pb-Bi Coolant and target

A lead-bismuth (Pb-Bi) eutectic alloy was selected as a coolant material for the HYPER system because Pb-Bi is rather safe in terms of chemical reactivity and can be used as a spallation target also. A preliminary design study was performed for its thermal hydraulics in the core in Phase I.

Figure 6. **Particle shape and size distribution of U-10Zr**

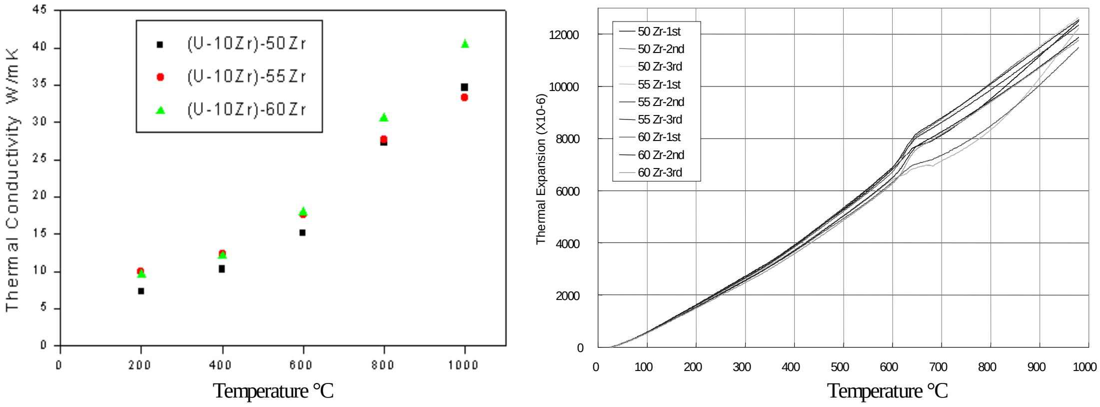


106 - 125µm Particle 63 ? 73 µm Particle ~45 µm Particle



Close up of 63 - 73µm particle

Figure 7. **Thermal conductivity and expansion coeff. of (U-10Zr)-Zr) type fuel**



The core inlet and outlet temperatures of Pb-Bi coolant have been determined as 340°C and 510°C, respectively by considering the melting point of Pb-Bi and the corrosion of the structural material, etc. The P/D (Pitch-to-Diameter) ratio of the HYPER core was chosen as 1.5 and the average Pb-Bi velocity as 1.5 m/s, which is a relatively low coolant velocity compared to that of typical LMR reactors using sodium as coolant. [10] The flowing velocity of Pb-Bi is limited to be less than 2.0m/sec in order to avoid any possible erosion problems and reduce the required pumping power. Instead of wire spacers commonly used for tight lattices, grid spacers are more suitable to ensure proper separation of the fuel rod in the HYPER system. A loop type configuration was adopted and a 3-loop concept was estimated to be the optimum. Each loop has one super-heater and two evaporators. Figure 8 and Table 3 show the design characteristics of cooling system of the HYPER.

Figure 8. **Heat removal system concept for the HYPER system**

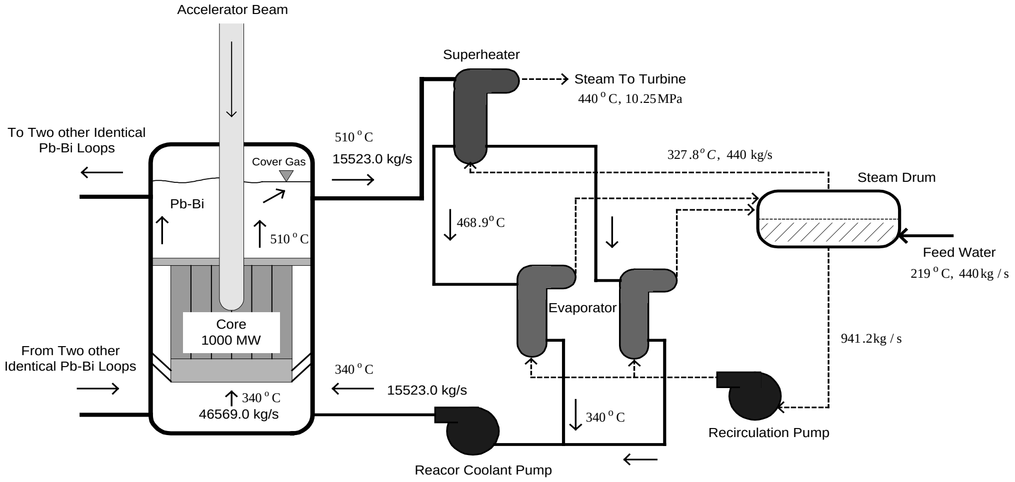


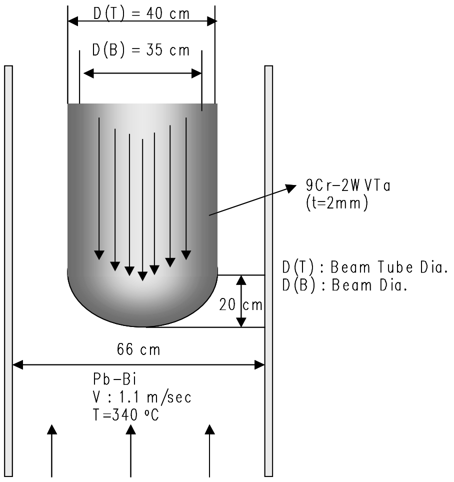
Table 3. **Thermal hydraulic design parameters for the HYPER system**

Thermal Power	1 000 MWt
Primary Heat Transport System	
Reactor Inlet/Outlet Temperature	340°C/510°C
System Flow Rate	40 155 kg/sec
Number of Loop	3 Loop
Primary Coolant Pump	Mechanical Type
Steam Generator	
Type	Separate Type (Evaporator/Superheater)
Superheater	Once-Through Type, Single Wall Tube
Thermal Power	132.8MWt
Primary Side	
Inlet/Outlet Temperature	510°C/465°C
Mass Flow Rate	20 077 kg/sec
Secondary Side	
Operating Pressure	156.7 Atm
Inlet/Outlet Temperature	347°C/490°C
Mass Flow Rate	195.2 kg/sec
Evaporator	Forced Circulation Type, Single Wall Tube
Thermal Power	367.2MWt
Primary Side	
Inlet/Outlet Temperature	465°C/340°C
Mass Flow Rate	20 077 kg/sec
Secondary Side	
Recirculation Ratio	5
Operating Pressure	156.7 Atm
Inlet/Outlet Temperature	312°C/347°C
Feedwater Flow Rate	195.2 kg/sec
Circulation Flow Rate	976 kg/sec

The Pb-Bi coolant flowing through the central channel will be used as the spallation target. The factors affecting the lifetime of the beam window are corrosion by Pb-Bi and radiation damage. The alloy 9Cr-2WVTa is being considered as a window material because the advanced ferritic/martensitic steel is known to have a good performance in a highly corrosive and radiative environment. A single beam window is adopted so that there is no independent window cooling system required. The design target for the lifetime of the window is no less than 6 months. The average energy of the spallation neutrons is estimated to be 14 MeV. The spallation reaction produces more than 800 different radioactive nuclides. One of the dominant long-lived radioactive nuclides due to the spallation is ^{205}Pb. About 9.3 grams of ^{205}Pb is generated when 1 GeV, 1 mA protons are injected into the Pb-Bi target for one effective full power year. Figure 9 shows the lay out of beam target zone.

A basic design analysis is being carried out using SLTHEN (Steady-state LMR core Thermal Hydraulics code based on ENergy model) [11] for core sub-channel analysis and CFX for the analysis of the thermal hydraulics in the target region. The maximum coolant outlet temperatures in the case of the hotest assembly were estimated to be higher than the average coolant outlet temperature by 22.8°C, when flow split and heat transfer between sub-channels were considered. Additional sensitivity calculations were performed for the various inter assembly gap flow rates and turbulent flow mixing. The maximum coolant and cladding temperatures, which are major parameters in the conceptual design stage, were not strongly affected by the turbulent mixing under the HYPER design conditions. In addition, some corrosion experiments on static conditions are performed for the core structural materials including beam tube material and fuel cladding.

Figure 9. **Beam target and window design concept**



Summary

The R&D activities for partitioning and transmutation of long-lived radionuclides are introduced in this work. An accelerator driven system, named HYPER, is being studied as a candidate transmutation system for the treatment of nuclear wastes. Trans-uranic elements and some long-lived fission products from LWR spent fuel will be the target materials for transmutation. Some part of the conceptual study was already performed in Phase I. The study of Phase II is focused on the evaluation of key unit systems of the HYPER. A conceptual design of the HYPER system will be completed at the end of Phase III. Further studies for the development of pyroprocessing technology will be extended to the employment of transuranic elements in the electrorefining or electrowinning on the basis of international collaboration. As for the HYPER system, the basic core design will be completed in Phase II. More detailed analysis for steady state and transient neutronic behaviours as well as thermal hydraulics in the core will be carried out for various cases including some accidental in Phase III. In-pile tests of simulated fuels will be carried out as an international joint study in the Phase III. HANARO or other research reactors are also considered for the irradiation facility. For the development of cooling system, an experimental loop of Pb or Pb-Bi will be designed and built in KAERI in order to test corrosive properties of the coolant.

Acknowledgements

This study was carried out with the financial support of the Korea National Mid- and Long-Term Nuclear R&D Programme by Ministry of Science and Technology.

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STATUS OF THE FRENCH RESEARCH PROGRAMME FOR ACTINIDES AND FISSION PRODUCTS PARTITIONING AND TRANSMUTATION

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Abstract

The global energy context pleads in favour of a sustainable development of nuclear energy. It is a technology with a future since the demand for energy will likely increase, whereas resources will tend to get scarcer and the prospect of global warming will drive down the consumption of fossil fuel sources.

How we deal with radioactive waste is crucial in this context. From the start, the CEA has devoted considerable effort to management of the back end of the cycle. It furnished the process and techniques used in the La Hague facility to extract the re-usable materials, uranium and plutonium, and condition the resulting waste. Towards the end of the 1960s, it developed the process of vitrification for highly active waste that has become the world reference. French industry was responsible for the introduction of standard international practices with respect to waste conditioned during the processing of spent fuels. The specifications for the packages are approved by more than ten countries across the world.

The law of 1991 specifically gave new momentum to the research into waste by requesting exploration not only into deep geological storage repositories, but also into reducing the quantity and toxicity of the long-life radioactive elements present in the waste by separation and transmutation and studying their conditioning for long-term disposal. Over the past ten years, all of the above-mentioned research has been conducted by CEA and ANDRA in close collaboration with partners from industry (EDF, COGEMA, FRAMATOME-ANP), with the CNRS and various universities. A review of the situation ten years on indicates a number of significant results that have changed the prospects for nuclear waste management.

The paper focus on separation and transmutation R&D programme and main results over these ten last years. The massive research programme on enhanced separation, conducted by CEA and supported by broad international co-operation, has recently achieved some vital progress. Based on real solutions derived from the La Hague process, the CEA demonstrated the lab-scale feasibility of extracting minor actinides and some fission products (I, Cs and Tc) using an hydrometallurgical process that can be extrapolated on the industrial scale. The CEA also conducted programmes proving the technical feasibility of the elimination of minor actinides and fission products by transmutation:

fabrication of specific targets and fuels for transmutation tests in the HFR and Phénix reactors, neutronics and technology studies for ADS developments in order to support the MEGAPIE, TRADE and MYRRHA experiments and the future 100 MW international ADS demonstrator. Scenarios studies aimed at stabilising the inventory with long-lived radionuclides, plutonium, minor actinides and certain long-lived fission products in different nuclear-power-plant parks and to verify the feasibility at the level of the cycle facilities and fuels involved in those scenarios. Three French Research Groups CEA-CNRS carry out partitioning (PRACTIS) and transmutation (NOMADE and GEDEON) more basic studies.

Introduction

The radioactive content of the waste generated by the nuclear-power cycle constitutes a potential risk for human beings and the environment. In order to control it, the safest management methods possible must be implemented. Although that management already has a long scientific and technical history, interrogations and concerns have emerged in the public and have prompted the legislator to address the issue.

In France, the Law of 30 December 1991 sets the major orientations of the public policy in that field by prescribing the research areas to be explored. It constitutes the first global legislative instrument for the management of high-level long-lived radioactive waste. It identifies the principles by which all radioactive-waste-management methods must abide: protection of nature, the environment and health, as well as respect for the rights of future generations. It prescribes the implementation of a significant structured research programme and its associated research schedule until 2006. In addition, it also institutes a National Review Board (*Commission nationale d'évaluation – CNE*) responsible for following up research and for reporting to the government on a yearly basis.

The Law of 1991 advocates a wide exploration of solutions concerning the management of radioactive waste. With that goal in mind, three research areas have been defined:

- Area 1 relating to partitioning and transmutation deals with various potential solutions capable of reducing substantially the mass and toxicity of long-lived radionuclides as a source of risk over the long term.
- Area 2 aims at defining the conditions under which a repository, whether reversible or irreversible, may be implemented and operated in a deep geological formation, where various high-level long-lived waste packages would be emplaced. Underground laboratories are essential tools to that research programme.
- Area 3 is dedicated to research on packaging and long-term storage. It covers the development and qualification of mechanisms ensuring that the waste is kept under satisfactory safety conditions over periods of several decades, pending the availability of the management methods to be developed in Areas 1 and 2.

The Law stipulates that, by 2006, the research programme shall provide to the legislator and public authorities the necessary elements to get an overall idea of the situation and to decide whether it is appropriate to create a repository for high-level long-lived radioactive waste.

This paper presents the large amount of results dealing with partitioning and transmutation that have been accumulated since the beginning of the national programme by the CEA and other important French R and D or industrial agencies, such as the CNRS (French National Council for Scientific Research), EDF (Électricité de France), COGEMA or FRAMATOME-ANP.

Overview of priorities for the partitioning and transmutation studies

The national programme for partitioning and transmutation is defined as a function of relevant priorities assigned in the framework of each research area, with due account to the fact that the objective is to provide the French government and Parliament by 2006 with sound elements that will allow them to implement a strategy for the management of long-lived radioactive waste. Those priorities include:

- to study the feasibility of various partitioning processes constituting a prerequisite common core for more specific management possibilities for long-lived radionuclides; to select and optimise those processes in relation to the efficiency of the actinide-burning systems and of the transmutation systems for long-lived fission products, and the foreseeable specific types of packaging for those various products; to study the reprocessibility of fuels and targets for transmutation purposes, particularly pyrochemical processes;

- to study scenarios aiming at stabilising the inventory with long-lived radionuclides, plutonium, minor actinides and certain long-lived fission products in nuclear-power-plant geometries (the so-called "single-stage" approach) and to verify feasibility at the level of the cycle facilities and fuels involved in those scenarios; to examine also elimination possibilities from that inventory;

- to assess different innovative reactor systems that ensure a good control of high-level long-lived waste with a significant effort dedicated to hybrid systems, by contemplating a mixed ("dual-stage") set of nuclear power plants, where a small number of specialised burner reactors would burn up the long-lived radionuclides generated by nuclear-power reactors, and by examining the possibilities of reducing significantly the waste inventory;

- to study the feasibility of an hybrid-system demonstrator.

Programmes and results for partitioning and transmutation of actinides and fission products

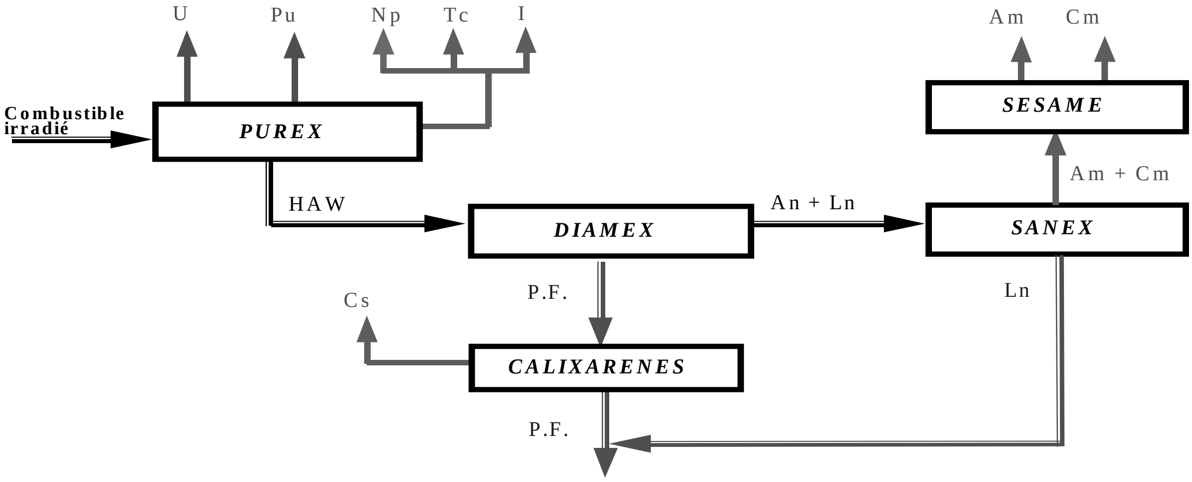
The overall objective is to investigate solutions capable of reducing the quantity of long-lived radioactive waste resulting from energy generation, by separating it (through chemical-separation processes before the reprocessing of spent fuels) from the other elements it contains and by transmuting the largest possible part of the isolated waste under a neutron flux either inside present or future critical (such as gas cooled thermal-spectrum or fast-spectrum) reactors or innovative systems (notably, hybrid systems) in order to transform it as soon as possible into stable (non-radioactive) atoms. [1]

The studies cover minor actinides (americium, curium, neptunium) that, except for plutonium, represent most of the long-term radiotoxic inventory of nuclear waste and certain fission products having a long-lived isotope, a high relative abundance in the spent fuel as well as chemical properties that make them potentially mobile: iodine, caesium and technetium. Since plutonium is both a recyclable energetic material and the main contributor to potential long-term radiotoxicity, all scenario studies considered must be consistent with the policies contemplated for the long-term management of plutonium. [2]

As a complement to the "Partitioning-Transmutation" reference strategy, studies are also undertaken on the alternative aspect of "Partitioning-Conditioning", where partitioned – yet "untransmutable" – radionuclides would be conditioned in new specific matrices. Conditioning studies concern particularly the development of new specific matrices for partitioned radionuclides. Since their chemical form is known, it is possible to integrate them very closely in a defined crystalline form and thus achieve a high durability level. Programmes cover in first priority very-long-lived fission products such as iodine 129 and caesium 135. The goal of the research programme is to bring all those processes to the technical-feasibility stage by 2006, while combining them with an industrial-feasibility assessment.

The reference approaches of the programme on extensive partitioning are based on extraction during the liquid phase, either by adapting the PUREX process used in the industry to reprocess fuel or in developing new PUREX-downstream complementary extraction processes (Figure 1). The scientific feasibility of these processes (development of extracting molecules and validation of basic designs at lab-scale) have been established in 2001 with values of separation as high as 99.9% for recovered americium and curium from HLW). Americium and curium are partitioned by new extracting molecules specifically developed for that purpose with the French process which has been selected at the end of the scientific feasibility stage; caesium is separated with calixarene-crown molecules, whereas neptunium, iodine and technetium are extracted by technical adaptations of the existing PUREX process which is already used at La Hague plant. The next goal of the study programme for partitioning processes will be to reach the technical feasibility stage before 2005 (complete process validation) with the assessment of the industrial feasibility (implementation conditions, production of secondary waste, safety conditions, costs, etc.).

Figure 1. **Diagram of separation processes**



Alternative processes are also being investigated, notably those involving pyrochemistry for the reprocessing of transmutation targets (hardly soluble in aqueous nitric acid solution) and some innovative fuels of future reactors.

That research on extensive partitioning relies on basic studies in theoretical chemistry and on models, notably in association with the PRACTIS Research Group that includes representatives from the CNRS, the CEA, ANDRA (National Radioactive Waste Management Agency) and EDF.

The purpose of transmutation programmes is to assess the possibility of eliminating long-lived radioactive waste through critical reactors (present or future) or innovative sub critical hybrid systems.

With regard to critical reactors, programmes are divided into three major themes:

- studies on reactor cores and transmutation neutronics in existing PWR-type reactors with evolutions of current management modes (evoluted CORAIL MOX assembly, APA concept RMA improved-moderation core, plutonium on an enriched-uranium support MIX fuel) and in future gas cooled thermal or fast-flux reactors;

- experimental studies on fuels and targets, including in particular an experimental irradiation programme;

- basic physics in order to complete and improve nuclear data (effective sections of nuclear reactions) and nuclear-reaction models. That task requires an evaluation at each step of uncertainty.

Programmes on transmutation within innovative systems are conducted notably in the framework of the GEDEON Research Group that includes representatives from the CEA, the CNRS and EDF. FRAMATOME-ANP and ANDRA are also members of its Scientific Board.

The experimental irradiation programme is based, for a large part, on tests in the fast flux Phénix reactor which power restart is planned at the very end of 2002. Flux conditions of Phénix are well suited to allow the studies of irradiation damages of fuels and targets for transmutation under representative conditions of fast and partly moderated flux, which are considered to be the most efficient for transmutation of minor actinides and some long live fission products. A first phase of experiments, ready at the power restart time, will include:

- targets ECRIX B and H, made of pellets containing americium oxide microdispersed in an inert magnesia matrix, under fast (B) and partly moderated (H) neutron flux;

- 3 sub assemblies METAPHIX 1, 2 and 3 containing experimental pins with metallic UPuZr fuel and dispersed minor actinides, inside an agreement with the Japanese CRIEPI agency;

- irradiation ANTICORP 1 consisting of 3 pins containing pure metallic ^{99}Tc;

- PROFIL R for the measurement of capture sections of fission products, lanthanides, actinides isotopes under fast flux neutrons.

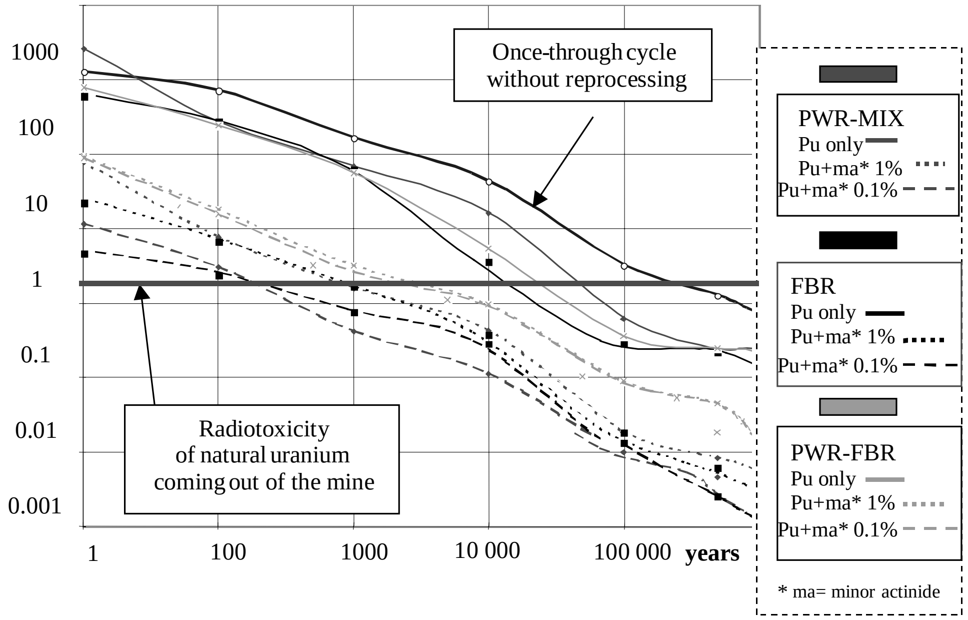
A second phase, which will integrate the knowledge gained with the experimental irradiations carried earlier in the thermal French SILOE and European HFR and the R and D results about fabrication process (macrodispersion and new matrix materials) will start in 2004; a joint CEA-DOE-ITU experiment (oxide, nitride and metallic ADS fuels) is also planned beginning in 2005.

Started in 1998, a reflection on innovative nuclear systems has resulted in a summary report on hybrid systems where the project of a European demonstrator was indicated. The CEA and the CNRS instituted a co-ordination group to prepare a documented report that was presented to the National Review Board in February 2001. This Development Plan is in the process to be updated with taking into account recent results and necessary evolutions for implementation of large and heavy cost experiments. Progress has been gained about the nuclear basic data still necessary to control the neutronic coupling and to design an ADS transmutation core (MUSE experiment corresponding to the first coupling of the CEA MASURCA reactor with a low power neutron source) and about the understanding of the behaviour of liquid spallation target with the specific irradiation and corrosion conditions to which the window (between beam and core) is submitted; a preliminary design of an experimental ADS is in progress inside the framework of an European project partly supported by nuclear industrials such as FRAMATOME and ANSALDO. Next steps will be the implementations of the 1 MW MEGAPIE lead-bismuth spallation target scheduled in operation in 2005, the construction of a demonstration experiment at a power of few hundreds of kW based on the Italian TRIGA reactor driven by a cyclotron accelerator with a solid tungsten target due to operation in 2007 and the possible implementation of the more powerful and representative experimental ADS MYRRHA facility in Belgium. All these projects are being developed with a clear support of the EURATOM Agency.

Finally, the potential performances of partitioning-transmutation are assessed globally through scenario studies. Different major scenario families are considered. The first families call upon current technologies: PWR/EPR-type facilities using plutonium in MIX fuel and burning minor actinides as an option; fast-breeder isogenerators ensuring the multirecycling of plutonium and minor actinides (monorecycling of minor actinides as an option); mixed PWRs (UOX and MOX) and fast-breeder reactors burning plutonium and, with certain variations, minor actinides and certain long-lived fission products. The other families rely on innovative technologies: mixed PWRs (UOX) and hybrid systems burning plutonium, minor actinides and long-lived fission products; "dual-stage" reactors where PWRs and new innovative high temperature gas cooled thermal then fast reactors ensure the multirecycling of plutonium and the transmutation of past and existing nuclear wastes.

A first appraisal of the scenarios with current technology reactors has been presented in 2001 in order to illustrate the achievements made so far on the stabilisation – and even reduction – perspectives over time of the quantities of long-lived radionuclides (Figure 2) resulting from energy generation and to quantify secondary waste that may be low, without being totally inexistent. These results indicate that the multi recycling of plutonium offers a first advantage by reducing the potential radiotoxicity of ultimate waste by a factor of 3 to 10, compared to once-through cycle, and that partitioning and transmutation of minor actinides would bring a further advantage reflected by a global reduction factor in the order of 100, depending on the partitioning/transmutation modes considered.

Figure 2. **Radiotoxicity after various partitioning and transmutation operations**



Conclusion

In France, spent nuclear fuels are reprocessed in order to recover uranium and plutonium. The resulting waste are conditioned in line and then, temporarily stored. For further waste management, the Parliament has launched in 1991 a research programme, which must converge in 2006. It has first to deal with the existing wastes and those that have yet to be produced by the existing energy production systems. Then, it has to answer the question whether it is possible to reduce the radiotoxic potential of the ultimate waste. The answer is a probable "yes", provided that important modifications are made on the reactors and fuel cycle systems, which means important investments. It will take time, several tens of years, as the nuclear energy production system is relatively young. However, if nuclear energy production is to be continued, the evolution is without doubt in the direction of reducing the long-term radiotoxic potential in the waste. Partitioning and transmutation is an inescapable channel.

Transmutation of separated radionuclides, mainly plutonium and minor actinides, could be done in existing PWR, although the time to reach equilibrium may be rather long. Fast reactors could do the job more efficiently. They would be either critical or driven by an accelerator.

CEA has chosen Gas Cooled Reactors as champions for the future generation of reactors. CEA is strongly involved in the US-started Generation IV forum. First, aiming at recovering knowledge on High Temperature Reactors, it aims at developing a fast neutron version of the concept. Ability to transmute minor actinides will be a part of the requested properties.

However, one must keep in mind that PWR can be operating in France up to the end of this century. Although ADS cannot compete with critical reactors for energy production, there is a niche where they have a possible role in burning the minor actinides that are produced by PWR. A fuel containing a large proportion of americium looses the quasi-magical properties of the mix U5-U8 in stabilising the neutrons dynamics of critical reactors (Doppler effect and delayed neutrons). In this context, CEA is wishing to share the development of a demo ADS somewhere in the world in collaboration large enough to cover the cost of it. From its own point of view, CEA is wishing to put most of its effort in the development of energy producing reactors.

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OVERVIEW OF CURRENT RUSSIAN ACTIVITIES IN P&T AREA

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Introduction

The general policy of radioactive waste management is consistent with the long-term plans for nuclear power development adopted in each country. Russian activities aimed at setting up in the future a fuel cycle of nuclear power with reasonably minimised quantities of Radwaste subject disposal are being carried out by Minatom as part of the general Strategy for development of national nuclear power. [1] Several key missions of this Strategy deserve special mention:

- in the next 20-40 years, construction of advanced thermal reactors which will run on enriched uranium until the economically acceptable reserves of natural uranium are exhausted;
- reprocessing of all spent fuel of thermal reactors to separate plutonium and long-lived nuclides;
- development of a new generation of fast reactors which will meet the requirements placed on innovative reactors for large-scale electricity production (economic efficiency, safety, minimised Radwaste, proliferation resistance);
- after 2030, deployment of a system of innovative fast reactors, using plutonium separated from spent fuel of thermal reactors, and solution with their help of the totality of problems associated with transmutation of long-lived nuclides.

Task named “Transmutation” was set up in 2001, within the general Minatom’s programme, to develop a scenario for transition to the fuel cycle of future large-scale nuclear power (Figure 1) as part of the above Strategy and to resolve the technological problems of minimising the quantities of long-lived nuclides generated in the closed fuel cycle and subject to final disposal. Transmutation Task combines and arranges the work in the following directions:

- to study various scenarios for transition from the current state of the industry to large-scale nuclear power whose fuel cycle will provide radiation-equivalent management of long-lived radioactive waste, including its disposal;

- to develop radiochemical technologies meant for homogeneous (small additions to fuel) or heterogeneous (special fuel rods or assemblies) transmutation of minor actinides (MA) and long-lived fission products (LFP) in the closed fuel cycle of fast reactors;
- to optimise the procedures and conditions of MA and LFP transmutation;
- to verify nuclear data libraries for MA and LFP, and to update the cross-sections in various neutron energy regions;
- to investigate alternative approaches to MA and LFP transmutation.

Sections 1-4 describe main activities in the above areas, funded by Minatom.

Nuclear power development scenarios

Spent nuclear fuel (SNF) is the main source responsible for long-term (a thousand years or more) radioactivity hazard generated by nuclear power. Reliable prediction of SNF behaviour after final disposal during tens or hundreds of thousands of years is impracticable.

The main contributors to the long-term radiation hazard of SNF are actinides (plutonium, americium, curium) and some fission products (^{129}I, ^{99}Tn, etc.). Transmutation is regarded as a means of reducing the mass (activity) of long-lived nuclides subject to burial. This term is usually interpreted as follows:

- in case of actinides – burning (fission) in a neutron flux, i.e. conversion to fission products whose biologically equivalent activity – with more than 500 years of cooling – is lower by 3-5 orders of magnitude than that of the initial actinide mixture (Pu, Am, Cm, Np);
- in case of long-lived fission products (LFP) – exposure to a neutron flux for their conversion to stable nuclides or those easily decaying to stable forms through nuclear reactions, mainly (n,γ) .

The strategy for Radwaste management proceeds from the principle of radiation equivalence between the natural radioactive material (uranium, or thorium) utilised in the fuel cycle of nuclear power and its Radwaste to be disposed. This is a quantitative criterion, which can be calculated and optimised. Long-lived high-level waste (LHW) should be transmuted at least till to the biologically equivalent activity of waste to be disposed drops down to the level of natural uranium consumed. Such equivalence may be achieved either at the time of disposal or after a relatively short – in historical terms – period of time (e.g. 200-1 000 years), which can be reliably estimated. This approach affords reasonable reduction of the LHW mass and activity, which clearly does not obviate the need for ensuring compliance of the specific disposal conditions with the local health regulations, as well as with other rules and requirements. The principle of radiation equivalence will be met in the most consistent way if the waste is disposed at the uranium mining sites developed by new, environmentally friendly methods. A promising and recommended option is to mine uranium together with its long-lived decay products (^{230}Th, ^{226}Ra, ^{231}Pa), which would facilitate remediation of the mining areas.

In the current open nuclear fuel cycle, which manage SNF as nothing but waste, radiation equivalence may be achieved only after 100 000-500 000 years of fuel cooling. It means that radiation equivalence is nonsensical from the pragmatic viewpoint. Some prior studies have shown that such radiation equivalence is feasible, given the following:

- The whole SNF amount from thermal reactors is reprocessed with partitioning, for plutonium, MA and LFP to be transferred to the fuel cycle of fast reactors.
- Fast reactors generating electricity and operating in a closed fuel cycle burn the bulk of actinides and transmute LFP.
- Plutonium, americium and some other long-lived nuclides are removed from waste to a fairly high degree.
- High-level waste should go through interim storage prior to final disposal.

In 2001, RDIPE and RRC-KI using system models of nuclear power, carried out the set of scenarios studies on nuclear power transition to the fuel cycle, depicted in Figure 1, according the Strategy implementation. The dynamics of changes in the installed capacities of plants with thermal and fast reactors was studied with regard to various estimates of Russian natural uranium reserves. The researchers also explored the possibility of resolving the problem of Pu and MA transmutation in a growing system of fast reactors without resorting to additional dedicated transmutation units. Thermal reactors in that study were exemplified by VVERs and RBMKs whose commissioning dynamics to the year 2020 was taken as determined in the Strategy. Fast reactors were represented by blanket-free BREST-1200 (lead-cooled) or BN-800 (sodium-cooled) with U-Pu-MA nitride fuel and core breeding ratio of 1-1.05 designs. Beginning with the year 2030, their commissioning rate varies depending on the reprocessing plant capacity to remove plutonium from SNF of thermal reactors required for the first fast cores loadings. The closed fuel cycle of fast reactors affords transmutation of actinides both generated in the fast reactors themselves and contained in the irradiated fuel of thermal reactors. The latter actinides are incorporated in the fuel of the first charge. Transmutation of minor actinides in fast reactors accompanies energy generation, leaving the efficiency of the nuclear power system practically unaffected. Transmutation of LFP was omitted in this study as a less urgent problem at the current stage of the work.

It has been demonstrated that transmutation of minor actinides is fully feasible in the system of thermal and fast reactors under consideration. Computation results for one of the examined cases are given in Figures 2-4. It was assumed that construction of new thermal generating capacities would not proceed beyond the year 2020 (meaning VVER-1000s with the operating life of 50 years). Beginning in 2030, BREST-1200 power reactors would be put in operation at a rate of 1 unit per year. The SNF of thermal reactors will have accumulated~570 t of plutonium (including 320 t of ^{239}Pu and ^{241}Pu) and 120 t of MA (Figure 2). By the year 2100, using this plutonium together with their own small breeding, fast reactors can raise their capacity to 82.8 GW (Figure 3). Minor actinides from SNF of thermal reactors will be included in the first charges of fast reactors till the year 2080 (Figure 4) and will be completely “burned” in the closed cycle of fast reactors towards the end of the 21st century. It has been shown that, given some 3% of MA in the starting fuel charge as loaded, about 40% of MA will burn up over the first fuel irradiation time.

In 2002, RDIPE and RRC-KI have continued scenarios studies on future nuclear power development. Some cases are under investigation, which, in addition to the above, envisage introduction of thermal reactors with the Th-U fuel cycle after the year 2050.

Radiochemical technologies

The initial round of R&D to support development of U-Pu-MA fuel reprocessing methods for the new generation of fast reactors, including transmutation of minor actinides, was carried out in 1999-2001. The development was based on the following assumptions:

- Uranium and plutonium are inseparable at all stages of the process (technological support of the non-proliferation regime).
- Neptunium and americium are not removed from fuel (uranium + plutonium) during reprocessing, or – if removed – are taken back for recycling; these elements may also be added to the regenerated fuel.
- In reprocessing, it is advisable to extract separate fractions of Cm, Cs and Sr for subsequent cooling and of I and Tc, for subsequent transmutation.
- The disposed waste must have no more than 0.1% of U, Pu, Am and Cm; 100% of the remaining actinides (Th, Pa, Bk, Cf); 1% of Cs, Sr, Tc and I.

At the initial stage, the researchers explored the feasibility of meeting the above requirements with the use of the following procedures:

- Upgraded Purex process (Bochvar Institute).
- Electrolysis of molten chlorides with reduction of actinides to metals or to nitrides – LINEX process (Bochvar Institute, RIAR).
- Metallurgical process, with nitrides kept intact at all stages of reprocessing (Bochvar Institute and collaborators).
- Pyrochemistry (ion exchange reactions) in molten fluorides and chlorides (Bochvar Institute, RRC-KI, IHTE).
- Dry fluoride volatility process (VNIICT, RRC-KI).
- Re-crystallisation in molten molybdates and phosphates (Bochvar Institute), etc.

Basic flow sheets have been prepared and equipment components identified. Laboratory experiments have been conducted to validate the key features of process design. The capital and operational costs have been estimated and the feasibility of technological options has been assessed. No procedure examined has shown fundamental difficulties for commercialisation with a production rate of 25-50 t of irradiated fuel per year; and the main requirements (see above) can be met under nominal conditions of the process. It is also possible to fulfil the Radwaste partitioning requirements by combining various methods. The difference in the costs of fuel processing by the examined methods does not exceed ±10%. According to economic estimations, the cost of a plant for fuel reprocessing and refabrication will make no more than 15% of the cost of the nuclear power plant with two BREST-1200 units (2x1 200 MWe) to be catered for by this plant. Studies are in progress on non-aqueous methods, including ion-exchange reactions and electrolysis processes. Work on dry volatility process and advanced Purex processes have been suspended due to its relatively easy transformation for the plutonium extraction.

In the recent years, RIAR has been engaged in studies (DOVITA Programme) on fuel manufacture technology, in manufacture of mock-up fuel rods with mixed $(U,Np)O_2$, $(U,Pu,Np)O_2$ and $(U,Pu,Am)O_2$ fuel and their irradiation in BOR-60 to a burn up of 13-20% as well as in post-irradiation examination of these fuel rods. These efforts are in fact the first practical attempts at MA transmutation; it provide experience of handling fuel with considerable MA amount (up to 5%) and demonstrate the effect of minor actinides on the irradiated fuel qualities.

Along with its industrial applications, this effort affords verification of the computation procedures involved in MA transmutation analyses.

Optimisation of MA and LFP transmutation procedures and modes

Computational studies on modes of MA and LFP transmutation in fast reactors have been performed at RDIPE and IPPE for the last 3 years, with focus placed on nuclear safety issues. Currently, for various reasons, transmutation of minor actinides is considered as small additions (no more than 3% by mass) to the core fuel (homogeneous approach). In this case, there is no need for setting up special production of targets for the separated MA fractions. Heterogeneous transmutation of minor actinides (as separate fuel assemblies) is also under investigation. Transmutation of LFP will take place in the fast reactor blanket, while the neutron spectrum will have to be made considerably "softer".

Nuclear data for MA and LFP

Prior to analysis of actinide transmutation in fast reactors and before validating the technology of the closed nuclear fuel cycle, the evaluated neutron cross-sections were revised for the following isotopes: ^{237}Np, ^{241}Am, ^{242}Am, ^{243}Am, ^{243}Cm and ^{244}Cm (IPPE). Complete files of recommended neutron cross-sections were compiled for the BROND-3 library, with refined fission, inelastic-scatter and neutron-capture cross-sections, fission neutron yields, gamma quantum generation cross-sections, as well as covariance matrices of errors in fission and radiation capture cross-sections. Neutron cross-section files are being prepared for curium isotopes and some long-lived fission products and this work will be continued in 2003.

For the purpose of testing the MA-related neutron data libraries, the first draft input decks have been prepared, which represent the results of earlier domestic experiments on MA irradiation (IPPE, ITEP, VNIIEF, RDIPE). Computational modelling of those experiments (RDIPE) with the use of neutron cross-sections from the libraries ENDF/B-VI, JENDL-3.2 and BROND-3, suggests the following conclusions:

- For the neutron spectrum in the core of a large fast reactor, the difference between the experimental and calculated fission rates of ^{237}Np, ^{241}Am and ^{243}Am – critical isotopes for analysis of a long-term radio toxicity balance – does not exceed 11% irrespective of the nuclear data library used; no measurements for curium isotopes were made in those experiments.
- For systems with harder or softer neutron spectra, the difference between the experimental and calculated fission rates for curium isotopes may reach 30%; better agreement is observed for americium isotopes and ^{237}Np, with greater discrepancies found in a system with a hard spectrum.

A round of experiments is planned to conduct irradiation of small fission chambers and thin MA foils in facilities with different neutron spectra.

MA neutron data libraries are being verified at IPPE using the results of previous experiments in BN-350 where separated actinide isotopes were subjected to irradiation. Similar irradiation work has been done in BOR-60 and is still going on. The experimental data analysis is expected to yield results in 2003.

Alternative approaches to MA and LFP transmutation

As mentioned above, fast reactors are capable of effecting transmutation of the minor actinides accumulated in SNF of thermal reactors and produced in the course of their own operation. On the other hand, computational studies show that under certain circumstances (increase in the pre-reprocessing average spent fuel cooling times to 50 years and more, higher burn up of thermal reactor fuels, etc.) there may appear problems with transmutation of minor actinides inside starting charges of fast reactors. In such a case, various approaches are possible including provision of dedicated reactors for transmutation of long-lived nuclides, e.g.:

- Sub critical blankets with a target driven by accelerator;
- dedicated blankets of thermonuclear reactors;
- critical reactors with liquid fuel (molten-salts and metals);
- critical reactors of traditional design with solid fuel.

Russian Institutes working through ISTC projects or under direct contracts with foreign collaborators are performing extensive experimental and calculation studies on alternative approaches to transmutation, its fuel cycles and associated technological issues. Recent years have seen completion of about 30 ISTC Projects dealing with the transmutation concepts, nuclear data and technologies. Among the efforts in progress or just starting at present, it may be worthwhile to mention ISTC Projects #1486 (RRC-KI, VNIIEF, RIAR; US and Japanese funding), #1786 (RRC-KI, US funding), #1606 (VNIITF, RRC-KI, IHTE, VNIICT; European funding), and #2267 (JINR, European funding).

Project#1486 titled "Experimental and theoretical justification of the cascade scheme of the sub critical MSR for transmutation of long-lived radwaste of the nuclear fuel cycle" is under way now. Project duration: 2 years, started March 2001. The goal of this project is to develop the optimal reactor flow sheet for the cascade sub critical MSR. The main experimental effort is placed on simulation of cascade neutronic effects on cold molten-salt assemblies fuelled by uranium and metallic neptunium.

Project#1786 (with the implementation period between March, 2002 and February, 2004) is aimed on development of a fusion reactor blanket and shielding concept and optimising it from the viewpoint of actinide transmutation, on consideration of the basic design features and determining the integral reactor parameters. It is required to determine the transmutation rate, the total thermal power of supported light-water fission reactors (LWR) and the efficiency of reducing the total mass and long-term biological hazard of high-level waste by bringing in a thermonuclear facility specially developed for transmutation.

Project#2267 (early 2002 through November of the same year) is focused on developing and licensing a prototype sub critical electronuclear facility – SAD. The facility will consist of a lead or lead-bismuth target, a blanket with U-Pu fuel, a lead reflector, shielding, and experimental channels. The target is to be exposed to a proton flux with the energy of 660 MeV and power of 0.5 kW, the thermal power of the blanket is set at ~20 kW, and $K_{eff} \approx 0.95$. SAD is planned to construct at JINR (Dubna) for performing research in physics and technology to support the electronuclear method for transmutation of Pu, MA and LFP.

Finally, studies on integral evaluation of Molten-salt Reactor technology potential as applied to commercial long lived actinides transmutation are underway within Project #1606 titled "Experimental study of molten-salt technology for safe, low waste and proliferation resistant treatment of plutonium and minor actinides in accelerator-driven and critical systems". Project#1606 is being carried out in close co-operation with EU MOST project. The major developments expected as result of project #1606 are the following: reactor physics & fuel cycle considerations; experimental study of fuel salt key physical and chemical properties; corrosion studies in natural convection loop. The first experimental data, are already obtained in terms of the project for the selected Na,Li,Be/F salt system, which include system phase behaviour, solubility of plutonium trifluorides/oxides and transport properties. The construction of corrosion loop made from Ni-based alloy for studies with PuF_3 and Redox control in Na,Li,Be/F system is under way now.

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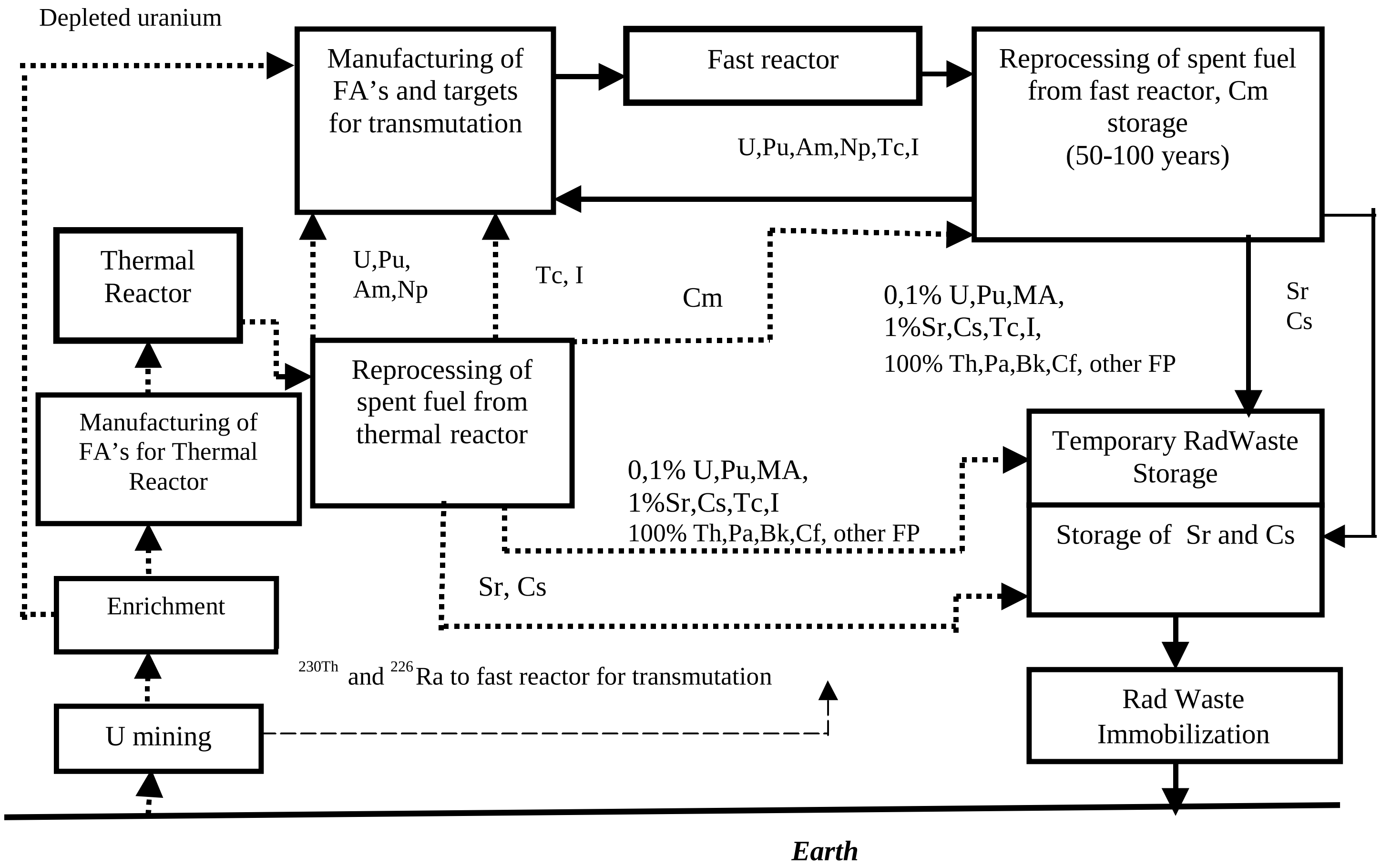
Figure 1. **Preliminary flow sheet for transmutation nuclear fuel cycle**



Radio toxicity of used uranium = Radio toxicity of disposed RAW

Figure 2. **Mass content of fissile Pu and minor actinides (Np+Am+Cm) in the spent fuel of thermal reactors in the adopted case of Nuclear Power Development (VVER-1000, RBMK-1000 and VVER-440) without SNF reprocessing**

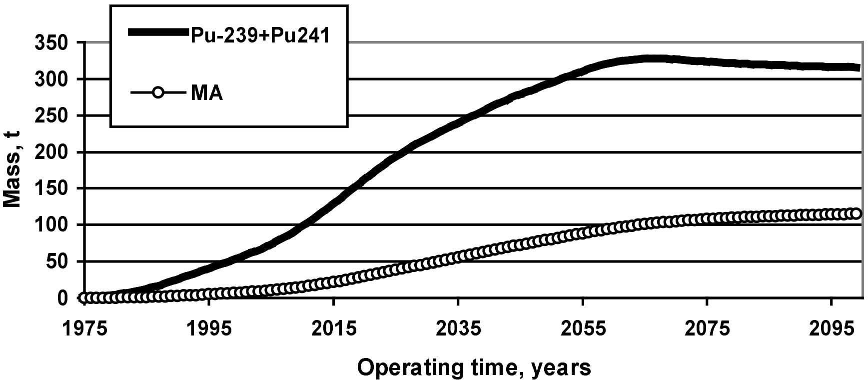


Figure 3. **Changes in the installed capacity of NPPs with thermal and fast reactors**

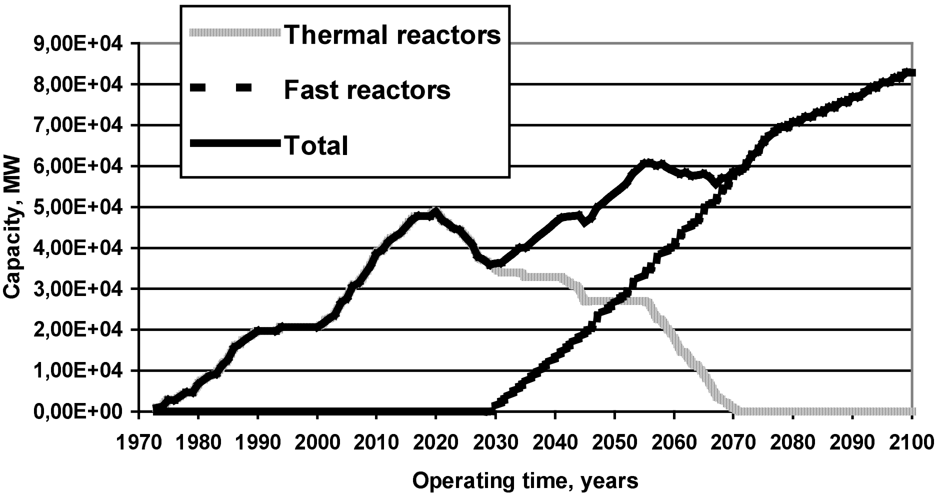
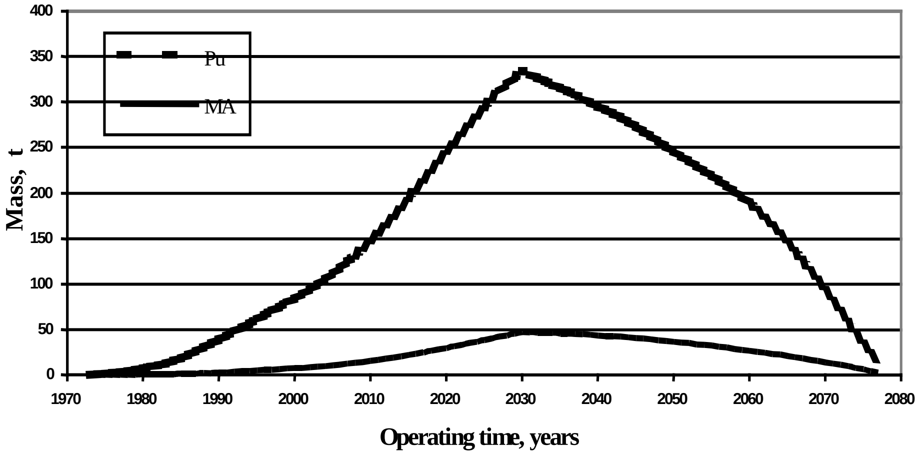


Figure 4. **Balance of Pu and minor actinides (MA=Np+Am+Cm) in the spent fuel of thermal reactors**



STATUS OF RESEARCHES ON ADVANCED NUCLEAR ENERGY SYSTEM IN CHINA

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Introduction

Energy resource is the basis of the national economy development. Along with the growth of economy and population, and improvement of people's living standard, electric power demands will be inevitable increased.

It is estimated that around the middle of this century China requires an installed capacity up to 1 200 GW. In order to realise this target, fully taking into account the production capacity of coal, oil, natural gas and the renewable energy sources such as waterpower, a fairly large gap still remains. To fill in this gap, the nuclear power is regarded as a best choice in China case because it is safe, reliable, economic-acceptable, realisable, and could be used in large scale, to replace coal burning step by step. The thermal power by burning coal constitute a leading position in electric power structure in china, which leads a serious environmental pollution and makes great pressure to national transportation system. The nuclear power as a clean energy source will be a best choice and play more and more important role in adjusting existing energy structure in China for the sustainable development of national economy.

Right now still only three nuclear power plants are in operation, which only share about 0.7% of total capacity in the China mainland. Four nuclear power plants (NPPs) with eight units are under construction. It could be envisaged that the total capacity of nuclear power in 2005 would reach 8.5 GWe as shown in Table 1. Other four new NPPs with eight units of 1 GWe each are under consideration to start construction before the year 2005.

Table 1. **Mainland nuclear power plants**

NPP	**Type**	**Power** (MWe)	**Start-up**	**Status**
Qinshan-I	PWR	300	1993	in operation
Dayabay	PWR	2×900	1994	in operation
Qinshan-II	PWR	2×600	2002	in operation
Lingao	PWR	2×944	2003	under construction
Qinshan-III	PHWR	2×720	2003	under construction
Tianwan	PWR	2×1 000	2004	under construction

To develop nuclear power in large scale, two problems must be solved. Firstly, as we understand the technically and economically exploitable natural uranium resources are limited domestically or overseas, so the uranium utilisation rate has to be raised greatly. Secondly, long-lived radioactive nuclear wastes have to be in disposal to remove its impact to environment and public fear to nuclear power.

Right now only small amount of spent fuels from NPPs has been accumulated in China. But the situation will be very serious in the future according to a prediction of nuclear energy development in China. The annual generation of waste is estimated to 2 275, 7 500 and 10 000 m^3 respectively for the year 2004, 2010 and 2020.

Because of the limited uranium resource in China, we pursue the closed-cycle policy for the nuclear fuels instead of once-through mode. We also believe that reprocessing is essentially a non-proliferation process. Our commercial spent fuel reprocessing plant is anticipated to be built around 2020. So, disposal of the high-level wastes is not an urgent matter in China for the time being. Some preliminary work is under way, such as siting of repository and migration behaviours of some key nuclides under deep geological conditions.

Considering MA and LLFP transmutation with more efficiency and non-criticality risk for new nuclear application, the fast breeder reactor technology and the accelerator-driven sub-critical system (ADS) have been started to develop as a national research projects in China.

Fast reactor technology development in China [1]

FBR is a good candidate for sustainable development of nuclear energy due to it can greatly increase uranium utilisation rate up to 60-80%, and it can be used as a burner to MA and LLFP deducing the stockpile of long-lived nuclear wastes. It is estimated that the transmutation rate to MA by FBR is roughly 50kg/Gwe/y in the case of 2.5% MA loaded in the fuel bars.

The basic researches for FBR in China could be divided in to two Phases. The activities from the middle-end of 60s to the year 1987 focus on fast neutron physics, thermohydaulics, materials, sodium technology and some sodium components in small size. During this period about 12 sodium loops and test facilities have been built up including a fast neutron zero power facility DF-V containing 50 kg ^{235}U. From the year 1987 to 1993, all research activities were arranged with a target of 65 MWt experimental fast reactor. The emphasis was put on fast reactor design study, sodium technology, and fast reactor safety, fuels and materials as well as sodium components. During this period about 20 sodium loops and testing facilities have been established and tested. After above period's researches the R&D of fast reactor technology are carried out as the design demonstration tests which more than 30 items.

The preliminary strategy study for fast reactor development points out that Chinese fast reactor engineering development will be divided in to three steps. As the first step, China Experimental Fast Reactor (CEFR) supported by the National High Technology Programme is under execution. In the second step, Prototype Fast Breeder Reactor (PFBR) will play as a prototype for next step Large Fat Breeder Reactor (LFBR) and as a module for Modular Fast Burner Reactor (MFBR) plants which may be suitable for MA burning. The LFBR and MFBR are third step in fast reactor development. The Table 2 gives the technical continuity of Chinese FBR engineering development and main technical selections.

The conceptual design of the CEFR with the power 65 MWt was started at 1990 and completed at 1993 including the confirmation and optimisation to some important design characteristics. Its preliminary design was completed in August 1997.

The CEFR is a sodium cooled experimental fast reactor with $(Pu,U)O_2$ as fuel, but UO_2 as first loading, Cr-Ni austenitic stainless steel as fuel cladding and reactor block structure material. Two main pumps and two loops for primary and secondary circuit respectively. The water-steam tertiary circuit is also two loops, but the super heat steam is incorporated into one pine, which is connected with a turbine-generator of 25 MWe.

Table 2. **Technical continuity of Chinese FBRs**

	CEFR	**PFBR**	**LFBR**	**MFBR**
Design beginning	1990	2001	2013	2013
Commissioning	2005	2015	2025	2025
Power, MWe	25	300	1 000-1 500	4-6×300
Coolant	Na	Na	Na	Na
Type	Pool	Pool	Pool	Pool
Fuel	UO_2 MOX	MOX Metal	Metal	MOX+Ac Metal+Ac
Cladding	Cr-Ni	Cr-Ni ODS	Cr-Ni ODS	Cr-Ni ODS
Core outlet temp., °C	530	500-550	500	500-550
Linear power, W/cm	430	450-480	450	450
Burn-up, MWd/kg	60-100	100-120	120-150	100
Fuel handing	DRPs SMHM	DRPs SMHM	DRPs SMHM	DRPs SMHM
Spent fuel storage	IVPS WPSS	IVPS WPSS	IVPS WPSS	IVPS WPSS
Safety	ASDS PDHRS	ASDS+PSDS PDHRS	ASDS+PSDS PDHRS	ASDS+PSDS PDHRS

Where DRPs means Double rotating plugs, SMHM Straight moving handling machine, IVPS In-vessel primary storage, WPSS Water pool secondary storage, ASDS Active shut-down system, PSDS Passive shut-down system, PDHRS Passive decay heat removal system.

The CEFR block is composed of main vessel and guard vessel which is supported from bottom on the floor of reactor pit with the diameter 10 m and height 12 m, reactor core and its support structure, internal structures on which two main pumps, four intermediate heat exchangers and two DHRS heat exchangers are supported. The double rotation plugs on which control rod driving mechanisms, fuel handling machine and some instrumentation structures are supported on the neck of the main vessel.

The CEFR is located in the China Institute of Atomic Energy (CIAE), about 40 km far away from Beijing City, which owns about 10 million inhabitants. According to the raising environment safety consideration, it is stipulated to have more strictly requests to radioactive materials release standards for normal operation, design basis accident (DBA) and beyond design basis accident (BDBA) which are 0.05 mSv/a, 0.5 mSv/accident and 5 mSv/accident for CEFR.

After two years review to preliminary safety analysis report by Chinese National Nuclear Safety Administration (CNNSA), the CEFR construction permission was issued in April 2000 and the CEFR was started to construct the 3 m×69 m×82.5 m foundation base of CEFR reactor building and completed in the November 2000. Then construction work stopped for two reasons: one is that the CNNSA asked us to make additional analysis, especially, of the sodium spray fire accidents and another is just winter arriving. After the additional analysis of some accidents has been submitted and approved by the CNNSA, the full construction permission for the CEFR was issued, in the early of spring, on March 15, 2001 the CEFR construction was restarted. The 57 m main building for nuclear island has been completed in this August. The main milestones for CEFR in the future include using electricity from grid in September of next year, the hot testing in September of 2004, and first criticality at the end of 2005.

Progress in ADS system research [2-3]

As a candidate of nuclear system which could meet more safer requirement than recent those to decrease the risk of core melt and unforeseen release of radioactive materials and could transmute the MA more efficiently, a new research field on accelerator-driven sub-critical system (ADS) was proposed in China in the year 1995 and a five years programme (phase 1, 1998-2002) has been launched. The main progress is summarised as follows.

Ion Source A microwave ion source is under developing for a demonstration prototype of a accelerator-driven sub-critical system at CIAE, 60 mA hydrogen beam has been extracted from the source through a 7.3 mm aperture in diameter, proton ratio is more than 85%, reliability has been test for 100 hours without any failures. The parameters of the source during the test include extraction voltage 30kV, microwave power 800 W, and vacuum pressure 1×10^{-3} Pa.

Accelerator The superconducting linac is a good selection of ADS accelerator because of its high efficiency and low beam loss rate. Our ADS accelerator consists of a 5 MeV radio frequency quadruple, a 100 MeV independently phased superconducting cavity linac and a 1 GeV elliptical superconducting cavity linac. The accelerating structures and main parameters are determined and the research and development plan is considered.

Table 4. **The main parameters of RFQ**

Input energy (keV)	80	total length (m)	7.1
Output energy (MeV)	5	intervane voltage (kV)	70
Beam current (mA)	30	transmission	95
Working frequency (MHz)	352	synchronous phase (deg)	90-30
Normal transverse RMS		modulation	0.29-0.32
Emittance (πmmmrad)	0.2	average aperture (cm)	1-1.94
Normal longitudinal RMS		cavity RF losses (MW)	0.58
Emittance (πMeVdeg)	0.2	beam power (MW)	0.15
		total RF power (MW)	0.73

A preliminary physical design of 5 MeV proton Radio Frequency Quadruple (RFQ) accelerator for the ADS system has been carried out, with the design parameters given in Table 3. The design study on intense proton Linac has been completed with design target of outlet current intensity 30 mA (continuously), out let energy 1 GeV.

AD-FBR System A medium size sodium cooled fast breeder reactor driven by an accelerator with 1 GeV/16 mA shows its advantages over the ordinary one, such as less Pu inventory required, higher breeding ratio and reasonable transmutation rate (which may support two units 1 000Mwe PWR) at expense of less 15% energy output. The calculation gives us some idea about how the fast sub-critical reactor is in favour of the MA's transmutation and fissile breeding.

AD-PHWR System The pressurised heavy water moderated reactor (CANDU type) was adopted for the analysis both for Th-U and U-Pu fuel cycles. The beam pipe and lead target substituted four central pressurised tubes. It is shown that AD-PHWR is favouring to Th-U fuel cycle not only higher burn up, but also with slight breeding capability. While in U-Up fuel cycle, the fuel may self-sustainable only with relative higher beam current, smaller K value and with a little higher burn-up than ordinary CANDU.

Spallation Target As the proton beam window and the spoliation target are the interface of the accelerator and the sub-critical reactor, which is the important component of the ADS. From the engineering application point of view the basic problems such as spallation neutron yield, energy deposition, the irradiation damage and radioactivity accumulation are concerned.

The calculations to the standard thick target were made by using different codes. The simulation of the of the thick Pb target with length of 60 cm, diameter of 20 cm bombarded with 800, 1 000, 1 500 and 2 000 MeV proton beam was carried out. The yields and the spectra of emitted neutron were studied. The spallation target was simulated by SNSP, SHIELD, DCM/CEM (Dubna Cascade Model/Cascade Evaporation Mode), and LAHET codes.

The simulation results were compared with experiments. The comparisons show good agreement between the experiments and the SNSP simulated leakage neutron yield. The SHIELD simulated leakage neutron spectra are good agreement with the LAHET and the DCM/CEM simulated leakage neutron spectra.

Materials Radiation damage effects were studied by using SHIELD codes system. The researches concern radiation damage cross section, displacement production, gas production in target, container window structure materials induced by intermediate energy proton and by neutron. And the study of radiation damage in the thick Pb target with long 60 cm, radius 20 cm was completed. The experimental study of radiation effects have been carried out for the home-made modified 316L stainless steel and standard stainless steel and tungsten irradiated by 80 MeV ^{12}C or 85 MeV ^{19}F ions. The experimental results show that the radiation resistant property of stainless steels is much better than that of tungsten and the home-made modified 316L. The compatibility tests for the forging tungsten with coolants have been performed in sodium at 500, 600 and 700°C and in water at 100°C.

In the next three years, a VENUS facility will be completed. This facility will be used to study the neutron flux distribution, neutron energy distribution, the neutron enhancement, the reactor fission rate, and k_{eff} in sub-critical assembly driven by pulsed fast external neutron source. The facility consists of two parts, a pulsed-neutron generator and a sub-critical assembly. The pulsed-neutron generator is a 300 keV Cockcroft-Walton type accelerator for generating 14 MeV neutrons by (d, t) reaction. The sub-critical assembly will be designed in different lattice structure with different enrichment U fuel and polyethylene to provide different spectra.

The P&T technologies related to ADS system will be also studied.

Concluding remark

The two new nuclear systems FBR and ADS have been started to develop with a rather moderate project in China and they are all still in the early stage. For fast reactor development, its first step, CEFR is foreseen to reach its first criticality at the end of 2005. The second step 300 MWe Modular Fast Reactor (MPFR) is under consideration. For ADS, we are making great efforts to accomplish the research tasks worked out in the first phase programme and enthusiastically preparing to step to the second phase programme which is marked by experimental facility VENUS.

As said before the researches for these two new systems are both in the early stage, the budgets spent up to now are limited, so we have long way to go to develop these advanced nuclear energy systems**.**

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PARTITIONING AND TRANSMUTATION RESEARCH IN THE EURATOM FIFTH AND SIXTH FRAMEWORK PROGRAMMES

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Abstract

Partitioning and Transmutation (P&T) of long-lived radionuclides in nuclear waste is one of the most notable research areas of the EURATOM Fifth (1998-2002) as well as the sixth (2002-2006) framework programmes (FP). The objective of research work in this area is to provide a basis for evaluating the practicability, on an industrial scale, of P&T for reducing the amount of long lived radionuclides to be disposed of thus easing the waste management problem. In FP5, there are 13 projects in the area of P&T with a total budget of about € 69 M of which the EU contribution is about € 28 M. A network ADOPT co-ordinates the activities of the accelerator-driven system (ADS) design project with those of the four clusters, one on chemical separation (i) PARTITION and three on transmutation, (i) Basic studies (BASTRA), (ii) Technological studies (TESTRA) and (iii) Fuel studies (FEUTRA). Each of these clusters is formed by 3-4 projects, which are briefly described. A sketch of the proposed P&T research work programme of FP6 is also given where one of the spot-lights is on the nuclear waste management. International co-operation in the area of P&T with non-EU countries including the Commonwealth of Independent States (CIS) is also outlined.

Introduction

The priorities for the European Union's research and development activities for the period 1998-2002 are set out in the Fifth Framework Programme (FP5). [1] The FP5 priorities were identified on the basis of a set of common criteria reflecting the major concerns of increasing industrial competitiveness and the quality of life for European citizens. To maximise its impact, FP5 focuses on a limited number of research areas combining technological, industrial, economic, social and cultural aspects. FP5 and its predecessors have contributed effectively to the policy of supporting science and technology by encouraging co-operation between research players of the Member States. Despite this achievement, no specific European research policy has yet emerged. National research programmes are still undertaken to a large extent independently of one another.

The objective is to achieve greater co-operation between Member States' research strategies and a mutual opening up of programmes. With the challenges and prospects opened up by the technologies of the future, there is a need that European research efforts and capacities should be more thoroughly integrated. With this view in mind, the European Commission launched the so-called "European Research Area" (ERA) initiative in January 2000. [2] The Sixth Framework Programme (FP6) [3] encompassing the period 2002-2006 is geared to make ERA a reality. [4]

The overall organisation of FP6 reflects the broad avenues of approach that are implicit in the proposed implementation of ERA. FP6 has three main blocks of activities:

- Integrating research in the well focussed research priority areas principally by using new research implementation instruments such as Networks of Excellence (NoE) and Integrated Projects (IP).
- Structuring the ERA by research and innovation, human resources and researcher mobility, research infrastructure and science and society issues.
- Strengthening the foundations of ERA by networking of national research and opening up of national programmes, closer links between EU and other European organisations (such as CERN), benchmarking of research policies, mapping of excellence etc.

In this context, the scientific and technical goals of the EURATOM FP6 specific programme "Research and Training Programme on Nuclear Energy" is to help exploit the full potential of nuclear energy, both in the long and short term. Its development and exploitation is to be done in a sustainable manner while combating the climate change and reducing the energy dependency of the EU. Research and development activities in this programme have been subdivided into (a) Controlled thermonuclear fusion, (b) Management of radioactive waste, (c) Radiation protection and (d) Other activities in the field of nuclear technologies and safety.

Controlled thermonuclear fusion is perceived to be one of the long-term options for energy supply whereas nuclear fission presently provides about 35% of the EU's electrical power. Some of the fission power plants of the current generation will continue to operate for at least 20 years. In the short term, the priority is to find a more permanent and safe solution for the management of long-lived, high-level waste that is acceptable to society. A priority in this area is to establish a sound technical basis for demonstrating the safety of disposal of spent fuel and long-lived radioactive wastes in geological repositories. This is to be supported by evaluating the practicability, on an industrial scale, for reducing the amount and/or hazard of the waste to be disposed of by partitioning (chemical separation) and transmutation (nuclide conversion). This is further supplemented by exploring the potential of system concepts that would by themselves produce less waste in nuclear energy generation**.**

The paper briefly recalls the goals of P&T, its position in the framework of nuclear waste management and disposal and its renewed interest world-wide. The research projects on P&T that are being funded in FP5 are then briefly described. A brief sketch of the proposed P&T research work programme of FP6 is also given where once again the focus is on the nuclear waste management. Finally, co-operation in this field with some countries of the Commonwealth of Independent States (CIS) through the International Science and Technology Centre (ISTC) in Moscow is also outlined.

The EURATOM Fifth Framework Programme (FP5) (1998-2002)

The Fifth Framework Programme of the European Atomic Energy Community (EURATOM) has two specific programmes on nuclear energy, one for indirect research and training actions managed by the Research Directorate General (DG RTD) and the other for direct actions under the responsibility of the Joint Research Centre of the European Commission (EC). The strategic goal of the first one, "Research and training programme in the field of nuclear energy", is to help exploit the full potential of nuclear energy in a sustainable manner, by making current technologies even safer and more economical and by exploring promising new concepts. [1] This programme includes a key action on controlled thermonuclear fusion, a key action on nuclear fission, research and technological development (RTD) activities of a generic nature on radiological sciences, support for research infrastructure, training and accompanying measures. The key action on nuclear fission and the RTD activities of a generic nature are being implemented through indirect actions, i.e. research co-sponsored and co-ordinated by DG RTD, but carried out by external public and private organisations as multi-partner projects. The total budget available for these indirect actions during FP5 is € 193 M. [5]

The key action on nuclear fission comprises four areas: (i) operational safety of existing installations; (ii) safety of the fuel cycle; (iii) safety and efficiency of future systems and (iv) radiation protection. The operational safety of existing installations deals with plant life extension and management, severe accident management and evolutionary concepts. In the safety of the fuel cycle, waste and spent fuel management and disposal, and partitioning and transmutation are the two larger activities, as compared to the decommissioning of nuclear installations. The objective of safety and efficiency of future systems is to investigate and assess new or revisited concepts for nuclear energy, that would be more economical, safer and more sustainable in terms of waste management, utilisation of fissile material and safeguards. Radiation protection has four sub-areas: (i) risk assessment and management, (ii) monitoring and assessment of occupational exposure, (iii) off-site emergency management and (iv) restoration and long-term management of contaminated environments.

The implementation of the key action on nuclear fission is made through targeted calls for proposals with fixed deadlines. The generic research on radiological sciences is the subject of a continuously open call. Following the three calls for proposals made since the start of FP5, 278 projects were funded in the area of nuclear fission and radiation protection. In the area of P&T, 13 projects were funded with a total budget of € 69 M out of which EU contribution is € 28 M.

Partitioning and Transmutation (P&T)

Spent fuel and high level waste contain a large number of radionuclides from short-lived to long-lived ones. The time-scales involved are very long before the waste becomes harmless which raises concerns in guaranteeing the safety of waste disposal in geological repositories. Partitioning and Transmutation aims at reducing the inventories of long-lived radionuclides (actinides and some fission products) by transmuting them into radionuclides with a shorter lifetime. [6,7] Partitioning in itself can be of help in the disposal strategy by specific conditioning of the minor actinides and long lived fission products.

Partitioning is the set of chemical and/or metallurgical processes necessary to separate from the high-level waste the long-lived radionuclides to be transmuted. This separation must be very efficient to obtain a high decontamination of the remaining waste. It should also be very selective to achieve an efficient transmutation of the long-lived radiotoxic elements.

Long-lived radionuclides could be transmuted into stable or short-lived nuclides in dedicated burners. These burners could be critical nuclear reactors and/or sub-critical reactors coupled to accelerators, the so-called accelerator-driven systems (ADS). An ADS is a concept that would allow large quantities of minor actinide waste to be burned efficiently. In a *sub*-critical reactor, additional neutrons are supplied by an external source, from spallation reactions, for instance, in which an energetic proton beam from a particle accelerator impinges on a heavy metal such as lead. Subject to more detailed studies, for minor actinide-rich fuel, an ADS seems likely to be safer than critical reactors, as the neutron chain reaction can, in principle, be stopped when desired by switching off the additional supply of neutrons (the accelerator). This, however, still leaves the task of removing the decay heat.

If successfully achieved, P&T will produce waste with a shorter lifetime. However, as the efficiency of P&T is not 100%, some long-lived radionuclides will remain in the waste, which will have to be disposed of in a deep geological repository. P&T are still at the research and development (R&D) stage. Nevertheless, it is generally accepted that the techniques used to implement P&T could alleviate considerably the problems linked to waste disposal.

There has been a renewal of interest in P&T world-wide [5] including Japan, Korea, Europe, China and the USA. In Europe, the most notable is the idea of Energy Amplifier (EA) developed by CERN, Geneva. In addition, there are a number of research activities on ADS going on in several EU countries including Belgium, France, Germany, Italy, Spain, Sweden as well as in Switzerland. P&T activities are also pursued in Czech Republic and Russia.

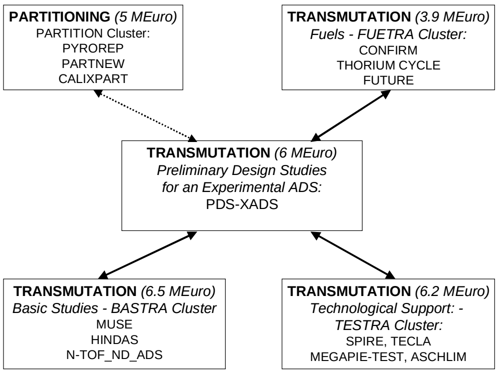
The interest for P&T in the EU is reflected in the increase of funding in this area over the successive EURATOM Framework Programmes, 4.8, 5.8 and about € 28 M for the Third, Fourth and Fifth Framework Programmes respectively. In the Sixth Framework Programme (2002-2006), the indicative budget for P&T of € 25-35 M.

The Research Activities on P&T in the EURATOM Fifth Framework Programme

The objective of the research work carried out under FP5 is to provide a basis for evaluating the practicability, on an industrial scale, of partitioning and transmutation for reducing the amount of long lived radionuclides to be disposed of. The work on partitioning concerns the experimental investigation of efficient hydro-metallurgical and pyrochemical processes for the chemical separation of long-lived radionuclides from high-level liquid waste. The work on transmutation is related to the preliminary design studies of an accelerator-driven sub-critical system (ADS) and acquisition of data, both technological and basic, necessary for its development including the development of fuel and targets for an ADS.

The selected projects in this area address various scientific and technical aspects of P&T and have therefore been regrouped. A network ADOPT co-ordinates the activities of the accelerator-driven system (ADS) design project with those of the four clusters of FP5 projects in the area of P&T (see Figure 1). One cluster is on chemical separation of radionuclides **(PARTITION)** and there are three on transmutation: (i) Basic studies **(BASTRA),** (ii) Technological studies **(TESTRA)** and (iii) Fuel studies **(FUETRA).**

Figure 1. **FP5 funded projects in the area of P&T under the umbrella of ADOPT network**



ADOPT network

The objectives of ADOPT network (see Table 1) are: (i) to formulate actions with a view to promote consistency between FP5 funded projects and national programmes, (ii) to review overall results of the FP5 projects, (iii) to identify gaps in the overall programme of P&T research in Europe, (iv) to provide input to future research proposals and guidelines for R&D orientation, (v) to maintain relations with international organisations and countries outside the EU involved in P&T and ADS development.

Table 1. **Advanced options for P&T (ADOPT) network and preliminary design studies for an experimental ADS (PDS-XADS)**

Acronym	**Subject of research**	**Co-ordinator** (country)	**No. of partners**	**Start date & duration**	**EC funding** (M€)
ADOPT Network	Thematic network on advanced options for P&T	SCK/CEN (B)	16	01-11-01 36 m	0.4
PDS-XADS	Preliminary design studies of an experimental accelerator-driven system	Framatome-ANP (F)	25	01-11-01 36 m	6.0

Design Studies of an experimental ADS

Successful operation of an ADS together with the coupling of an accelerator to the neutron spallation target and the sub-critical core is a first step for demonstrating the practicability of a transmuter of this type of transmuter on an industrial scale. Aim of the PDS-XADS project (see Table 1) is to make well documented study with supporting evidence to choose and adopt the most promising technical concepts for ADS. It will also address the critical points of the entire system, identify the research and development (R&D) required in support, define the safety and licensing issues, assess the preliminary cost of the installation and consolidate the road mapping of the XADS development. The assessment and comparison studies of the different conceptual designs of the main systems (accelerator, spallation target unit, sub-critical core, primary system) will allow to identify the most promising solution which could be studied in detail during the next phase of the design activities.

Partitioning projects

The PARTITION cluster includes three projects, the main characteristics of which are given in Table 2. The first one, **PYROREP**, aims at assessing flow sheets for pyrometallurgical processing of spent fuels and targets. Two methods, salt/metal extraction and electrorefining, investigate the possibility of separating actinides from lanthanides. Materials compatible with corrosive media at high temperature will be selected and tested.

Table 2. **PARTITION cluster projects**

Acronym	**Subject of research**	**Co-ordinator** (country)	**No. of partners**	**Start date & duration**	**EC funding** (M€)
PYROREP	Pyrometallurgical processing research	CEA (F)	7	01-09-00 36 m	1.5
PARTNEW	Solvent extraction processes for minor actinides (ma)	CEA (F)	10	01-09-00 36 m	2.2
CALIXPART	Selective extraction of ma by organised matrices	CEA (F)	9	01-10-00 40 m	1.4

The two other projects deal with the development of solvent extraction processes to separate minor actinides (americium and curium) from high-level liquid waste (HLLW). In the project **PARTNEW**, the minor actinides are extracted in two steps. They are first co-extracted with the lanthanides from HLLW (by DIAMEX processes), then separated from the lanthanides (by SANEX processes). Basic studies are being performed for both steps, in particular synthesis of new ligands and experimental investigation and modelling of their extraction properties. The radiolytic and hydrolytic degradation of the solvents are also studied and the processes are tested with genuine HLLW.

The **CALIXPART** project deals with the synthesis of more innovative extractants. Functionalised organic compounds, such as calixarenes, will be synthesised with the aim of achieving the direct extraction of minor actinides from HLLW. The extraction capabilities of the new compounds will be studied together with their stability under irradiation. The structures of the extracted species will be investigated by nuclear magnetic resonance (NMR) spectroscopy and X-ray diffraction to provide an input to the molecular modelling studies carried out to explain the complexation data.

Transmutation projects

(i) BASTRA cluster:

Three projects are grouped in the cluster of Basic Studies on Transmutation (BASTRA) (see Table 3). The **MUSE** project aims to provide validated analytical tools for sub-critical neutronics, data and a reference calculation tool for ADS study. The experiments are carried out by coupling a pulsed D-T/D-D neutron generator source (GENEPI) to the MASURCA facility loaded with MOX fuel operated as a sub-critical system with different coolants (such as sodium and lead). Cross-comparison of codes and data is foreseen. Experimental reactivity control techniques, related to sub-critical operation are being developed.

The other two projects deal with nuclear data. The objective of the **HINDAS** project is to collect most of the nuclear data necessary for ADS applications. This is achieved by basic cross-section measurements at different European accelerator facilities, nuclear model simulations and data evaluations in the 20-200 MeV energy region and beyond. Iron and lead (materials used for ADS) and uranium have been chosen to have a representative coverage of the periodic table.

The **n-TOF-ND-ADS** project aims at the production, evaluation and dissemination of neutron cross sections for most of the radioisotopes (actinides and long-lived fission products) considered for transmutation in the energy range from 1 eV up to 250 MeV. Measurements are being carried out at the n-TOF facility at CERN, at the GELINA facility in Geel and using other neutron sources located at different EU laboratories. An integrated software environment is being developed at CERN for the storage, retrieval and processing of nuclear data in various formats.

Table 3. **Basic studies for transmutation (BASTRA) cluster projects**

Acronym	**Subject of research**	**Co-ordinator** (country)	**No. of partners**	**Start date & duration**	**EC funding** (M€)
MUSE	Experiments for sub-critical neutronics validation	CEA (F)	13	01-10-00 36m	2.0
HINDAS	High and intermediate energy nuclear data for ADS	UCL (B)	16	01-09-00 36m	2.1
n-TOF-ND-ADS	ADS nuclear data using time-of-flight facility	CERN(CH)	18	01-11-00 36m	2.4

(ii) TESTRA cluster:

Four projects are grouped in the cluster of Technological Studies on Transmutation (TESTRA) (see Table 4). This cluster deals with the investigation of radiation damage induced by products of spallation reactions in materials, of the corrosion of structural materials by lead alloys and of fuels and targets for actinide incineration.

The **SPIRE** project addresses the irradiation effects on an ADS spallation target. The effects of spallation products on the mechanical properties and microstructure of selected structural steels (e.g. martensitic steels) are being investigated by ion beam irradiation and neutron irradiation in reactors (HFR in Petten, BR2 in Mol and BOR60 in Dimitrovgrad). Data representative of mixed proton/neutron irradiation are being obtained from the analysis of the SINQ spallation target at the Paul Scherrer Institute in Villigen (CH).

The objective of **TECLA** project is to assess the use of lead alloys both as a spallation target and as a coolant for an ADS. Three main topics are addressed: corrosion of structural materials by lead alloys, protection of structural materials and physico-chemistry and technology of liquid lead alloys. A preliminary assessment of the combined effects of proton/neutron irradiation and liquid metal corrosion is being carried out. Thermal-hydraulic experiments are being performed together with numerical computational tool development.

Table 4. **Technological studies for transmutation (TESTRA) cluster**

Acronym	**Subject of research**	**Co-ordinator** (country)	**No. of partners**	**Start date & duration**	**EC funding** (M€)
SPIRE	Effects of neutron and proton irradiation in steels	CEA (F)	10	01-08-00 48 m	2.3
TECLA	Materials and thermal-hydraulics for lead alloys	ENEA (I)	16	01-09-00 36 m	2.5
MEGAPIE-TEST	A megawatt heavy **liquid** metal spallation target experiment with proton beam	FZK (D)	17	01-11-01 36 m	2.4
ASCHLIM	Computational fluid dynamics codes for heavy liquid metals	SCK/CEN (B)	14	01-01-02 12 m	0.12

The major objective of the **MEGAPIE-TEST** Project is to develop and validate the design and operation of a heavy liquid metal (Pb-Bi) spallation target at a level of a megawatt. The project aims to provide a comprehensive database from single-effect experiments, a full-scale thermal-hydraulic simulation experiment, and the first beam-on experiments. In parallel, numerical computational tools will be validated for Pb-Bi target design. The studies include neutronic calculations, materials, corrosion, thermal-hydraulics, structure mechanics, liquid metal technology, safety and licensing issues. Prospects on the extrapolation and applicability of the obtained results to an ADS spallation target will also be given.

The ASsessment of Computational fluid dynamics codes for Heavy LIquid Metals (ASCHLIM) project aims at bringing together various actors (industry, research institutions and university) in the field of heavy liquid metals both in the experimental and numerical fields and creating an international collaboration to (i) make an assessment of the main technological problems in the fields of turbulence, free surface and bubbly flow and (ii) co-ordinate future research activities in this area. The assessment is being made on the basis of existing experiments whose basic physical phenomena are analysed through the execution of calculational benchmarks using commercial and research codes.

(iii) FUETRA cluster

There are three projects in this cluster. The objectives of the **CONFIRM** project are to develop methods for fabrication (such as carbo-thermic reduction process) of uranium-free nitride fuels (Pu,Zr)N and to model and test their performance under irradiation up to 20% burn-up in Studsvik (Sweden) R2 reactor. Carbo-thermic process will also be used for the production of (Am, Zr)N pellets at ITU, Karlsruhe. Successful high temperature (≈2 500°C) stability tests of (U,Zr)N have been made and a study of C-14 production has been completed.

The objective of the project **THORIUM CYCLE** is to investigate the irradiation behaviour of thorium/plutonium (Th/Pu) fuel at high burn-up and to perform full core calculations for thorium-based fuel with a view to supplying key data related to plutonium and minor actinide burning. Two irradiation experiments are being carried out: (i) four targets of oxide fuel (Th/Pu, uranium/plutonium, uranium and thorium) will be fabricated, irradiated in HFR in Petten and characterised after irradiation, (ii) one Th/Pu oxide target is also irradiated in KWO reactor at Obregheim (D). Though this project was accepted for funding in the area of “safety and efficiency of future systems”, it has been grouped with the FUETRA cluster.

Table 5. **Fuel studies for transmutation (FUETRA) cluster**

Acronym	**Subject of research**	**Co-ordinator** (country)	**No. of partners**	**Start date & duration**	**EC funding** (M€)
CONFIRM	Uranium-free nitride fuel irradiation and modelling	KTH (S)	7	01-09-00 48 m	1.0
THORIUM CYCLE	Development of thorium cycle for PWR and ADS	NRG (NL)	7	01-10-00 48 m	1.2
FUTURE	Development of transuranic oxide fuels for transmutation	CEA (F)	7	01-12-01 36 m	1.7

The main objective of the FUTURE project is to study the feasibility of oxide compounds (Pu, Am)O_2, (Th, Pu, Am)O_2 and (Pu, Am, Zr)O_2 to be irradiated as homogeneous fuel for an ADS. The R&D programme is largely devoted to the synthesis of the compounds, their characterisation (thermal and chemical properties at relevant temperatures) and the development of fabrication processes. Modelling codes will be developed to calculate the fuel performance. The input data for the codes will be based on experimental results. Assessment of the fuel behaviour under accident conditions will be analysed using the experimental data obtained at high temperatures.

The EURATOM Sixth Framework Programme (FP6) (2002-2006)

Research and development activities of the EURATOM FP6 specific programme “Research and Training Programme on Nuclear Energy” have been subdivided into four areas (a) Controlled thermonuclear fusion, (b) Management of radioactive waste, (c) Radiation protection and (d) Other activities in the field of nuclear technologies and safety.

The priority in nuclear fusion area is to make progress towards demonstrating the scientific and technological feasibility of fusion energy by contributing to international activities for the successful realisation of the Next Step/ITER device which will be supported by Associations’ programme in fusion physics and technology.

In nuclear fission, the priority is to find a more permanent and safe solution for the management of long-lived, high-level waste that is acceptable to society. This includes establishing a sound technical basis for the demonstration of long lived high level waste disposal in geological formations. This is to be supported by studies on P&T and further supplemented by exploring the potential of system concepts that would by themselves produce less waste in nuclear energy generation.

The priority of the research in the field of radiation protection is to consolidate and further advance European knowledge and competence in radiological sciences. This is essential for the safe and competitive use of nuclear energy and other industrial and medical uses of ionising radiation, including the management of natural sources of radiation and the effects of low levels of exposure**.**

In other activities in the field of nuclear technologies and safety, the thrust of research is (i) to evaluate the potential of innovative concepts and develop improved and safer processes for the medium-term exploitation of nuclear fission, (ii) to improve the safety of the operation of existing nuclear installations and (iii) to combat the decline in both student numbers and teaching establishments by a better integration of European education and training in nuclear safety and radiation protection.

The detailed work programme of EURATOM FP6 is currently under preparation. In P&T, the research areas include a fundamental assessment of the system and safety aspects of the overall concept of P&T and, in particular, of its impact on waste management and geological disposal. In the area of partitioning, continued R&D of hydrometallurgical and pyrochemical processes is envisaged with a view to the demonstration of the most promising techniques. In the area of transmutation, the development of basic knowledge and technologies for transmutation and evaluation of their industrial practicability, in particular, of transmutation devices such as accelerator-driven sub-critical systems (ADS) is proposed.

The first Calls for proposals will be made at the end of November 2002 where the so-called new instruments will be used as a priority. The Networks of Excellence (NoE) are aimed at strengthening and developing Community scientific and technological excellence by means of the integration, at European level, of research capacities currently existing or emerging, that are somewhat scattered, at both national and regional levels. The Integrated Projects (IP) are designed to give increased impetus to the Community's competitiveness or to address major societal needs by mobilising a critical mass of research and technological development resources and competencies. Avoiding the micro management, increased autonomy will be given to the consortiums in the management (both scientific and financial) of the projects that will be judged on the global end-results.

ADS related Research Activities in the Framework of the International Science and Technology Centre (ISTC)

The International Science and Technology Centre (ISTC) was established by an international agreement in November 1992 as a non-proliferation programme through science co-operation. It is an intergovernmental organisation grouping the European Union, Japan, the USA, Norway, the Republic of Korea, which are the funding parties, and some countries of the Commonwealth of Independent States (CIS): the Russian Federation, Armenia, Belarus, Georgia, Kazakhstan and Kyrgyzstan. The ISTC finances and monitors science and technology projects to ensure that the CIS scientists are offered the opportunity to use their skills in the civilian fields. A similar organisation, the Science and Technology Centre in Ukraine (STCU) has been established in 1995, in which the EU, Canada, the USA, Georgia and Uzbekistan are involved.

Five topics have been identified by the ISTC Contact Expert Group (CEG) for the ADS related projects: (i) accelerator technology, (ii) basic nuclear and material data and neutronics of ADS, (iii) targets and materials, (iv) fuels related to ADS and (v) aqueous separation chemistry. The EU CEG has started to develop co-operation between ISTC and FP5 EU funded projects especially in the above area (ii) by organising joint meetings of BASTRA cluster with related ISTC projects and PARTITION cluster with related ISTC/STCU projects.

Conclusions

The research activities in the field of partitioning and transmutation under the EURATOM Fifth Framework Programme are well underway. The research projects have been regrouped into four clusters one on partitioning, and three on transmutation: basic studies, technological studies and fuel studies. These clusters and the design project form a balanced programme on P&T that are co-ordinated by the ADOPT network. With a view to thoroughly integrate the EU research efforts, a European Research Area (ERA) initiative has been launched. Preparations are well underway for the launch of FP6 making the ERA a reality and the first calls for proposals are expected at the end of November 2002. The collaboration of EU funded FP5 projects and the ISTC/STCU projects on partitioning and basic studies of transmutation is progressing satisfactorily.

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IAEA ACTIVITIES IN THE AREA OF PARTITIONING AND TRANSMUTATION

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Abstract

Nuclear power is a mature technology that makes a large contribution to the energy supply world-wide. At the end of 2001, there were 438 nuclear power plants operating in the world representing some 353 GW(e) of generating capacity. According to the projections published by the Inter-governmental Panel on Climate Change (IPCC), the median electricity increase till 2050 will be by a factor of almost 5. It is reasonable to assume that nuclear energy will play a role in meeting this demand growth. However, there are four major challenges facing the long-term development of nuclear energy as a part of the world's energy mix: improvement of the economic competitiveness, meeting increasingly stringent safety requirements, adhering to the criteria of sustainable development, and public acceptability. Meeting the sustainability criteria is the driving force behind the topic of this paper. More specifically, in this context sustainability has two aspects: natural resources and waste management. IAEA's activities in the area of Partitioning and Transmutation (P&T) are mostly in response to the latter. While not involving the large quantities of gaseous products and toxic solid wastes associated with fossil fuels, radioactive waste disposal is today's dominant public acceptance issue. In fact, small waste quantities permit a rigorous confinement strategy, and mined geological disposal is the strategy followed by some countries. Nevertheless, political opposition arguing that this does not yet constitute a safe disposal technology has largely stalled these efforts. One of the primary reasons that are cited is the long life of many of the radioisotopes generated from fission. This concern has led to increased R&D efforts to develop a technology aimed at reducing the amount of long-lived radioactive waste through transmutation in fission reactors or accelerator-driven hybrids. In recent years, in various countries and at an international level, more and more studies have been carried out on advanced waste management strategies (i.e. actinide separation and elimination). In the frame of the Project on *Technology Advances in Fast Reactors and Accelerator-driven Systems for Actinide and Long-lived Fission Product Transmutation*, the IAEA initiated a number of activities on utilisation of plutonium and transmutation of long-lived radioactive waste, accelerator-driven systems, thorium fuel options, innovative nuclear reactors and fuel cycles, non-conventional nuclear energy systems, and fission/fusion hybrids.

Introduction

At the end of 2001, there were 438 nuclear power plants (NPPs) operating worldwide. [1] These NPPs represented some 353 GW(e) of generating capacity. According to IAEA's *Reference Data Series*, [2] the share of nuclear electricity generation in 2000 was 15.9%. At the end of 2001, NPPs represented 10.2% of the global electricity generating capacity. Also at the end of 2001, there were 32 NPPs under construction world-wide, with most current constructions in Asia or in countries with economies in transition.

The most significant trend in recent years has been that of steady increases in NPP availability factors through improvements in operational practices, engineering support, strategic management, fuel supply and spent fuel disposition. These have reduced costs and improved safety. Their cumulative impact has been substantial – since 1990 they have increased availability factors by an amount equivalent to the building of 33 GW(e) of new capacity. [3]

If only to meet the needs of the world's growing population (without considering the expected economic development, particularly in developing countries) which the United Nations estimates will approach 8.5 billion people by the year 2025, world-wide energy use will increase substantially over the next decades, making nuclear energy an indispensable option to meet these needs. According to the projections published by the Intergovernmental Panel on Climate Change (IPCC), by 2050, the global primary energy use will grow by a median factor of 2.5, while electricity demand will grow by a median factor of 4.7 (economic development shifts the demand towards electricity, given its convenience and flexibility). As mentioned earlier, sustainability goals are a major challenge to be met when developing advanced nuclear technology as a long-term option in the world's energy mix. In our context, the sustainability challenge has two aspects: resources and radioactive waste. Looking at the resources aspect, one has to acknowledge that nuclear power production cannot be sustainable if only 0% of the fissile resources in natural uranium are used. That means that ultimately, the fertile reserves (uranium-238, which makes the remaining 99.3% of the natural uranium, and thorium) will have to be tapped. Utilisation of breeding to secure the long-term fuel supply for electricity generation with nuclear power has been the main aim of fast reactor development, and remains the ultimate goal. However, the aims of R&D and fast reactor deployment in the medium term, say during the first decades of this century, are not the same in all countries: West European and North American countries, due to the low growth rate of electricity consumption and the availability of gas, liquid fossil fuel and uranium at stable prices intend to utilise the fast reactor to incinerate and transmute actinides and long-lived fission products. Thus, there is an immediate interest in developing fast reactors (critical and sub-critical) with higher concentrations of actinides and long-lived fission products in the core to enhance the transmutation and incineration rates, and to decrease the contaminated part of the fuel cycle. In Asian countries, on the other hand, particularly China, India, and the Republic of Korea, that have few indigenous gas/oil and uranium reserves, and where significant economic expansion is expected, the governments take a long-term perspective on the need for nuclear power. Near-term financial gains are seen to be less important, and the development of fast reactors is directed at ensuring reliable energy supplies in the long-term. To this end, China and India are now in a position to embark on the construction of experimental and prototype fast reactors.

Thus, in addition to the more long-term "breeder mission" of fast reactors, plutonium recycle (utilisation) in fast reactors, as well as transmutation/incineration of minor actinides (MA) and long-lived fission products (LLFP) (and here we touch upon the second aspect of the sustainability goal) in various types of fission reactors, accelerator-driven systems and molten-salt reactors is under investigation in several Member States. The advantages of some of these concepts (e.g., Accelerator-driven Systems (ADS)) that are put forward are intrinsic low waste production, high transmutation capability, enhanced safety characteristics, and better long-term resources utilisation (e.g., with thorium fuels). Important R&D programmes are being undertaken by various institutions in many IAEA Member States to substantiate these claims and advance the basic knowledge in this innovative area of nuclear energy development. For these groups, as for those focusing more on evolutionary and/or advanced Liquid Metal Reactor development, there is the clearly perceived need for co-ordinating their efforts and also for getting access to information from nationally and internationally co-ordinated activities. Whatever the medium term perspective, the flexibility needed to meet the above mentioned sustainability requirement with regard to natural resources and long-lived radioactive waste management asks for a continuous development of the fast neutron spectrum reactor technology. As a matter of fact, flexibility with regard to breeding or incineration/transmutation is attained only in reactors based on fast neutron cores due to their favourable neutron balance. Moreover, fast spectrum systems are the only ones that provide a high degree of flexibility with regard to isotopic separation (i.e., reprocessing), going as far (at least for sub-critical concepts) as to envisage systems that would both incinerate plutonium, and transmute MA and LLFP without isotopic separation. All these R&D activities, covering the spectrum from evolutionary/advanced fast reactors to hybrid systems (e.g., ADS), have to rely on, firstly, the capability to develop and validate reprocessing technologies for the advanced fuels envisaged (taking into account all criteria and requirements, e.g., non proliferation, and simplification of the fuel cycle), and, secondly, on the availability of a fast neutron spectrum irradiation facility for fuel and material testing.

This paper presents the activities being implemented by the IAEA in this area in support of its Member States’ needs for information exchange and collaborative R&D.

IAEA activities

As in all the other fields of advanced nuclear power technology development, the Agency is relying also in the P&T area on broad, in-depth staff experience and perspective. The framework for all the IAEA activities in the P&T area is the Technical Working Group on Fast Reactors (TWG-FR). In responding to strong common R&D needs in the Member States, the TWG-FR acts as a catalyst for international information exchange and collaborative R&D.

Given the common technical ground between plutonium utilisation R&D activities and the development of technologies for the transmutation of long-lived fission products and actinides, both activities are performed within the framework of a single Agency project: *Technology Advances in Fast Reactors and Accelerator-driven Systems for Actinide and Long-lived Fission Product Transmutation*. [4]

The TWG-FR is a standing working group within the framework of the IAEA. It provides a forum for exchange of non-commercial scientific and technical information, and a forum for international co-operation on generic research and development programmes on advances in fast reactors and fast spectrum accelerator-driven systems. Its present members are the following 14 IAEA Member States: Belarus, Brazil, China, France, Germany, India, Italy, Japan, Kazakhstan, Republic of Korea, Russia, Switzerland, United Kingdom, and United States of America, as well as the OECD/NEA, and the EU (EC). The TWG-FR advises the Deputy Director General-Nuclear Energy on status of and recent results achieved in the national technology development programmes relevant to the TWG-FR's scope, and recommends activities to the Agency that are beneficial for these national programmes. It furthermore assists in the implementation of corresponding Agency activities, and ensures that through continuous consultations with officially nominated representatives of Member States all the project's technical activities performed within the framework of the Nuclear Power Technology Development sub-programme are in line with expressed needs from Member States. The scope of the TWG-FR is broad, covering all technical aspects of fast reactors and ADS research and development, design, deployment, operation, and decommissioning. It includes, in particular: design and technologies for current and advanced fast reactors and ADS; economics, performance and safety of fast reactors and ADS; associated advanced fuel cycles and fuel options for the utilisation and transmutation of actinides and long-lived fission products, including the utilisation of thorium. Given the TWG-FR's broad scope, the coverage will generally be in an integrative sense to ensure that all key technology areas are covered. Many specific technologies are addressed in detail by other projects within the IAEA and in other international organisations. The TWG-FR keeps abreast of such work, avoiding unproductive overlap, and engages in co-operative activities with other projects where appropriate. The TWG-FR thus co-ordinates its activities in interfacing areas with other Agency projects, especially those of the International Working Group on Nuclear Fuel Cycle Options, and the Department of Nuclear Safety, as well as with related activities of other international organisations (OECD/NEA, and EC). The TWG-FR normally meets once per year; the last meeting was hosted in May 2002 by the Forschungszentrum Karlsruhe (FZK), Germany, the next meeting will be hosted in May 2003 in the Republic of Korea by KAERI.

Recent accomplishments

Comparative assessment of thermophysical and thermohydraulic characteristics of lead, lead-bismuth and sodium coolants for fast reactors

So far, all prototype, demonstration and commercial liquid metal cooled fast reactors have used liquid sodium as a coolant. Sodium-cooled systems, operating at low pressure, are characterised by very large thermal margins relative to the coolant boiling temperature and a very low structural material corrosion rate. In spite of the negligible thermal energy stored in the liquid sodium available for release in case of leakage, there is some safety concern because of its chemical reactivity with respect to air and water. Lead, lead-bismuth or other alloys of lead, appear to eliminate these concerns because the chemical reactivity of these coolants with respect to air and water is very low. Some experts believe that conceptually, these systems could be attractive if high corrosion activity inherent in lead, long term materials compatibility and other problems will be resolved. Extensive research and development work is required to meet this goal. Preliminary studies on lead-bismuth and lead cooled reactors and ADS (in which the coolant can also double as the neutron spallation source that drives the sub-critical core) have been initiated in France, Japan, the United States of America, Italy, and other countries. Considerable experience has been gained in Russia in the course of the development and operation of reactors cooled with lead-bismuth eutectic, in particular propulsion reactors. Apart from being quite rare and hence expensive, bismuth is also a source of the volatile α-emitter ^{210}Po. Thus, studies on pure lead cooled fast reactors are also under way in Russia. Presently, there is no clear view on the relative advantages and drawbacks of heavy liquid metals vs. sodium, and the preferred options vary considerably from Member State to Member State, sometimes even among various institutions in one Member State. In trying to meet the needs of clarification and exchange of information, the IAEA has published a TECDOC on the review and comparative assessment of the main characteristics of sodium, lead, and lead-bismuth eutectic. [5]

Co-ordinated research project (CRP) on the "Potential of Thorium-based fuel cycles to constrain plutonium and to reduce the long-term waste toxicity"

Large stockpiles of civil plutonium have accumulated world-wide from nuclear power programmes in different countries. There is a serious public and political concern in the world about misuse of this plutonium and about accidental release of highly radiotoxic material into the environment. It is therefore necessary to safeguard the plutonium under strong security. One alternative for the management of plutonium is to incinerate it in reactors. However, if the reactors are fuelled with plutonium in the form of U-Pu-mixed oxide (MOX), second-generation plutonium is produced. A possible solution to this problem is to incinerate plutonium in combination with thorium. The thorium cycle produces ^{233}U that, from a non-proliferation point of view, is preferable to plutonium for two reasons. Firstly, it is contaminated with ^{232}U, which decays to give highly active daughter products. This would make handling and diversion difficult. Secondly, in case this is not sufficient a deterrent, the ^{233}U could be denatured by adding some ^{238}U to the thorium. The quantity of ^{238}U could be fine-tuned so as to be sufficient to denature the ^{233}U, but not so much as to produce a significant quantity of plutonium. The thorium option not only produces electricity, but also replaces the plutonium with denatured ^{233}U, which can be used in other reactors at a later date. All this can be done in existing reactors.

A CRP on this topic was initiated by IAEA in 1995. The Member States joining into the CRP were: China, Germany, India, Israel, Japan, Republic of Korea, the Netherlands, Russia, and the United States of America. This CRP examined the different fuel cycle options in which plutonium be incinerated by recycling it with thorium. The potential of the thorium-matrix has been examined through computer simulations. Each participant has chosen his own cycle, and the different cycles are compared through certain predefined parameters (e.g., annual reduction of plutonium stockpiles). The radio-toxicity accumulation and the transmutation potential of thorium-based cycles for current, advanced and innovative nuclear power reactors are investigated. The research programme was divided into three stages: Benchmark calculations, studies on the optimisation of the plutonium incineration capability in various reactor types, and assessment of the resulting impact on the waste radio-toxicity. The results of the three stages were presented in [6-8], respectively. The CRP was completed in 2001, and the final IAEA TECDOC will be published shortly.

Co-ordinated Research Project (CRP) on the "Use of Thorium-based fuel cycles in Accelerator-driven Systems (ADS) to incinerate plutonium and to reduce long-term waste toxicities"

The IAEA established this CRP in 1996. The Member States and international organisations joining into the CRP were: Belarus, Czech Republic, France, Germany, Italy, Netherlands, Russia, Sweden, Spain, and CERN. The scope of the CRP was to quantify the potential of the ADS in conjunction with thorium-fuel to burn transuranics (TRU) from LWR-MOX discharge, MA from both LWR-MOX and fast reactor fuel discharge, as well as long-lived fission products (LLFP). The specific objective of the CRP was to investigate the neutronics of ADS, and evaluate its TRU incineration and LLFP transmutation capabilities. The CRP addressed the main neutronics issues for both the thorium fuelled and the TRU/MA ADS incinerator concepts. In the first stage of the CRP, benchmark simulations of an Energy Amplifier (EA) [9] like system fuelled with ^{233}U/thorium were performed. In this stage of the CRP, the principal neutronics features of the EA were inter-compared (i.e., fuel enrichments corresponding to a different sub-criticality levels, sensitivity of sub-criticality levels to fuel burn-up, evolution of proton current requirements, void effect, long-term fuel activity under irradiation. The main goal in this stage was to identify the uncertainties due to the different methodologies, nuclear data and codes used by the various participants. An important achievement of this stage was the clarification of the significant differences in the analytical approach to sub-critical systems (i.e., the full understanding of the importance of the k-source concept, and the limitations of the k-effective approach in the analysis of sub-critical systems). Stage 2 of the benchmark was devoted to the assessment of the neutronics characteristics of a modular fast spectrum ADS for long-lived radiotoxic waste transmutation. The benchmark exercise was based on the simplified modelisation (restricted to the sub-critical reactor part) of an ADS fuelled with TRU or MA ($k_{eff} = 0.96$). In Stage 3, calculations of an existing experimental sub-critical facility have been performed. Using their respective methodologies, the CRP participants have simulated the thermal sub-critical zero power system "YALINA" set up at the Joint Institute for Power and Nuclear Research of the Academy of Sciences of Belarus in Minsk, and the results have been compared with the experimental data. The CRP was completed in 2001, and the final IAEA TECDOC is under preparation. Preliminary results have been presented in. [10]

International database on ADS related research and development programmes

Based on the needs for strengthening the international co-operation in the field of the R&D for ADS expressed by Member States, and on the recommendations of various international forums, the IAEA decided to establish a database on existing and planned experimental facilities for ADS related R&D. During the course of the implementation work, it proved practical to include – apart from the experimental facilities – also other ADS and P&T related aspects, e.g., ongoing and planned R&D programmes, studies of conceptual designs, and so forth. The database is WWW-based (http://www-adsdb.iaea.org/index.cfm) and operational. Data collection has started, and all Member States having R&D activities in the ADS and Partitioning and Transmutation (P&T) area are encouraged to contribute to the database (request login information from a.stanculescu@iaea.org).

"Three-Agency Study"

The IAEA has contributed to the "Three-Agency Study" on *Innovative Nuclear Reactor Development: Opportunities for International Co-operation*, a joint project among the OECD/IEA, the OECD/NEA and the IAEA. The "Three-Agency Report" is a "first step in examining the scope for enhanced international co-operation in developing nuclear-fission reactor technologies. It shows how new technologies are being developed to address the challenges facing nuclear power today and identifies potential areas for co-operation among technology developers. The focus is on 'innovative' fission reactor technologies, which are those that go well beyond the incremental, evolutionary changes to current technology that have been developed and are the subject of ongoing work". [11]

Workshop on "Hybrid Nuclear Systems for Energy Production, Utilisation of Actinides and Transmutation of Long-lived Radioactive Waste"

The main objective of this workshop that was held in Trieste, Italy, from 3-7 September 2001 in collaboration with the International Centre for Theoretical Physics (ICTP) was formation and training. It achieved this objective through lectures, tutorials, and computer exercises. Approximately 50 participants from 26 countries (mostly from Eastern Europe and Asia, but also from Africa, Western Europe, and South America) participated in this week-long workshop. The topics treated ranged from the design of ADS, the simulation methodologies, and the ADS safety to fuel cycle issues. Encouraged by the very positive feedback from the participants, the IAEA has decided to organise another training and formation Workshop in October 2003. [12]

Ongoing and planned activities

Co-ordinated research project (CRP) on "Studies of Advanced Reactor Technology Options for Effective Incineration of Radioactive Waste"

The overall objective of the CRP is to perform R&D tasks contributing towards the proof of practicality for long-lived waste transmutation. In particular, to contribute towards providing the basis for the assessment of both the short and long term benefits – or lack of those – to the nuclear fuel backend of ADS, as compared to other existing, advanced, and innovative concepts. In pursuing this objective, the CRP considers the results and recommendations of the OECD/NEA "Second P&T Expert Group", [13] and concentrates on the assessment of the transient behaviour of various transmutation systems. For a sound assessment of the transient and accident behaviour, the neutron kinetics and dynamics have to be qualified, especially as the margins for the safety relevant neutronics parameters are becoming small in a "dedicated" transmuter. The CRP will integrate benchmarking of transient/accident simulation codes focusing on the phenomena and effects relevant to various critical and sub-critical systems under severe neutron flux changes and rearrangements. The main thrust will be on long (as compared to the neutron lifetime) time-scale effects of transients initiated by strong perturbations of the core and/or the neutron source. Changes of flux-shape and power caused by reactivity perturbations in systems with dedicated fuels and varying MA content will be one focus. For the transient analysis of such transmuters, besides neutronics, thermal-hydraulic and fuel issues are of importance. The behaviour of different transmuter systems under various transient conditions will be assessed. The CRP will investigate future needs both for theoretical means (data, codes), and experimental information related to the various transmutation systems. In a nutshell, the final goals of the CRP are to (a) deepen the understanding of the dynamics of transmutation systems, e.g., the accelerator-driven system, especially systems with deteriorated safety parameters, (b) qualify the available methods and specify their range of validity, and (c) formulate requirements for future theoretical developments.

Should transient experiments be available, the CRP might also pursue experimental benchmarking work. In any case, based on the results, the CRP will conclude on the potential need of transient experiments and make appropriate proposals for experimental programmes. The CRP has received 17 proposals from various R&D institutions in 13 Member States (Belgium, China, Czech Republic, France, Germany, Hungary, India, Japan, Republic of Korea, Netherlands, Poland, Russia, and U.S.A.), and the EC (JRC). Its first research co-ordination meeting, hosted by Forschungszentrum Karlsruhe (FZK), was held from 5-8 November 2002. The CRP is presently scheduled to terminate on 31 December 2005.

International conference on "Innovative Technologies for Nuclear Fuel Cycles and Nuclear Power"

The objective of this conference is to provide a forum for the exchange of information between senior experts and policy makers from developed and developing countries relating to evolving and innovative nuclear technologies that are being considered for future applications. Strategists, decision makers, managers, and technical leaders in public and private institutions are expected to both contribute to and benefit from participation in the conference. The conference will examine the background conditions – social, environmental and economic – in which sustainable nuclear technologies can be expected to be developed in the foreseeable part of this century. The conference will address the requirements set by these expected conditions on technological solutions for the peaceful use of nuclear applications. An awareness of ongoing national and international programmes will be developed within the Member States of the IAEA, and opportunities for developing collaborative work will be made available. The conference will be held in Vienna, from 23-26 June 2002. [14]

Coordinated research project (CRP) on "Benchmark Analyses on Data and Calculational Methods for ADS Source-related Neutronics Phenomenology with Experimental Validation"

This activity has been proposed for implementation in IAEA's 2004-2005 Programme and Budget Cycle. The specific objective of the CRP is to improve the present understanding of the coupling of the ADS spallation source with the multiplicative sub-critical core. As outcome, the CRP aims at advancing the efforts under way in the Member States towards the proof of practicality for ADS based transmutation by providing the information exchange and collaborative research framework needed to ensure that the tools to perform detailed ADS calculations, namely from the high energy proton beam down to thermal neutron energies, are available. The CRP will address all major physics phenomena of the spallation source and its coupling to the sub-critical system. Integrated calculation schemes will be used by the participants to perform computational and experimental benchmark analyses. Considering that the major focus of the CRP will be on the comparison between calculations and experiments, in preparation of the CRP it is intended to convene a (possibly joint NEA/IAEA) technical meeting having the objective of getting a precise status of the world-wide ongoing and planned experimental activities on the coupling of spallation (or other neutron sources) with sub-critical configurations.

Planned topical technical meetings

In 2003, two topical meetings are planned within the framework of the project on *Technology Advances in Fast Reactors and Accelerator-driven Systems for Actinide and Long-lived Fission Product Transmutation*: the first technical meeting will be on Review of Solid and Mobile Fuels for Partitioning and Transmutation, and the second one on Theoretical and experimental Studies on Heavy Liquid Metal Thermo-hydraulics.

Conclusions

For nuclear energy to remain a long-term option in the world's energy mix, nuclear power technology development must meet sustainability goals with regard to fissile resources and waste management. The utilisation of breeding to secure long-term fuel supply remains the ultimate goal of fast neutron spectrum system. Plutonium recycle in fast reactors, as well as incineration/transmutation of minor actinides and long-lived fission products in various hybrid reactor systems (e.g., ADS) also offer promising waste management options. Several R&D programmes in various Member States are actively pursuing these options, along with the energy production and breeding mission of fast reactor systems.

In line with the statutory objective expressed in Article II: The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, insofar as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose, the IAEA will continue to assist the Member States' activities, also in the area of advanced technology development for utilisation and transmutation of actinides and long-lived fission products, by providing an umbrella for information exchange and collaborative R&D to pool resources and expertise.

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OECD/NEA PARTITIONING AND TRANSMUTATION ACTIVITIES

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Abstract

Partitioning and transmutation (P&T) has gained interest during the past decade and the OECD Nuclear Energy Agency (NEA), in response to the interest from member countries, has included P&T in its programme of work since 1989. The information exchange meetings are one of key components of this international project, aiming at giving experts a forum to present and discuss current developments in the field. Within the NEA, the P&T project is one example of horizontal activity, involving several Divisions and Committees. Most of the work on P&T have been and are being undertaken under the auspices of the Nuclear Development Committee (NDC) and the Nuclear Science Committee (NSC). The work of the NDC mainly comprises strategic and assessment reports by expert groups on the broad field of P&T and its impact on the nuclear fuel cycle, while the NSC work includes specific projects and specialist meetings on particular scientific aspects of P&T. The Radioactive Waste Management Committee (RWMC) is also kept informed of the outcome of the NDC and NSC activities, as the potential application of P&T would impact waste management systems. P&T would not eliminate the need for geological disposal of high level waste, but potentially reduce the radiotoxic inventory to be disposed of. This paper gives an overview of past and on-going P&T activities of the OECD/NEA.

Introduction

In nuclear power generation, the efficient and safe management of spent fuel produced during the operation of commercial power plants is one of the most important issues not only to the nuclear community but also to the general public. Partitioning and transmutation of nuclear waste, i.e. to separate minor actinides (MA) and long-lived fission products from the spent fuel and transmute them into short-lived or into stable radio-nuclides in appropriate reactor systems for the reduction of the volume and toxic potential into the nuclear waste stream, is complementary to the option of long-term geological disposal of spent fuel together with other nuclear waste.

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Whenever relevant, the NEA closely co-operates with the European Commission (EC) and the International Atomic Energy Agency (IAEA) on specific topics of interest to both agencies.

This paper summarises past activities, and overviews on-going activities on P&T within the NEA programme of work.

NEA information exchange meetings on P&T

The OECD/NEA activities in the field of P&T were initiated in 1989 by the proposal form the Japanese Government to establish an international Information Exchange Programme on Actinide and Fission Product Partitioning and Transmutation. The first information exchange meeting was held in Mito, Japan in 1990, and a wide range of topics from basic research to P&T scenarios and advanced transmutation systems were discussed at the meeting. [1] At the meeting, the need to discuss more specific areas was expressed and two specialists meetings were later organised: one on partitioning technology at Mito, Japan in 1991, [2] and the other on accelerator-based transmutation at Paul Scherrer Institute, Switzerland in 1992. [3] It was also decided to organise information exchange meetings on P&T every two years.

Seven information exchange meetings have so far been organised (Mito, Japan in 1990; ANL, USA in 1992; Cadarache, France in 1994; Mito, Japan in 1996; Mol, Belgium in 1998; Madrid, Spain in 2000 and now Jeju, Korea in 2002). [4-8] While the NDC was responsible for organising the information exchange meetings up to the 5th meeting at Mol, the 6th and 7th meetings in Madrid and Jeju have been organised jointly by the NDC and NSC.

Activities of the Nuclear Development Committee (NDC)

First systems study

The Nuclear Development Committee (NDC) has conducted two P&T systems studies. The first P&T systems study (1996-1998), entitled “Status and Assessment Report of Actinide and Fission Product Partitioning and Transmutation”, reviewed the advances in the separation of long-lived isotopes, the transmutation options and the impact of P&T on waste management and disposal. [9] Minor actinides and long-lived fission products contributing mostly to the long-term radiotoxicity and risk were also discussed. A comprehensive analysis was made for three specific fuel cycle options: Once-Through Cycle with direct disposal, Reprocessing Fuel Cycle, and Advanced Fuel Cycle with P&T. However, the more effective transmutation strategies with fully closed fuel cycles and the specific role of accelerator-driven systems (ADS) in these fuel cycles were not addressed in the study.

Among the general conclusions of the report could be mentioned:

- Fundamental R&D for the implementation of P&T needs long lead times and requires large investments in dedicated fast neutron spectrum devices, extension of reprocessing plants and construction of remotely manipulated fuel and target fabrication plants.
- The short-term impact of partitioning would be to reduce long-term radiotoxic inventory of the resulting HLW at the expense of an increase of the operational requirements for the nuclear facilities concerned.
- Recycling of Pu and minor actinides could stabilise the transuranic element inventory of a reactor park. Multiple recycling of transuranic elements is a long-term venture, which may take decades to reach equilibrium in transuranic element inventories.
- Conditioning of separated long-lived nuclides in appropriate matrices, which are much less soluble than glass in geological media, or which could serve as irradiation matrix in a delayed transmutation option, is a possible outcome for the next decades.
- P&T will not replace the need for appropriate geological disposal of high-level waste, irradiated transuranic element concentrates, and residual spent fuel loads from a composite reactor park.

Second systems study

The second P&T systems study (1999-2000), entitled “A Comparative Study of Accelerator-driven Systems and Fast Reactors in Advanced Nuclear Fuel Cycles”, aimed at comparing the role and relative merits of both systems in closed fuel cycles. [10] To quantitatively assess the advantages and drawbacks of different fuel cycle strategies, seven representative fuel cycle schemes were selected and compared with the current once-through cycle: Pu burning, Heterogeneous minor actinide recycling, transuranic (TRU) burning in fast reactors, TRU burning in accelerator driven systems (ADS), MOX recycling combined with TRU burning, Double strata fuel cycle and Fast reactor strategy.

The study confirmed that all transmutation strategies with fully closed fuel cycles can in principle achieve similar reductions in the TRU inventory and in the long-term radiotoxicity of high-level waste.

The study also provided some general conclusions, which could influence policy decisions. These conclusions are:

- While P&T will not replace the need for appropriate geological disposal of high-level waste, the study has confirmed that different transmutation strategies could significantly reduce, i.e. a hundred-fold, the long-term radiotoxicity of the waste and thus improve the environmental friendliness of the nuclear energy option. In that respect, P&T could contribute to a sustainable nuclear energy system.
- Very effective fuel cycle strategies, including both fast spectrum transmutation systems (FR and/or ADS) and multiple recycling with very low losses, would be required to achieve this objective.
- Multiple recycle technologies that manage Pu and MA either together or separately could achieve equivalent reduction factors in the radiotoxicity of wastes to be disposed. The study shows that pyrochemical reprocessing techniques are essential for those cycles employing ADS and FRs where very high MA-content fuels are used.
- In strategies where Pu and MA are managed separately, ADS can provide additional flexibility by enabling Pu-consumption in conventional reactors and minimising the fraction of dedicated fast reactors in the nuclear system.
- In strategies where Pu and MAs are managed together, the waste radiotoxicity reduction potential by use of FRs and ADS is similar and the system selection would need to be made based on economic, safety and other considerations.
- Further R&D on fuels, recycle, reactor and accelerator technologies would be needed to deploy P&T. The incorporation of transmutation systems would probably occur incrementally and differently according to national situations and policies.
- Fully closed fuel cycles may be achieved with a relatively limited increase in electricity cost of about 10 to 20%, compared with the LWR once-through fuel cycle.
- The deployment of these transmutation schemes need long lead-times for the development of the necessary technology as well as making these technologies more cost-effective.

In addition, the study concluded that in order to keep the P&T option open, focused R&D should be continued on

- critical and sub-critical fast reactors;
- demonstration of reprocessing technologies and associated advanced fuels at appropriate scale;
- structural and coolant materials;
- irradiation experiments;
- improvement of modelling tools to simulate materials behaviour under irradiation and high temperature;
- safety analysis of ADS, and
- performance assessment of geological repositories using a P&T source term.

Planned activities

Advanced fuel cycles, including fast or thermal reactors or accelerator-driven systems, linked to a variety of P&T schemes have the potential to greatly alter specifications of nuclear waste. In consequence, an expert group will be created to carry out a study on "Impact of Advanced Nuclear Fuel Cycle Options on Waste Management Policies". The study will focus on advanced nuclear fuel cycle options and associated waste forms, repository performance assessment studies using source terms for waste arising from such advanced nuclear fuel cycles, and identification of new options for waste management and disposal. A close collaboration with the NEA Radioactive Waste Management Committee and with the NSC will be sought.

Past activities of the Nuclear Science Committee (NSC)

Nuclear data and computer codes (1991-1997)

In the early 1990s, the NSC launched an international code comparison exercise on the calculation of intermediate energy nuclear data for accelerator-based transmutation applications to assess the predictive ability of computer codes used. [11-15] The data calculated comprised double-differential cross-sections, neutron yields, and mass distributions of spallation products. The results were collected, analysed and compared against experimental data. A specialists' meeting on intermediate energy nuclear data, held in 1994, recommended a systematic compilation of experimental intermediate energy data and the NEA Data Bank started to compile these data into the EXFOR database.

Physics benchmarks (1992-2000)

In 1992, under the guidance of the NSC, a Task Force on Physics Aspects of Different Transmutation Concepts was created to assess the fundamental scientific issues of transmutation concepts at that time. The group examined more than 20 different transmutation concepts. However, a consistent comparison analysis of different concepts could not be made due to inconsistencies in analysis methods used for each system. [16]

An international benchmark exercise was therefore launched to better understand the basic physical phenomena and to provide a basis for a more systematic system analysis methodology. The benchmark examined different transmutation concepts based on pressurised water reactors (PWRs), fast reactors, and an accelerator-driven system. The physics of complex fuel cycles, involving reprocessing of spent PWR reactor fuel and its subsequent reuse in different reactor types, was investigated. For the PWR benchmark, the results showed consistency well within the limits associated with multiple plutonium recycling, as established by the NEA Working Party on Plutonium Fuels and Innovative Fuel Cycles (WPPR). For the Fast Reactor benchmark, calculation code systems used by the participants showed a good general agreement in the predictions of the nuclear characteristics of the minor actinides loaded fast reactor core. For the ADS benchmark, large discrepancies were observed in main neutronic characteristics such as initial k_{eff} and burn-up behaviour. [17]

The unsatisfactory outcome of the ADS benchmark indicated a need for refining the benchmark specification, especially addressing the neutronics of minor actinide dominated sub-critical cores. The NSC therefore launched a new benchmark in 1999. A model of a lead-bismuth cooled sub-critical system driven by a beam of 1 GeV protons was chosen for the exercise. The design of the sub-critical core was similar to that of the Advanced Liquid Metal Reactor (ALMR). The benchmark reactor was assumed to operate as a minor actinide burner in a “double strata” fuel cycle scheme, featuring a fully closed fuel cycle with a top-up of pure minor actinides. Two fuel compositions for a start-up and an equilibrium core were considered, both differing considerably from normal U-Pu mixed-oxide fuel compositions.

Although significant differences in normal integral reactor physics and safety parameters, as well as neutron flux distributions, were again observed, the main outcome of the benchmark indicated that the overall status of the nuclear data and computational tools for the analysis of ADS minor actinide burners is satisfactory for scooping calculations, but not for detailed design calculations. [18]

Accelerators

R&D activities and construction plans related to high power proton accelerators (HPPAs) are being considered in various countries to promote basic and applied sciences, including accelerator-driven nuclear energy systems (ADS). The performance of such hybrid nuclear systems depends to a large extent on the specification and reliability of the particle accelerator, as well as the integration of the accelerator with spallation targets and in some cases, sub-critical assemblies. However, for practical applications, there are improvements to be accomplished in terms of beam losses and frequency of the beam trips.

The NSC therefore decided to organise workshops on “Utilisation and Reliability of High Power Proton Accelerators” to discuss actual problems and possible solutions. The scope of the first workshop, held in Mito, Japan in 1998, comprised the experience and prospects of HPPAs and the required accelerator reliability in various applications, especially focused on beam trips and power fluctuations. [19] More thorough discussions on issues and concepts was held in the following workshops in Aix-en-Provence, France in 1999 [20] and in Santa Fe, USA in 2002. [21] The 4th Workshop will be organised in Korea in spring 2004.

Chemistry

Recognising that the feasibility of P&T directly depends on the capability to separate actinides and fission products with a very high recovery efficiency, the NSC has organised various activities in fuel cycle chemistry. In 1993, a Task Force on Actinide Separation Chemistry reviewed the existing, and the need for additional, basic actinide chemistry data, the types of actinide waste streams, hydrometallurgical and pyrochemical separation processes, including new processes developed for the minor actinide separation in P&T systems. [22]

Following the report from the Task Force, the NSC organised a workshop at Villeneuve-les-Avignon, France in 1997 to review separation strategies of long-lived nuclides from nuclear waste. [23] The workshop proposed follow-up meetings devoted to the application of X-rays to radioisotope chemistry and to the evaluation of speciation technology. Consequently, the NSC held a workshop on “Speciation, Techniques and Facilities for Radioactive materials at Synchrotron Light Sources” in Grenoble, France in 1998, [24] and a workshop on “Evaluation of Speciation Technology” in Japan in 1999. [25]

Regarding pyrochemical processes, the NSC organised a workshop on “Pyrochemical Separations” at Villeneuve-les-Avignon, France in March 2000, dealing with the national and international R&D programmes, pyrochemical reprocessing requirements in future fuel cycles, and process simulation and design. [26] Following one of the recommendations from the workshop, to promote efficient international collaboration and to provide a common scientific base on pyrochemistry, the NSC created an Expert Group on Pyrochemistry in 2000. The work scope of this group was not restricted to P&T applications. The Expert Group will produce a state-of-the-art report summarising its findings on the technology status and the necessary R&D by end of 2002. This group was later integrated in the chemical partitioning subgroup of the new Working Party on Scientific Issues in P&T. The subgroup covers both aqueous and dry processes.

On-going activities of the Nuclear Science Committee

The Nuclear Science Committee decided to establish a Working Party on Scientific Issues in Partitioning and Transmutation (WPPT) in 2000, to better co-ordinate different its on-going activities related to P&T. The scope of the WPPT is to deal with the status and trends of scientific issues in Partitioning and Transmutation (P&T), comprising different disciplines such as accelerators, chemistry, material science, nuclear data and reactor physics. The objectives of the WPPT are to provide the member countries with up-to-date information on the development of P&T technologies, to liaise closely with other NEA working groups such as the Working Party of Plutonium fuels and Innovative Fuel Cycles (WPPR) and to provide advice and support to the nuclear community on the developments needed to meet the requirements (data and methods, experiment validations, scenario studies) for implementing different P&T scenarios.

To cover a wide range of the P&T fields, the WPPT comprises four subgroups: accelerator utilisation and reliability for ADS applications, chemical partitioning, fuels and materials, and physics and safety for transmutation systems. All the subgroups will publish a state-of-the-art report on their specialised field by 2004.

Accelerator utilisation and reliability for ADS applications

The scope of the subgroup is to

1. Evaluate the potential utilisation of accelerator-driven spallation targets as part of transmutation systems.
2. Organise one or more workshop(s) of experts on accelerators, spallation targets, and beam entrance windows in order to consider, evaluate, and rank potential issues related to system performance and reliability.
3. Evaluate expected performance of accelerators, spallation targets, and beam entrance windows for applications associated with accelerator-driven transmutation systems, and
4. propose a prioritised list of issues that need to be resolved relating to the interaction of an accelerator and target system.

The subgroup will publish a final report with up-to-date information on: technology status of the proposed accelerators and targets, data available to support an accelerator application, on-going R&D, the gaps to be overcome, R&D required to fill these gaps, and international collaborations, emphasising on accelerator and spallation target reliability and any associated safety issues, target performance and toxicity of any spallation products, and beam entrance window performance, including thermal stress and radiation damage.

The third workshop on utilisation and reliability of high power proton accelerator was hosted by LANL and held in Santa Fe, USA on 12-16 May 2002. Main topics discussed were:

1. reliability of the accelerator and impact of beam interrupts on the design and performance of the ADS;
2. spallation target design characteristics and impact on the multiplier design, including materials, radiation damage and embrittlement, enhanced corrosion, cooling issues with high-power density, and windowless design concepts;
3. safety and operational characteristics of a multiplying system driven by a spallation source, and
4. test facilities.

The main findings of the workshop will be summarised in a report by October 2002. According to the normal rotation, it was suggested that the next workshop take place in Asia, most probably in Korea. The approximate date would be spring 2004.

Under the accelerator subgroup, two working groups (WG) will be formed for working on the Accelerator reliability database and the LBE technology handbook. A more detailed plan of work of the two WGs is being prepared.

The WG on Accelerator reliability database will:

- collect the beam interrupt data from various HPPAs and develop a database for the raw data;
- analyse the data for improvements based on already existing technology and recommend number of beam-trip vs. duration database in today’s technology;
- the raison for the improved reliability in the extrapolated database will be documented for reference.

The WG on LBE technology will:

- co-ordinate and guide the LBE research in participating organisations, while enhancing closer and broader-based collaboration;
- develop a set of requirements and standards and a consistent methodology for experimentation, data collection and data analyses;
- publish the results in a consistent format within a single document in the form of a handbook to guide the subsequent development efforts.

The WG on LBE will publish a joint 5-year test plan in October 2003 and the final handbook will be issued by October 2007. The handbook will contain corrosion, liquid metal embrittlement data mapping as a function of thermal-hydraulic parameters, structural alloys, various proton and neutron spectral fluxes and fluences.

Chemical partitioning

The chemical partitioning subgroup incorporates members of the NSC Expert Group on Pyrochemistry, together with a set of world experts in aqueous separations processes. Its work is focused on separations processes relevant to different partitioning and transmutation systems, covering a wide range of fuel types; oxide fuel (uranium oxide, mixed uranium plutonium oxide, inert matrix fuels), fertile and non-fertile nitride fuel, composites (cermet, cercer), fertiel and non-fertile metal alloy, TRISO-coated graphite particulate fuel, and uranium and/or thorium based molten-salt fuel.

The group will perform a thorough technical assessment of separations processes in application to a broad set of P&T operating scenarios, including technical feasibility assessments, mass balance flow sheet development, technological maturity assessment, and decision analyses on technical issues. Important research, development and demonstration necessary to bring preferred technologies to a deployable stage will be identified and collaborative international efforts to further technology development will be recommended.

A state-of-the-art report on pyrochemistry will be issued by the Expert Group on Pyrochemistry by June 2003. The report will comprise four main chapters on national programmes, research needs, international collaboration, and future applications

The first publication of the chemical partitioning subgroup will be a report on national programmes in partitioning. The report will contain activities in USA, UK, Russia, Japan, Korea, Spain, France, Czech Republic and EC JRC and it will be published by June 2003. Further activities of the subgroup will be discussed at its next meeting.

Since a close co-ordination between P&T fuels developers and separations chemists is essential for assurance of success in the P&T enterprise, the subgroup will organise a joint workshop with the subgroup on fuels and materials (see below) in USA in May-June 2003.

Fuels and materials

The work of the subgroup on fuels and materials puts emphasis on the evaluation of expected performance of fuels and materials for transmutation systems. Fundamental properties of fuels, fuel selection criteria, fabrication and behaviour prediction, cladding and coolant compatibility issues, and long-lived fission products will be revisited and summarised by the subgroup. The main objective of the subgroup is to provide member countries with up to date information on the state-of-the-art technology on fuels and materials for transmutation, the availability of pertinent data and the necessary R&D to supplement the existing database.

The outcome of the work will be published as a report including information on:

- Fundamental thermophysical and thermochemical properties of relevant actinide compounds and alloys.
- Fuel selection criteria specific to representative transmutation scenario: single (LWR/FBR) stratum and double (LWR/Dedicated system) strata.
- Fuel fabrication (effects of radiation, heat, thermochemical issues. Compatibility with reprocessing).
- Fuel behaviour prediction (differences between (U,Pu)-based power reactor fuels and transmutation fuels. recognised technological problems of transmutation fuels, and uncertainties in their performance).
- Materials issues (existing database of cladding and fuel assembly materials, compatibility with lead/lead-bismuth, and high energy environment in ADS systems).
- Long-lived fission products.
- Ongoing R&D and international collaboration.

The first draft of the final report will be issued by September 2003 and a peer reviewed final report will be published by mid 2004.

The subgroup will organise a joint workshop with the subgroup on chemical partitioning in USA in May-June 2003.

Physics and safety for transmutation systems

The main tasks of the subgroup are to organise theoretical and experiment-based benchmarks for transmutation systems, evaluate beam-trip consequences in accelerator-driven systems, perform sensitivity studies on the main physics parameters, and propose a safety approach for new P&T systems.

The performance of both critical and sub-critical systems will be analysed and homogeneous as well as heterogeneous concepts for the transmutation of transuranics, minor actinides, and long-lived fission products will be considered. An evaluation of safety approaches for new transmutation systems, including the beam-trip issue in ADS, will be undertaken and reactor control options including the optimum sub-criticality level will be investigated.

MUSE-4 benchmark

To study the neutronic of ADS, some international experiments have been proposed, in particular the experiment MUSE-4 (using the MASURCA reactor) at Cadarache, France. A benchmark was launched, based on the “liquid” metal fast sub-critical MUSE-4 experiment configurations, to compare simulation predictions based on available codes and nuclear data libraries with experimental data related to: TRU transmutation, criticality constants and time evolution of the neutronic flux following source variation. [27]

The benchmark has been divided into three steps. The first step allows an understanding of the simulation methods of the different groups and tuning of the simulation programmes with the experimental data of one already measured configuration (COSMO). In the second step, the MUSE-4 reference configuration (1 112 cells) is proposed to simulate different reactor parameters (criticality constant, flux distribution, etc.) in a nearly critical configuration. Finally, the third step is oriented to the simulation of reactor response to the external source in the sub-critical reference configuration (976 cells). Static parameters are also considered in this sub-critical reference configuration.

More than 25 solutions for the steps 1 and 2 were contributed from 14 institutions world-wide and the submitted results are being analysed. Calculations for the step 3 have recently been started and the complete MUSE-4 benchmark results will be analysed and compared with experimental results. *Beam-trip benchmark*

Taking into account the fact that beams from existing accelerators are not entirely stable (beam trips), it is crucial to understand the effects of such beam trips on different sub-critical systems (thermal shocks). Therefore, the subgroup plans to organise an ADS beam trip transient benchmark. Up to now, two benchmark specifications have been proposed:

- a “Na-cooled” ADS “overpower” and beam-trip benchmark and
- a transient induced by 3 sec, 6 sec, 12 sec and a definitive beam trip in a lead-bismuth cooled 80 MWth XADS-type system.

The subgroup will examine both of proposals and perform the beam trip transient study.

Licensing study

There is a strong need to develop the technical basis for the licensing case for a future ADS. In particular, it is felt that work on a real project is needed to advance the discussions between the accelerator and reactor communities. Therefore, a specific working group within the subgroup on physics and safety for transmutation will be formed to examine the licensing case of two designs (Belgian MYRRHA and the high power reference design being developed within the US AAA project) and to obtain consensus between accelerator, reactor safety, and licensing experts, as to the safety and licensing approaches of these two projects.

The subgroup will launch time dependant studies to complement the existing steady state scenarios. These studies will be started on the basis of the scenarios recommended in the previous study, and will be focused on understanding the consequences of various implementation scenarios on R&D programmes.

Other activities within the NSC related to P&T

Working Party on International Co-operation on Nuclear Data Evaluation (WPEC)

The Working Party was established to promote the exchange of information on nuclear data evaluations, measurements, nuclear model calculations, validation, and related topics, and to provide a framework for co-operative activities between the participating nuclear data evaluation projects (ENDF, JEFF, JENDL, BROND and CENDL). The Working Party assesses needs for nuclear data improvements and addresses those needs by initiating joint evaluation and/or measurement efforts. [28]

Regarding P&T, the Working Party co-ordinates activities in intermediate energy nuclear data measurements and evaluations, and also Nuclear Model Code development and validation. In addition, the Working Party produced a High Priority Request List for Nuclear Data which covers a list of data needs, especially in the energy range above 20 MeV.

Working Party on Plutonium Fuels and Innovative Fuel Cycles (WPPR)

The Working Party carries out studies on plutonium physics, together with the Task Force on weapons-grade plutonium disposition. Moreover, in responding to recent initiatives to develop new advanced reactors, the WPPR organises Workshops on “Advanced Reactors with Innovative Fuels” (ARWIRF), covering reactor core behaviour, fuel material technology of advanced reactors, and different types of innovative fuels (advanced MOX, U-free, non-oxide, molten-salts). Although the workshops are organised under the auspices of the WPPR, the scope of the workshops is wider than that of the WPPR and covers the homogeneous and heterogeneous recycling of minor actinides. The first Workshop was held at PSI, Switzerland in 1998 considering water-cooled and fast reactors, and accelerator-driven systems with fast and thermal spectra. [29] At the second Workshop held at Chester, UK in 2001, the scope was extended to include high temperature gas-cooled reactors. [30] A third Workshop will be organised in 2004.

Shielding Aspects of Accelerators, Targets and Irradiation Facilities (SATIF)

This activity consists primarily of the organisation of a series of specialists' meetings (SATIF meetings) jointly organised by the NEA, the Shielding Working Group of the Reactor Physics Committee (Japan) and the RSICC (USA). The SATIF meetings have become a suitable forum for exchanging views and sharing experiences on thin and thick target neutron yields and radiation shielding modelling (computer codes and nuclear data aspects). The SATIF group also co-ordinates benchmark exercises, exchange of data for high energy radiation dosimetry purposes, of relevance also to transmutation applications.

Radioactive Waste Management Committee (RWMC)

The interest and involvement of the RWMC in P&T activities have been rather limited so far. However, a topical session on "The potential impacts on repository safety from a P&T programme" will be organised at the meeting of Integration Group for the Safety Case (IGSC) of RWMC in November 2002 and further discussions on the subject will be held at the RWMC in early 2003. A close co-operation among NDC, NSC and RWMC is foreseen.

Summarising remarks

The OECD Nuclear Energy Agency (NEA) organises, in response to the need of its Member Countries, a well-structured programme of work in the field of partitioning and Transmutation (P&T). It will also continue to play a significant role in the co-ordination of international activities in this field of research. The involved committees within the NEA will pursue necessary activities in nuclear data, physics of P&T systems (critical and sub-critical systems), fuel cycle chemistry, material science and transmutation fuels, safety of P&T related installations, and fuel cycle impacts, etc. Due to an increasing need to evaluate the impact of advanced fuel cycles and P&T applications on radioactive waste management strategies, a closer interaction between the P&T and the waste management communities will be sought within the NEA infrastructure. Finally, the good collaboration with other international organisations, such as the EC and the IAEA, will be also pursued.

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TECHNICAL SESSION SUMMARIES

SESSION I

Fuel Cycle Strategy and Future Reactors

Peter Wydler (Switzerland) and Joo-Ho Whang (Kyung-Hee University, Korea)

Papers presented:

National and international policy papers (Korea, IAEA)	2
Overviews of R&D programmes (Czech Republic, FZK)	2
Phase-out study	1
Fuel cycle schemes (ORIENT cycle, Double Strata, CORAIL, PEACER)	4
TRU burners (Core design and optimisation)	2
Molten-salt transmuter	1
Thorium-based systems (Thorium-based LWRs, generic study)	2
Fission product transmutation	1
Total	**15**

Role of P&T on Permanent Disposal of HLW in Korea

Y-S. Hwang and J-H. Park (KAERI, Korea)

To increase the capacity of the currently considered repository, i.e. a repository for the direct disposal of the spent fuel arising from 28 operating or retired reactors by 2015, Korea develops the metallisation process by lithium reduction.

The concept allows to separate FPs with high decay heat (^{90}Sr and ^{137}Cs), which go to the salt, from the other FPs and the TRU, which form a metal ingot. The solidified salt is stored above ground until most of the activity is decayed; the metal ingot goes to HLW.

The paper describes the process and presents thermal analysis and nuclide transport results. The repository volume reduction is estimated to be 60% relative to the direct disposal concept.

It is not yet decided whether or not the process will ultimately be combined with a transmutation system.

Long-term Issues Associated with Spent Nuclear Power Fuel Management Options

J-S. Lee et al. (IAEA)

Reviews the status and trends for spent fuel management options with regard to country-dependent preferences. Notable points are:

- Today, the bulk of the spent fuel in the world is in storage. Interim storage, dry for the longer term, allows to adopt a "wait for better solution" policy based on P&T and other sustainable technologies as discussed e.g. in the Gen IV and INPRO projects.
- Non-proliferation and the limited attractiveness of single-recycle strategies have motivated countries to move from reprocessing to direct disposal strategies. However, only a few disposal projects have been finally endorsed.
- For economic reasons, the launching of P&T and similar options will depend on an increase in the future nuclear energy demand.
- Interest in regional/international co-operation may be revived.

Current Status of Czech R&D Programme in Partitioning and Transmutation

J. Uhlíř et al. (NRI Rez, Czech Republic)

In the Czech Republic, the transmutation of spent fuel from LWRs is considered as a prospective alternative to the direct disposal of the fuel. At NRI Rez, the respective R&D is focused on molten-salt transmuters using fluoride-salt based liquid fuel and pyrochemical/pyrometallurgical fluoride partitioning for the spent fuel.

Particular areas of research comprise:

- Technological research on the "fluoride volatility method" and laboratory research on electroseparation methods.
- Development of static and transient computer codes for the neutronic analysis of liquid-fuelled systems.
- Reactor physics experiments at the VR-1 and LVR-15 facilities.

The activities are embedded in EC research projects.

Overview of the P&T Activities at Forschungszentrum Karlsruhe

J.U. Knebel (FZK, Germany)

Overviews the long-term perspectives of the nuclear safety research programme at FZK with emphasis on P&T activities and reports recent technological achievements in the Karlsruhe Lead Laboratory KALLA. The activities comprise:

- Feasibility, design and scenario studies on systems with and without ADS (neutronics, thermalhydraulics, materials, safety).
- Development and study of efficient separation processes.
- Studies on heavy liquid metal technologies and related phenomena in KALLA (thermalhydraulic phenomena, corrosion and oxygen control in liquid Pb-Bi, measurement techniques).
- Participation in international projects (MEGAPIE and TRADE).

The activities are embedded in EC research projects and contribute to the network ADOPT which supports the development of a European ADS demonstrator.

Transmutation Capability of Once-through Critical or Sub-critical Molten-salt Reactors

E. Rodriguez-Vieitez et al. (UCB, USA)

Reports results of a parameter study for a graphite-moderated, molten-salt fuelled TRU burner as originally proposed by Bowman.

The variables of interest are the pitch and the diameter of the fuel channels, the feed and removal rate of the liquid fuel, and the actinide concentration in the feed. The results pertain to the optimisation of the fuel channel parameters while the other parameters are kept constant.

Under the assumptions made, important conclusions are:

- The k_{eff} peaks in the C/MS range 1 to 5 and can achieve the critical value (implies operation with an epithermal spectrum).
- For C/MS=1, the “fractional transmutation” exceeds 90%, the equilibrium actinide concentration is at a minimum and well below the solubility limit.

Detailed Phase-out TRU Transmutation Scenarios Studies Based on Fast Neutron ADS Systems

E. González et al. (CIEMAT, Spain)

Addresses the issue of the remaining fuel inventory when a reactor park is closed down.

CIEMAT has analysed the different phases of a transient LWR-ADS scenario, where the LWRs produce 100 t of TRU over a 50 year time period. The ADS is a fast spectrum, alloy-cooled system with fertile-free fuel.

It is shown that the chosen type of ADS can be used throughout the scenario, but the core has to be re-optimised to account for changes in the fuel composition.

The phase-out takes 140 to 180 years, i.e. 3 times as long as the production period of the LWR.

The evolution of the installed power, the fuel composition, the required reprocessing capacity, and the fuel losses to the repository are evaluated.

"ORIENT-CYCLE" – An Evolutional Recycle Concept with Fast Reactor for Minimising High-level Waste

N. Takaki et al. (JNC, Japan)

Proposes an all-FR system with fully closed fuel cycle and "rough removal of unnecessary material". The following categories of unnecessary material are considered:

- Cs, Sr (heat producers); they are stored until they are decayed.
- Non-radioactive FPs (60%), including strong neutron absorbers; they go to a repository for stable or low-level waste.
- LLFPs: they go to HLW (iodine is transmuted in the FRs).

The HLW can thus be reduced by an order of magnitude.

The special aqueous separation processes are described, and the neutronic feasibiliy of the multiple fuel recycling is analysed.

Analysis of Mass Flow and Cost for Double-strata Fuel Cycle

K. Nishihara et al. (JAERI, Japan)

Presents mass flows and electricity generation costs for six “fuel cycle schemes”, i.e. the LWR once-through cycle, FRs with fully closed fuel cycles, and four double strata schemes. The latter are based on the following conventional reactors: normal LWRs, LWRs with a single MOX recycle, RMWRs with multiple Pu recycle, and FR-MOX reactors. The cost data base is mostly that of the recent NEA study “ADS and FR in Advanced Nuclear Fuel Cycles”.

Result

- Comparing the double strata schemes, the LWR-based scheme features the highest cost and the FR-based scheme features the lowest cost.
- Higher mass flows to the 2nd stratum imply higher generation costs, but the RMWR-based scheme is also penalised by a large amount of reprocessing.
- The pure FR scheme and the FR-based double strata scheme feature similar costs which appear to be ~25% above those of the current LWR once-through cycle.

An Investigation of TRU Recycling with Various Neutron Spectrums

Y-N. Kim et al. (Hanyang University, Korea)

Investigates the influence of the neutron spectrum on the burning of the non-fissile TRU species and important core safety parameters (fuel Doppler, kinetic parameters) using HYPER as the reference system.

Conclusions

A reduction in core size “hardens” the neutron spectrum and hence improves the burning of the non-fissile TRU species (especially for ^{240}Pu), but leads to a deterioration of the core safety characteristics.

→ Trade-offs are necessary.

Saturation Condition and Evolution of the Nuclides for Sub-critical System Driven by Accelerator

S. Fan et al. (CIAE, China)

Reports results of a generic study aimed at investigating the evolution and equilibrium concentration of actinides in different materials (natural U, ^{232}Th, ^{232}Th-^{233}U mixtures) under neutron irradiation.

The neutron spectrum and the flux are considered as parameters.

Fully homogeneous calculations are carried out using a simplified burn-up algorithm. Based on the results, optimum parameters for different applications are recommended.

Transmutation of Long-lived Fission Products in a Sodium-cooled ATW System

Y. Kim, R.N. Hill, W-S. Yang and H. Khalil (ANL, USA)

Presents results of a design optimisation study for the transmutation of ^{99}Tc and ^{129}I in a sodium-cooled ATW system.

FP targets from metallic Tc and CaI_2, placed in ZrH_2-moderated assemblies, as well as homogeneous concepts are investigated.

Spectral sensitivity studies, followed by full core depletion calculations, were carried out to find optimum target assembly designs and target loading options.

Notable conclusions are:

- A heterogeneous loading enables higher FP burn-ups.
- Target assemblies are preferably loaded at the core periphery.
- A 1:1 ratio for the Tc and iodine assemblies is compatible with the FP ratio in the spent fuel.
- With a 5 year irradiation, consumption fractions of ~29% (Tc) and ~37% (iodine) can be achieved.
- All together 24 target assemblies can be loaded at the cost of a 10% increase in fuel inventory.

Partitioning and Transmutation of Spent Nuclear Fuel by PEACER

B-G. Park et al. (SNU, Korea)

Reports the development status of the PEACER concept which combines LWRs with critical Pb-Bi cooled TRU burners using an IFR-type fuel cycle.

^{99}Tc and ^{129}I are transmuted in a thermal neutron trap located between the fuel and the top reflector zone of the core.

A PEACER plant consists of four 550 MWe transmuters and two reprocessing units, each with a throughput of 322 t/a. Only pyrochemical processes are used, and these are designed to produce practically no HLW.

The concept has been optimised for a good support ratio (LWR-to-FR electric ratio = 2), favourable reactor safety characteristics (hypothetical core accidents have also been analysed), and good proliferation resistance (low content of Pu in fissile isotopes).

A preliminary assessment of the waste volumes has also been made.

PWR to Accelerator-driven System (ADS) Fuel Cycle Employing Dry Process

M. Iqbal, C-J. Jeong and G-H. Roh (KAERI, Korea)

Describes a Monte Carlo burn-up analysis of a Pb-Bi cooled ADS core which is designed to burn complete spent fuel from PWRs.

For non-proliferation reasons, only an oxide-to-metal reduction, but no separation process is employed. To achieve a k_{eff} of 0.97 at BOL, a similar amount of 20% enriched uranium driver fuel is loaded into the core.

Results

- The time evolution of the reactivity, the power distribution and neutron spectra are given.
- During the one-year cycle, the accelerator power increases by a factor of 3, but this could be reduced by an appropriate fuel shuffling.

Assessment of the Equilibrium State in Reactor-based Plutonium or Transuranics Multi-recycling

T-K. Kim et al. (ANL, USA)

Investigates the equilibrium state of CORAIL and other special fuel assemblies for the multi-recycling of Pu or TRU in PWRs using a special equilibrium searching algorithm.

Conclusions

- Indices for full-MOX and multi-recycled CORAIL assemblies are roughly similar.
- Additional MA recycling reduces waste radiotoxicity significantly, but leads to very high decay heat and neutron source strength levels of the fuel.
  - → Further studies needed to determine practical number of recycles.

Use of Thorium for Transmutation of Plutonium and Minor Actinides in PWRs

E. Shwageraus et al. (MIT, USA)

Reports results of a parameter study aimed at the investigation of Pu and MA destruction rates in Th-based PWR fuel. The analysis is performed at the pin-cell level, using the CASMO4 code.

Regarding TRU destruction, important conclusions are:

- Destruction rates of ~1 000 kg/GWe-a and residual TRU fractions of ~50% per fuel pass are reasonably achievable for optimised, denatured fuel elements. However, the TRU destruction arises mainly from the burning of Pu.
- To achieve these values, the H/HM ratio has to be increased with respect to that of a normal PWR. This is also beneficial from the reactivity coefficient and reactivity control viewpoints.

SESSION II

Progress in Partitioning and Waste Forms

James Laidler (ANL, USA) and Jean-Paul Glatz (ITU, Germany)

Papers presented: **19**

Overview (*J-P. Glatz*):

Regarding MA partitioning, major progress was presented by U.S., Russia and Japan.

In Japan a simplified PUREX is proposed with co-extraction of U, Pu, Np to be combined with

- TRUEX where salt-free reagents such as hydroxylaminenitrate are used to reduce waste volumes;
- TODGA in the so called ARTIST process aims at discrimination between tetra- and hexavalent Ans;
- Pyroprocessing where large scale deposits of Pu-MA by electrodeposition in liquid Cd and engineering scale casting of Zr based fuels are tested.

In Russia the DOVITA process initially foreseen to fabricate FR fuel by the vibropack technique is now extended to MAs. Irradiation of Np and Am fuels are irradiated and should be extended to higher MAs. Reprocessing of the MA fuels seems to be still somehow problematic.

In the US P&T developments are driven by the wish to avoid in any case the construction of a second spent fuel repository. A dual tier strategy is proposed. In the first tier Np/Pu are recycled in LWRs, in the second tier remaining Np/Pu and other MAs are burned in a fast spectrum combined eventually with ADS. Reprocessing includes DIAMEX/SANEX for MA separation and also Cs/Sr separation. A decision on the process scheme should be made in 2006 and deployment is expected for 2015.

As far as the problematic An/Ln separation is concerned, the following progress was made:

- For aqueous techniques
  - Two of the most promising molecules were compared at FZK-INE. A slightly better performance of BTP over derivates of DTPA was found, the latter has however a better transfer rate. A new small hollow fibre module gave a good separation from Ln with a recovery rate better than 99.95%.
  - At ITU it was shown that a direct selective extraction of MAs from the PUREX raffinate is possible.

  - In CEA derivates of BTP were synthesised with very good hydrolysis stability, glycolic acid improves significantly the back extraction. Only the radiation stability needs to be further improved.

- For the pyro-techniques
  - The use of solid cathodes (Al) allows to achieve an efficient Ln/An separation due to larger differences in the electrodeposition potentials in comparison to liquid Cd or Bi cathodes. Basic thermodynamical and electrochemical data should further enhance the performance of these processes.

The problem of long-lived fission products was addressed several times during the meeting. A flowsheet optimisation, i.e. in the TRUEX process, is proposed. Also new techniques and technologies such as catalytic electrolytic extraction could solve the problem without producing secondary wastes.

If metallic pyroprocessing and oxide fuels are selected in a P&T strategy, conversion processes are required. LiO_2 is one solution proposed, in the future direct electroreduction could be a promising alternative. Fluoride volatilisation of U is completed by electrodeposition in view of a molten-salt reactor development. Alternatives are F_2 and HF; direct solid-gas interaction seems to be more efficient.

As far as the waste issue is concerned, it has to be addressed whether partitioning and transmutation or partitioning and conditioning are adopted. Pyrochlores are proposed as host materials for both MAs and long-lived fission products.

The clean-up of molten-salt after pyroprocessing could happen through a pyrohydrolysis process using the vacuum distillation technique. The process was demonstrated using a Zr surrogate as stand-in material for MAs.

Finally one should mention the safeguards issue, which was briefly discussed during the session. It became evident, that for advanced aqueous and especially pyro-techniques new safeguard regimes have to be developed. In general the tendency is even for the PUREX process to make the schemes less attractive to proliferation, knowing well that an absolute proliferation resistance does not exist.

Technical paper summary (*J. Laidler*)**:**

Dr. Shishalov of SSC/RF-RIAR presented a paper describing progress over the past ten years in the DOVITA programme. This system utilises the Dimitrovgrad Dry Process (DDP) for spent oxide fuel treatment and a vibratory compaction method for recycle fuel fabrication. Dr. Shishalov presented a wealth of information regarding recycle fuel performance and experimental details. The recycle fuel tested has included both $(U, Pu)O_2$ and $(U, Pu, N_p)O_2$, and irradiated fuels from both BOR-60 and BN-600 have been processed. A number of fuel rods totalling about 25 kg HM have been recycled to the BOR-60 reactor.

Dr. Yokoo of CRIEPI (Japan) described their work with recovery of uranium and plutonium from a simulated LiCl-KCl salt mixture, using a liquid cadmium cathode. They have progressed to the point at which the actinide solubility in Cd has been exceeded, a very important step in establishing an industrial-scale electrochemical process for metal fuel treatment. He observed the formation of Ucd_{II} and $PuCd_6$ intermetallics and reached 50 wt.% concentration of heavy metal in the cadmium. He also described CRIEPI work with the injection casting process for metal fuel slugs, showing that multi-use of quartz molds has been achieved with acceptable dimensional variances in the fuel slugs.

Dr. Laidler of ANL described the U.S. programme for advanced separation technology development under the scope of the new Advanced Fuel Cycle Programme. He showed that the programme has two major elements, one directed toward the treatment of commercial LWR spent fuel by 2015 and the other related to the ultimate elimination of minor actinide residues, for the purpose of radiotoxicity reduction. Both programme elements are integral to facilitating spent fuel management in the U.S and together are expected to preclude the need for a second geologic repository. This concern, together with the large number of LWR plants in operation, tend to drive the U.S programme.

Dr. Glatz of the JRC of the EC discussed work at the ITU on the treatment of high active raffinate (HAR). The DIAMEX-SANEX combination of aqueous processing is successful at recovering 99.9% of the Am and Cm in the HAR, and the work has been extended to consider volume reduction of the HAR to produce a High Active Concentrate (HAC) that will enable the use of more compact, and hence less expensive, process equipment. He showed that it is essential to control the concentration factor (CF) to avoid the precipitation of Mo, Zr and lanthanide fission products. He also described what may prove to be a breakthrough in electrochemical separations. Rather than achieve improved separations by adjusting the electrolyte composition, the JRC group obtained a broader voltage discrimination band by varying the composition of the cathode. Using an Al cathode, they were able to achieve good uranium purity in the deposit.

Dr. Hirano of JNC described their research with the SETFICS variation of the TRUEX process, and Dr. Jun-Bo Shim of KAERI discussed excellent and extensive cyclic voltammetry studies aimed at clarifying the behaviour of the lanthanides Nd and Gd in a FLINAK salt.

The KAERI group reported on some valuable insights into the mechanism for electrochemical reduction of UO_2, in a LiCl salt containing a small amount of Li_2O. When lithium oxide contacts UO_2 in the cathode crucible, Li_2O is reduced to metallic lithium and the Li reacts with UO_2 in a replacement reaction to produce metallic U. Reasonable conversion efficiencies have been achieved, but a number of materials issues (both anode and cathode) have been identified. Pyrolytic carbon seems to be a good choice for the cathode.

The Nuclear Research Institute of the Czech Republic is working on an electrochemical process that they propose to use as a supplement to the fluoride volatility process for removal of residual uranium from PWR or FR spent fuel, using FLINA and FLINAK electrolyte salts.

A team from FZK reported on some specialised extractions at very small scale using miniature hollow polypropylene fibers, as a continuation of work reported two years earlier at the Madrid meeting. The miniaturisation allowed them to work with very small fluid volumes, and they obtained excellent Am-Ln separation with BTP in a surrogate Am-La-Gd-Y acid solution.

Dr. Tachimori and colleagues at JAERI described the ARTIST process, which uses advanced amide-based extractants to separate actinides from fission products. The separation produces two streams, U- and TRU-bearing phases that are then solidified and stored for future treatment.

Dr. Fujii and his co-workers from Kyoto University described work with the TRUEX process, evaluating extraction performance as a function of the acidity of the feed solution.

SESSION III

Progress in Fuels and Targets

Yasuo Arai (JAERI, Japan) and Sylvie Pillon (CEA, France)

Papers presented:

Papers covered research areas from fuel preparation and basic properties, fabrication processes, irradiation program to design and modelling calculation.

Papers covered chemical forms from alloy, inter-metallic dispersion, oxide (pellets, VIPAC), nitride, molten salt to FP target (Tc and I).

Russia	2
USA	1
Netherlands	2
France	3
Japan	2
Korea	2
Total	**12**

Highlight of preparation and basic research

Akabori et al. (JAERI, Japan)

- Preparation of oxide-free (Am,Zr)N and (Am,Y)N by carbothermic reduction.
- Thermal property (thermal expansion, specific heat) of Tc-Ru alloy.
- Preparation and compatibility test of CuI and $Ca(IO_3)_2$.
- Construction of new facility TRU-HITEC for gram-order test of ^{241}Am.

Ignatiev et al. (RRC-KI, Russia)

- Transport properties of Na,Li,Be/F and Li,Be,Th/F for MSB (Molten-salt Burner Reactor).
- Viscosity, thermal conductivity, phase transition behaviour, heat capacity, density and thermal expansion.
- Comparison of obtained data with previous ones, such as obtained in ORNL.

Highlight of irradiation test program

N. Schmidt et al. (CEA, France)

- Transmutation of MA-targets in FR (high neutron flux), but in spectrum locally moderated.
- Sample preparation and modelling calculation before start of irradiation (Phenix).
- ECRIX: AmO_X micro-dispersed in MgO.
- CAMIX n°1: (Am-YSZ) solid solution.
- CAMIX n°2: (Am-YSZ) micro-dispersed in MgO.
- COCHIX n°3: (Am-YSZ) macro-dispersed in MgO.

Y. Arai et al. (JAERI, Japan)

- Start of irradiation test of (Pu,Zr)N and PuN+TiN at JMTR.
- Preliminary results of PIEs of (U,Pu)N irradiated at JOYO.
- Progress of pyrochemical process for treatment of MA fuel.

F.C. Klaassen et al. (NRG, Netherlands)

- Speculation from extensive irradiation tests of $MgAl_2O_4$ -IMF at HFR.
- EFTTRA (for incineration of Am) and OTTO (for Pu).
- Its chemical property and thermal conductivity are good, but
  - large volumetric swelling is observed : amorphisation and He production;
  - instability under irradiation makes very doubtful.

S. Pillon et al. (CEA, France)

- From the THERMHET in Siloe and MATINA1 in Phenix: $MgAl_2O_4$ swells at $T < 1\,200°C$ by amorphisation: abandon.
- MgO is the reference inert matrix: T5, MATINA 2/3, CAMIX-COCHIX.
- Irradiation project of different dedicated fuels (nitride/metal/oxide) in Phenix.

R. Schram et al. (NRG, Netherlands)

- Results of irradiation tests of $MgAl_2O_4$ + 11 wt% AmO_2.
  ==> significant swelling (He, amorphisation).
- New ideas: He should be released from the target in early stage of irradiation: porosity control, increasing Pu content to raise temperature.
- New candidates: $(Am, (Pu) Zr, Y)O_2$, $Am(Pu)_2Zr_2O_7$, $(Am, Zr, Y)O_2$ +metal or MgO.

O. Shishalov et al. (RIAR, Russia)

- Synthesis by pyroelectrochemistry of (U, Np)O_2 / 5% NpO_2).
- Granulation and vibropacking.
- Irradiation in BOR-60 (2 pins)
  - BU>13.7 at%
  - BU>20 at%.
- Very good behaviour, similar to UO_2 and (U, Pu)O_2.

Highlight of design and modelling calculation

J. Laidler (ANL, USA)

- Function and required fuel performance described.
- Long-term development program:
  - Phase 1: Screening and selection of fuel (completed)
    ==> metal and nitride.
  - Phase 2: Concept definition and feasibility (started), including irradiation examinations.
  - Phase 3: Design, implement and evaluation.
  - Phase 4: Fuel qualification and demonstration.

Lee et al. (KAERI, Korea)

- Modelling of alloy fuel (TRU-Zr and U-TRU-Zr) and inter-metallic dispersion fuel ((TRU-Zr)-Zr and (U-TRU-Zr)-Zr) performance at HYPER.
- Temperature profile, swelling/FGR behaviour (with and without contribution of He) and cladding (HT-9) deformation calculation at burn-up progressing.
- Preliminary design of the fuel rod and burn-up limit under several conditions are evaluated.

S. Pillon et al. (CEA, France)

- Design of moderated assembly for once-through strategy.

Highlight of fabrication study

S. Pillon (CEA, France)

- Proposal of flowsheet for fabrication of (Am,Cm)O_2+MgO target after partitioning process to assembly mounting stage in technological scale.

- But technical feasibility of the fabrication process is far from demonstration stage, because of high decay heat and neutron emission mainly from Cm.
- Innovative processes for remote handling and hot cells are requested (simple, robust, compact and dust free processes): sol-gel/infiltration (ITU), VIPAC (RIAR).

B-S. Lee (KAERI, Korea)

- Dispersion type (U-10%Zr)-Zr and alloy-type U-Zr fuels were fabricated and characterised.
- A centrifugal atomisation method was adopted for fabrication of metal and alloys particles.

Conclusions (progress since last meeting)

- Completion of the PIE irradiation tests (T4, MATINA1, THERMET, RIAR programmes)
  - $MgAl_2O_4$ is abandoned, MgO is still the reference matrix;
  - Macrodispersed fuel is promising for the high BU objective;
  - VIPAC $(U, Pu, Np)O_2$ fuel runs very well as $(U, Pu)O_2$.
- New irradiation tests for transmutation are carrying out and planned
  - T5 for new concepts testing (Pu-based target, porous targets, optimised actinide compounds);
  - CAMIX-COCHIX (optimised actinide compounds, microstructure);
  - FUTURIX (comparison of different TRU fuels in representative and similar conditions).
- Experimental study on fuel containing Am has proceeded for a few years, although still in a laboratory scale.
- However, there are still open questions:
  - Behaviour of He during irradiation: preference for releasing it (high temperature operating, porous fuel).
  - Selection of inert matrices: $MgAl_2O_4$ dropped, still MgO (to be proved), metallic matrices: steel, Mo?
  - Chemical form for transmutation of ^{129}I.
  - Processing with Cm: VIPAC/SPHEREPAC.
- Metallic fuel vs ceramic fuel (nitride, oxide).
- International collaboration is essential for further development. Effective usage of fabrication facility (inauguration of MA-lab, ITU), reactor (restart of Phenix, beginning of 2003), PIE facility and compilation of previous data.

SESSION IV

Progress in Materials: Spallation Targets and Advanced Coolants

Guenter Bauer (FZJ, Germany) and Joachim Knebel (FZK, Germany)

Papers presented:

Four papers submitted from Germany-Korea, Germany-China, USA-Russia, Switzerland-France-Italy-Germany and six papers from Italy, Germany, Spain, India, Belgium, and USA

Total	**10**

Overall theme of work presented

Provide validated data and tools in the area of

- materials,
- thermalhydraulics,
- engineering design,

to enable the design of ADS components, mainly the spallation target.

Approach chosen

- Fundamental experiments and physical model development
  - corrosion experiments in controlled environment;
  - irradiation experiments including Russian ADS steels;
  - thermalhydraulic measurement techniques for Pb-Bi;
  - supporting thermalhydraulic experiments & calculations.
- Applied large scale experiments
  - CIRCE at ENEA, KALLA at FZK, other.
- Design validation of spallation targets
  - next generation spallation source projects (ESS, SNS, JSNS);
  - international MEGAPIE initiative;
  - VICE experiment in support of MYRRHA.

Target design options

- Closed / open spallation target system.
- Windowless option:
  - flow configuration at surface;
  - evacuation of vacuum space;
  - retention of volatile spallation products.
- Solid window option:
  - coolability and flow shaping;
  - radiation effects including gas production;
  - corrosion / erosion / cavitation issues.

Status and next steps

- Status:
  - scientific work is at a very advanced stage;
  - strengthen interdisciplinary interaction;
  - international collaboration have proven to be very effective.
- Next steps:
  - build-up of common data base;
  - build-up of common design tools;
  - define design standards and criteria.

Status and future

Emphasise international projects such as MEGAPIE and MYRRHA to realise an international ADS in the near future.

SESSION V

Progress in Physics and Nuclear Data

Toshitaka Osugi (JAERI, Japan) and Enrique Gonzalez (CIEMAT, Spain)

Papers presented:

Studies of basic physics processes on ADS	4
Reactor-based integral experiments for cross-section and basic nuclear data validation and measurements	2
Differential accelerator-based experiments for cross-section and basic nuclear data measurements	3
Development of specific measurement techniques	2
New simulation tools for ADS and transmutation systems	3
Studies of transmutation scenarios and devices	2
Total	**16**

Studies of basic physics processes on ADS

First Measurements of the Kinetic Response of the MUSE-4 Fast ADS Mock-up to Fast Neutron Pulse
D. Villamarin (CIEMAT) et al.

Determination of Reactivity by a Revised ROD-DROP Technique in the MUSE-4 Programme – Comparison with Dynamic Measurements
G. Perret (CEA) et al.

Investigation of Local Spectral Differences between Critical and Driven Sub-critical Configurations in MUSE-4
M. Plaschy (PSI) et al.

MUSE-4 Benchmark Calculations using MCNP-4C and Different Nuclear Data Libraries
N. Messaoudi (SCK-CEN) et al.

- Wide spectrum of ADS physics tests performed on MUSE.
- New experimental results both on Spectral index and on Kinetic response will improve our understanding of ADS.
- Development of reactivity monitoring and measuring techniques.
- Experimental base for advanced computer simulation benchmarks in the ADS research.

Reactor-based integral experiments for cross-section and basic nuclear data validation and measurements

Calculation and Experimental Studies on Minor Actinides Samples Irradiations in Fast Reactors
A. Kotchetkov (SSC IPPE) et al.

Experimental Studies of MA Nuclear Data Correction on Critical Assemblies
V. Doulin (SSC IPPE) et al.

- Large programme of integral test and validations on BN-350, BOR-60 and BFS.
- Combination of fission chambers, radiochemical analysis and other special methodologies.
- Covering many very relevant Np, Pu, Am and Cm isotopes.
- Already existing data base of experiments to be used for cross-section benchmarking and updating.
- New measurements in preparation to complete the studies for transmutation purposes including attention to Pb-cooled cores.

Differential accelerator-based experiments for cross-section and basic nuclear data measurements

HINDAS, a European Nuclear Data Programme for Accelerator-driven Systems
Arjan Koning (NRG) et al.

Light Charged Particle Production Induced by Fast Neutrons (E_n = 25 – 65 MeV) on ^{59}Co and ^{nat}Fe
E. Raeymackers (UCL) et al.

Neutron Cross-section for P&T and ADS at the n_TOF Facility at CERN
E. Gonzalez (CIEMAT) on behalf of the n_TOF collaboration

- Measurements covering the full energy spectrum from thermal to 200 MeV.
- Two large collaborations supported by the 5th FWP of EU.
- New data specifically relevant for ADS design has been and being measured using a variety of European facilities.
- The list of isotopes includes actinides, fission fragments, coolant and structural materials.
- The projects combine experimental measurements and model development with cross-section evaluation.
- Proposal to complete the work are in preparation for the 6th FWP of EU.

Development of specific measurement techniques

Feasibility Study of New Microscopic Fission Chambers dedicated for ADS
M. Fadil (CEA) et al.

The Use of Ge Detectors for (n,xn) Cross-section Measurements at Intense and Low Frequency Pulsed Neutron Beams
Strahinja Lukic (IN2P3/CNRS) et al.

- Specific needs of ongoing and planned integral and differential experiments and mock-ups require new detectors and measuring techniques.
- New µFCs chambers developed for the particular MegaPie target conditions, will allow on-line experimental determination of both thermal and fast components of the neutron flux, including their time- and space-variations.
- Adapting Ge detectors, and its associated electronics, to work on-line in installations like n_TOF (CERN) will allow to perform precise measurements of (n, xn) reactions on future coolant and transmutation fuel isotopes.

New simulation tools for ADS and transmutation systems

The Physics Problem of the Spallation Neutron Production Source Related to Accelerator-driven System
S. Fan (CIAE) et al.

New Methods for the Monte Carlo Simulation of Neutron Noise Experiments in ADS
M. Szieberth (Budapest University) et al.

Nuclear Data for ADS: Code System and Theoretical Data Library (full paper not available)
S. Yavshits (KRI) et al.

- New version of SHIELD with improved capabilities for spallation source simulations.
- MC and deterministic codes are being adapted to handle in a more efficient and flexible way the kinetic aspects that have gain relevance in the ADS associated reactor physics.
- Two codes, MCFx and TALYS, are being developed to compute from basic physics (and some adjustments to data) the differential cross-sections for the most relevant reactions taking place on transmutation devices (ADS or critical reactors). They will be important tools for cross-section evaluation.

Studies of transmutation scenarios and devices

Minor Actinides Transmutation Scenario Studies with PWRs, FRs and Moderated Targets
J.P. Grouiller (CEA/DEN) et al.

Reactor Physics Calculations on MOX Fuel in Boiling Water Reactors (BWRs)
C. Demazière (Chalmers University of Technology)

- Studies proposing transmutation based on the closest to existing technologies including thermal LWR.
- The proposals handle in specific ways the different component of the HLW from LWR and show the difficulties to handle some components of these wastes.

Concluding remarks

The contributions to this session show that if all the efforts worldwide on the R&D for transmutation and ADS are put together, it is possible to obtain a coherent and rather comprehensive development framework:

A) The experiments on basic physics processes in mock-ups of Transmuter/ADS and the associated simulation benchmarks allow to develop the correct concepts to understand these systems and allow to identify the needs and deficiencies of the presently available nuclear data.

B) A combination of reactor based integral experiments and differential accelerator-based experiments, using new specific measurement techniques, should provide the cross-section and basic nuclear data required as well as the models needed to predict non-measured data.

C) These efforts are, and will continue, leading to new simulation tools for ADS and Transmutation systems (models, data and programs), that are then used to optimise the proposals for elements of transmutation scenarios and devices.

Lets keep exchanging experience and knowledge and developing even closer collaborations, using in particular experimental data driven benchmarks within the OECD/NEA and IAEA Agencies.

SESSION VI

Transmutation Systems (Critical and Sub-critical): Design and Safety

Luciano Cinotti (Ansaldo, Italy) and Stuart Maloy (LANL, USA)

Papers presented:	**19**

Most papers are related to reactors at conceptual or preliminary design stage in critical or subcritical configuration, intended to fission actinides and to transmute long-lived fission products: it appears that a great number of options are still under evaluation and that accelerator-driven test facilities are proposed for construction in the short term, relying as much as possible on existing installations.

Safety of accelerator-driven systems has also been largely dealt with in several papers.

The following basic options/topics have been considered in the session:

Neutronic

Reactors in critical as well as subcritical configuration have been presented, in general with fast spectrum. An approach to the determination of the operational subcritical level of an 80 MW lead-bismuth-cooled, pool-type ADS has been proposed, which, basing on the results of the safety analysis, excludes criticality while demanding reasonable accelerator performances.

Primary coolant

While Pb-Bi is the preferred target material, it is also mostly selected as the primary coolant for the subcritical reactor. Use of Pb-Bi as well as Na, gas or molten salts is proposed for critical reactors.

Fuel

Proven MOX fuel is proposed for Demo Plants. More advanced fuels are also considered and their potentialities investigated: metallic thorium-based fuels, mixed uranium-transuranics carbide, molten-salts containing Pu and MA, nitride fuels.

Target

Liquid Pb-Bi or solid tungsten cooled by sodium are under consideration as the target material.

Pb-Bi is proposed both for the window and the windowless target units.

The window target unit is the reference solution worldwide. In Europe, however, two Pb-Bi cooled ADS designs propose the windowless target unit, a solution which exempts from the need to develop and test materials able to withstand irradiation from high-energy protons.

Power level

Power level ranges from the 40 MW of MYRRHA and the 80 MW of the eXperimental Accelerator-Driven System (XADS), currently under study in the frame of the 5th European Framework Programme, to the 100 MW of the Accelerator-driven Test Facility (ADTF) proposed in the frame of the U.S. Advanced Accelerator Application (AAA), and to the 1 000 MW of the Korean Hybrid Power Extraction Reactor (HYPER).

Safety aspects

A comparative analysis between Na and Pb-Bi cooled reactors shows the advantage of the Pb-Bi in case of unprotected loss of flow scenarios, indicating that with a proper design it would be possible to provide sufficiently high natural circulation cooling capability of the reactor core to prevent cladding and fuel overheating. This is confirmed by the safety analysis made on the basis of a detailed plant design and RELAP model simulations presented for the 80 MW European PDS XADS cooled by Pb-Bi.

Design aspects

In USA emphasis is put on the spallation target technology. In Europe a great effort is being made on the system integration of accelerator, target unit and sub-critical system: in particular the impact of the Target Unit on the Core and Primary System design as well as on the Fuel and Primary Component Handling System is object of detailed study.

Future (short-term) experimental facilities

Two papers propose facilities (SAD and TRADE) able to provide in short term valuable data for implementation in large-scale designs.

SAD can make use of an existing accelerator and can provide fast neutron flux, but no reactivity feedback owing to the low power density (big core and low power, ≈20 kW).

TRADE can make use of an existing core, and cannot provide fast flux, but reactivity feedback can be tested. In TRADE, experimental investigations can be performed over a wide range of core power (till about 0.5 MW) and sub-criticality from in “source dominated” deeply sub-critical configurations to “core dominated “ near criticality configurations when the standard feedback effects are dominant.

PANEL DISCUSSION SUMMARY

Perspectives for the Future Development of P&T

Chairs: T. Mukaiyama (JAIF, Japan) and J. Laidler (ANL, USA*)*

Panelists:

Takehiko Mukaiyama (JAIF, Japan), James Laidler (ANL, USA), Chang-Kue Park (KAERI, Korea), Toshitaka Osugi (JNC, Japan), David Hill (ORNL, USA), Peter Wydler (Switzerland) and Joachim Knebel (FZK, Germany)

Each panellist made a presentation on perspectives for the future development of P&T. These presentation were followed by a general discussion involving all participants. Summaries of the presentations made by the panellists and highlights of the open discussion are given below.

Presentations of the panellists

Dr. T. Osugi (JNC, Japan)

First of all, I would like to emphasise the needs for international collaboration in the development of P&T systems. If we look at the long-term programme for P&T, using ADS, we mainly have to consider three fields of P&T. They are partitioning, fuel technology, and ADS technology. For partitioning, improvements in processes will be realised by 2010, and an engineering scale development will be pursued for a pilot plant construction in between 2020 and 2030. Concerning the fuel technology, fabrication tests of minor actinide (MA) nitride fuels and irradiation tests in reactors will be performed before constructing a pilot plant. At the same time, the ADS technology, including sub-critical system, spallation target and accelerator issues, will be developed and improved.

The development of ADS technology, we can be divided into three steps. The first step is being performed on a voluntary bases, using existing facilities, such as FCA, MUSE-4, MEGAPIE, and TRADE. The second step is to undertake experiments, using unique facilities, dedicated to ADS. They could include TEF-P, TEP-T, Myrrha or other future facilities that can also be used for fuel irradiation tests for ADS. These experiments are needed to realise the ADS, especially for the construction of a demonstration ADS. The final step will be the construction of a proto-type ADS plant. I do not yet know exactly what it would look like. For all that, I would like to propose a kind of "**Mailing Network System**" to exchange information of the facility specifications and to discuss ideas for the design of the next facilities. I think we really need a mailing network system as a first step to a close international collaboration for a prototype ADS plant. And time is now!! Thank you very much.

Dr. C-K. Park (KAERI, Korea)

Let me begin with reviewing the last ten years of P&T studies and what we have achieved during this period. As you may know, since I'm not directly technically involved in this area, this is what I believe you have been doing.

Please understand that this is my personal view. There are two roadmaps – one US and one EU. I think it is very important to know where you are going and what obstacles you would expect on the way. Another significant achievement, I think, is the OECD/NEA report "A Comparative Study on ADS and Fast Reactors in Advanced Nuclear Fuel Cycles". Through these efforts, there seems to be **some technical convergence on the reactor types, fuel and corresponding coolants**. You would like to have a dedicated burner with fast neutron spectrum, instead of utilising existing LWR's or liquid metal reactors for the transmutation. As a coolant, you may have lead-alloy or sodium. There are three fuel types – metal, nitride and oxide. You would like to have a pyro-process as a main recycling scheme with aqueous processes as a backup.

On the other hand, let me briefly mention the international collaboration programmes. The international programmes, I believe, have been component based rather than system based. And the co-operations were between institutions and between programmes, rather than between countries. They have occurred on a very regional basis.

Now, what are you going to do for the future? The environment has changed. So far, studies on P&T are based on a fuel cycle strategy where LWR is the major reactor type, but this will probably not be the case in the future. There are multinational multilateral nuclear system development initiatives for the next generation recators. As you know, there is the Generation IV initiative led by ten countries and the INPRO initiative led by the IAEA. I have to emphasise here that **these efforts are for new nuclear systems, including both reactor and the fuel cycle, rather than just the reactor development**. As you may know, the Generation IV programme is aiming at around 2030 for initial deployment. There are six Generation IV candidates with strong emphasis on sustainability, safety, economy and proliferation resistance and physical protection. I believe the R&D scope for these candidate systems will soon be available. Many technologies that we have been developing in this area are overlapping with these future reactor systems, especially the sodium or lead alloy fast reactors. The Generation IV and INPRO programmes are based on **government-level agreements**. With these environmental changes in mind, I would like to conclude my comments by the following two points. First, we have to look very carefully at the roles of P&T systems once again and decide when we are going to need them, and second, how we are going to achieve our goal in the framework of either Generation IV or INPRO. For both points, the two roadmaps that I already mentioned would be a big help. Thank you.

Dr. J. Laidler (ANL, USA)

I am going to emphasise the fuel cycle issues and I hope to stimulate some responses with some of the proposals that I will present.

In future developments, related to the fuel cycle, I propose that we address in some detail the **development of fabrication methods for minor actinide bearing fuels**. I think you will probably realise, if you look into it, that we just don't have a reasonable process at the moment for fabricating those fuels in a way that reduces the amount of waste generation or losses of material.

We need to operate at low sintering temperatures, perhaps by using cermet fuels produced by the infiltration methods that you've heard of. We can perhaps use external gelation processes to fabricate the fuel particles and I would also submit that we maybe should look at cermet fuels that are dispersions of oxide in metal. We should in addition consider the innovative fabrication techniques, such as vibratory compaction (VIPAC) processes and perhaps other more advanced techniques. I think the conventional present sintered pellet fuel fabrication method is not going to be economical, if we are dealing with minor actinides that are very high heat generators and create high radiation levels, especially after multiple recycling.

We need to look at the issue of whether it is necessary to separate americium from curium, for the purpose of storing curium for a period of decades to avoid the complications that it presents in fabrication.

In addition, I repeat the plea that I present virtually at every one of these meetings and that is: we absolutely need **a consensus set of international criteria** on what sort of parameters should to be imposed upon the separation processes, upon the fabrication processes, as far as purity of products, as far as recovery efficiencies, as far as losses of waste are concerned. We've tried to do this within various international bodies. The US programme now, the Advanced Fuel Cycle Programme, is beginning to develop its own set of criteria and we certainly would like to get some international participation. We also need to look at the feasibility of inserting minor actinide targets in a heterogeneous way in fast reactor systems. Is this a feasible approach?

I also submit that it's necessary to establish **a role for pyrochemical separations**. As one who has been involved in pyrochemical separations work almost from the beginning, I must say that it is misinterpreted as the answer to all of our dreams. It is not necessarily that. It may be very appropriate in certain applications and very inappropriate in other applications, and if we persist in trying to oversell this technology, then I think we'll find that we create more problems for ourselves than we create solutions. Pyrochemical separations are probably well advised for metal fuels and probably for nitride fuels. They may be useful for coated particle fuels and for inert matrix oxide fuels, if the matrix happens to be a material that's difficult to dissolve in nitric acid.

I think we should look at **processes such as UNEX**, single processes, which do a complex separation. This is one of them. There are other possibilities, but we need to look at efficient systems for separating actinides, lanthanides, cesium and strontium and other fission products.

Further, we should be open to the **development of hybrid systems, which are combinations of aqueous and non aqueous systems** to exploit the best features of each one of those methods and maybe a different combination for different fuel systems, but we have to facilitate among other things the removal and separation of the minor actinides from the lanthanides.

Finally, we need to be very sensitive to the **economics of the systems**. We cannot afford to have somebody make an unwise decision as far as the deployment of a process, which proves to be totally uneconomical, because this is a very small world and if one of us makes a stupid decision, it is going to impact everybody.

Dr. D. Hill (ORNL, USA)

I'm afraid this is going to sound like a conspiracy. In common with Dr. Park, I have to advise you that this is a personal view.

I spend a lot of time talking to members of the US government trying to convince them that they need to make investments in what I'll call fuel cycle R&D, as opposed to partitioning and transmutation. The question on my mind is "**Is there a viable alternative to long-term storage of spent fuel and/or minor actinides**?" But if you're a government official, that is part of a larger question. The larger question, which they're wrestling with today, is "what is the role of nuclear power and nuclear energy in the future energy supply". We, in the R&D community and in DOE as well, have evolved two initially separate but converging approaches. First, to understand the future role of nuclear energy, we asked what are the nuclear systems for the future? Criteria were set up and an international study was done (commonly known as Generation IV). The second question is: what can we do with spent fuel today? The role of partitioning and transmutation, to help Yucca Mountain utilisation, has become a key question in the current incarnation of advanced fuel cycle issues.

The comment to be emphasised here is, as best as I can remember, quoted directly to me by a senior member of the administration, who tried to explain why he should not be investing the government money in partitioning and transmutation. He said, "We don't have a fuel cycle problem, we have a reactor problem. We are not building reactors in the US". With the current reactors I can guarantee you that with Yucca Mountain, with some modest expansion, I can store the spent fuel. I don't have a fuel cycle problem.

Now, in my first viewgraph I emphasise the word viability. I'm going to just replay a couple of things you've heard from Dr. Jim Laidler. We need, as a community, **solid performance criteria**. When I go in and talk to a government official, he would say, what are you going to do? How much will it cost? How much R&D? And even if you are successful, how will it be implemented? When will R&D give me an answer? The US government is sceptical about the value of fuel cycle R&D. It won't stay convinced unless clear priorities are chosen, together with time scales. I don't like to depress you but this is what it looks like trying to generate a programme for what is a crucial question. Remember the question is really, in one form or another, what is the long-term future of nuclear power? The key to answering that question, as I think everybody is aware, lies in technologies for fuels and separations. The US programme is formulated for the coming year in two main areas. One, which is asking the question what can you do with the 100 or so PWRs in the US. They are going to be around for a long time and they are almost all going to have life extension. Is there anything rational you can do with thermal neutrons? And the second part of the programme is cast in the Generation IV context. It's making the link explicitly that Dr. Park alluded to. The other part of what we call the advanced fuel cycle initiative is being closely coupled now with the Generation IV programme.

Now, as Dr. Laidler said, we are a small community, we are small especially in the size of budget related to the magnitude of the problem. So, **we have to prioritise**. Now, the US will prioritise on its basis of what's important to the US, other countries will prioritise differently. Another issue important in the US is **practicality** – how do you imagine transmutation being implemented in the deregulated energy market. You burn an actinide, it generates power. The government in the US is not in the business of selling power. So how do you implement? What are the financial and economic incentive structures you set in place to get this to operate?

The state of the art, as described this week, is that we have more questions than answers. Almost every type of concept is still under consideration somewhere, and I agree completely with Dr. Park – **international co-operation, not at the micro scale, but at the macro scale is essential**. This is the only way we are really going to make progress – before, frankly, governments lose enthusiasm. I've never met a government yet that's willing to promote R&D with no particular outcome for an indefinite period.

Dr. P. Wydler (Switzerland)

agrees that, **in the future, the available R&D funds will have to be concentrated more effectively on the most promising concepts.** He would also like to draw the attention of the audience to the respective conclusions of the recently published NEA study “Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles – A Comparative Study”. This study assessed the technological challenges of P&T in general and the ADS in particular, and it prioritised the needed R&D with respect to a representative set of fuel cycle strategies.

The table below summarises the R&D priorities for three transmutation strategies using fully closed fuel cycles. The strategies comprise the burning of the transuranic elements discharged from LWRs in IFR-type fast reactors (TRU burning in FR), the fast-spectrum accelerator-driven systems (TRU burning in ADS), and the Double Strata strategy initially proposed by Japan.

R&D area		**TRU burning in FR**	**TRU burning in ADS**	**Double strata**
Reactor	Accelerator		++	++
	Target		+++	+++
	Sub-critical core		+	+
Reprocessing	Urex for LWR-UOX	+	+	
	Purex for FR-MOX			+
	Pyro	+	++	+++
Fuel fabrication and testing	Oxide			+
	Nitride			+++
	Metal	++	+++	
Waste management	New waste forms	++	++	++
	Repository performance	++	++	+

Priority: + medium; ++ high; +++ very high

In the executive summary of the NEA report, the R&D needs are summarised as follows:

- *For the advanced systems in general:*
  Basic R&D in the fields of neutronics, liquid metals (mainly Pb/Pb-Bi), structural materials, fuels, and their reprocessing with emphasis on pyrochemistry.

- *For the ADS:*
  R&D on high power accelerators, spallation targets, neutronic behaviour of sub-critical systems, and safety analysis.
  - Demonstration at appropriate scale of fuels with high contents of minor actinides, involving fabrication, irradiation, and reprocessing of the fuels (requires fast-spectrum irradiation facilities).
  - Improvement of models for the simulation of materials behaviour under unusual load, irradiation and temperature conditions.
  - Comparative assessment of the advantages and disadvantages of alternative coolants for fast-spectrum systems.
  - Performance assessment of geological repositories using a P&T source term.

Dr. J. Knebel (FZK, Germany)

I think that it is a difficult and challenging job to combine national programmes, national ideas or industrial ideas into a big international issue that is, in the end, an operating transmutation machine. And when I look to Europe, we have the transmutation roadmap and within the European Community we have the ADOPT network. ADOPT combines different tasks looking at design, partitioning, fuel, nuclear data and fundamental support. In the task of fundamental support, we have to look into critical issues of materials and thermo-hydraulics and develop applicable solutions. Today, each of the already operating national laboratories looks at a certain small issue, but there should be a much better collaboration between laboratories and more exchange of scientists should be practised.

A good example of such a collaboration is the MEGAPIE Initiative, which aims at operating a heavy liquid metal spallation target at Paul Scherrer Institute (PSI), Switzerland. MEGAPIE has 1 MW of proton beam power, so that there is still a long way to go to prototypical conditions. In order to perform the scaling up, I would propose a centre of excellence to concentrate on single-effect and integral experiments that are larger in scale.

Therefore, for the successful future development of fundamental support work, my point is the following: we do need **a world-wide co-ordination and work plan of the analytical/ experimental/numerical activities in the fields of heavy liquid metal technologies, thermo-hydraulics and corrosion studies**. Right now, each association tries to do developments of their own, kind of hiding the latest know-how from others, and not combining the best solutions. However, in this politically difficult situation, we – scientists – have to join together and form a homogeneous community. This means: **Collaboration instead of competition!**

Dr. T. Mukaiyama (JAIF, Japan)

The first topic I would like mention is **nuclear data**, especially the nuclear data needs for designing a dedicated system for transmutation. The definition of a dedicated system is that a major fraction of the fuel comprises minor actinides, say around 50 or 60 percent of the fuel material is composed of minor actinides. In this case we need reliable neutron cross-section. But at the moment, as far as conceptual designing is concerned, these cross-section or data libraries are not adequate. We need, for example, much more reliable (n, 2n) cross-section, especially for hard neutron spectrum systems.

When we go further to the detailed designing of a dedicated system, we need a much more reliable data libraries and maybe similar levels of reliability of uranium and plutonium isotopes. Beyond that, we have very sparse measured data of minor actinides, fission yields and delayed neutron data, such as delayed neutron fractions and delayed neutron energy spectra. As far as I know, the majority of minor actinide cross-section activities are devoted to the field of evaluation and library development, based on a limited number of measured data or on theoretically predicted values, because measured data are non-existing. Handling of minor actinide samples for measurements is extremely difficult, but we need real measured data for a reliable system design. We need more work in the field of cross-section.

Now for the **partitioning and separation**, we have seen many processes presented at this meeting and in the past. Outside of these specialities, I wonder how far the chemists want to continue their scientific research. I believe we now need a scale-up for the engineering feasibility and with that we can also get some idea of what would be the radioactive waste from these partitioning and separation processes. The question is then how far chemists can continue their science; this means that at some time **we have to go from science to engineering**.

For the **development of fuel**, we need irradiation experiments. The problem we are facing now is that there is only a very limited number of reactors available for such experiments.

Now, the big issue for P&T is how to manage the **post transmutation waste**. P&T waste management is a key issue for discussing the merits of P&T. Merits and justification of P&T is not clear until P&T waste management methods are clearly understood. So far, most activities on P&T concentrate only on the front-end of P&T; front-end meaning partitioning and transmutation. Concerning the back-end of P&T, i.e., treatment of post transmutation waste, only limited activities are going on. Even after P&T, final disposal is needed for most short-lived nuclides, and you should remember that around 85% of the fission products from minor actinides are stable. And the waste from P&T is quite different from the waste before P&T. The waste after P&T consists of a significant reduction of long-lived fission products and minor actinides. So present evaluations of the P&T effect comes from the geological community, based on its own scenario and using the current design of a final repository and the performance evaluation methods. However, the final disposal of P&T waste may need a different geological repository design than current designs, because this waste contains mostly short-lived nuclides; and for this waste, what kind of waste repositories are needed? Will solidification be needed? If so, is vitrification the only solution or not; and even in the case of vitirification, what is the concentration limit for most short-lived nuclides in a waste form? In addition, how should one dispose of solidified waste? For instance, placing them in a regular grid or dumping into a silo? However, these considerations may not be for the first repository, in order not to interfere with the existing final disposal policy. Once management of P&T waste is clearly understood, it can provide feedback to the design of P&T scenarios. In some cases, only partitioning will be needed. If Sr/Cs are separated for heat source removal, the concentration of the other materials in vitrified waste will be much higher. And also, the separation of Sr, Cs, Mo and stable fission product elements will reduce the waste volume up to 10 times. This was presented by Dr. Takaki of JNC in his presentation at this meeting.

So, in some scenarios, only partitioning will be sufficient. When further reduction of long-lived nuclide and Pu inventory is sought, transmutation is definitely needed. So in this case **when the management of P&T waste is really understood, then we can discuss how to optimise P&T.** Currently, the designers of P&T systems are proposing very high P&T efficiency, up to 99.9% or higher. Do we need such a high efficiency? Critical or sub-critical, power reactor or dedicated system? Thermal spectrum or fast spectrum? Once-through or multi-recycle?

The discussion should be based on the management of P&T waste. For this waste management form, **we need involvement of the geological community for developing transmutation waste management concepts**. This is inevitable. Around three years ago, the IAEA organised an international conference on the safety of waste management with around 300 participants, and 99.9% of the participants were from the waste management community. I was the only panellist from the P&T community, and in these circumstances, I felt as if being an alien amongst nuclear waste management community people. From the viewpoint of the geological community, P&T is still not a desirable approach. But in the further discussion on P&T, we have to invite the geological disposal community. **From the general viewpoint of nuclear waste management, the time may soon come when the geological disposal community will have to discuss how to avoid the necessity of a second or third repository.** In this context, the geological disposal community should seriously think about P&T.

Finally, I note that we have already lots of international collaborations. But **we need a kind of burden sharing collaboration** such as the MEGAPIE and MUSE initiatives; especially for information exchange or concept discussion. All such initiatives need big facilities. Currently, the nuclear community is facing inadequate resources for R&D. P&T is just a waste management issue and not a power generation issue. It is quite different from activities such as fast breeder reactor development, because the latter was a kind of competition and **waste management is a common issue among the nuclear countries**. So burden sharing and international collaborations are becoming much more important. One of these examples is the ITER-type co-operation in fusion development. This may be preferable also in the area of P&T.

Summary from the general discussion

Nuclear data issues

D. Hill (ORNL, USA)

The nuclear data issue is a case where co-operation at a lower level can be extremely valuable. Generation of data and subsequent evaluations will proceed world-wide; the data are being developed and we will all benefit from continuing **expansion of the co-operation**.

IPPE, Russian Federation

The problem of neutron data for an accelerator-driven system is very similar to that for new types of fast reactors, because both systems are similar. When we speak about neutron data for advanced sub-critical systems with minor actinides, new types of coolant and new types of other materials, we need to employ the design practices use for new fast reactors. **Integral experiments are a very essential part of this programme**. And our experience from the design of fast reactors showed that by using integral experiments it is possible **to reduce uncertainties in neutron data** to levels that are suitable for real engineering design. At IPPE, experiments are planed that will give us new information about minor actinides and various neutron data together with neutron data for lead bismuth and other materials. Any international co-operation in addition to specialists from France, Japan, and USA are welcome.

E. Gonzalez (CIEMAT, Spain)

We have seen that very valuable data from integral experiments are coming from Russian installations. We should not miss the opportunity to learn from these data for the new concepts like BREST or other reactors being developed, and also for the transmutation devices being developed.

We should try to find a way in which these data are combined with new data coming from differential measurements sponsored by the European Union and from other international co-operation frameworks. **All these data should be brought together and introduced into reactor physics simulation and prediction methods within an international framework** for example the NEA or the IAEA. Then we will make a breakthrough in nuclear data for minor actinides and transmutation systems.

Separations issues

J. Laidler (ANL, USA)

It is absolutely essential for us to **move to a scale** at which we can convincingly prove to decision making people that the processes that we have are indeed **economically and technically viable**. In the

US programme we are proceeding with a very large scale demonstration of separation processes, both aqueous and non-aqueous to be completed by 2007, and these are demonstrations that are 1/20 of production scale, which is significant and is adequate to answer questions concerning the economical feasibility as well as the technical feasibility, and also give some information on waste generation and ability to meet specifications to criteria. It’s absolutely essential. The other point is that we absolutely need **co-ordination on an international scale**.

S. Tachimori (JAERI, Japan)

Reprocessing always involves high cost. An economical model should be developed. However, some more time would be needed before going to the engineering scale. **The aqueous process is a proven technology and pyrochemistry is a future technology. What to do in the future would depend on the situation in each country.**

J-P. Glatz (ITU, Germany)

Aqueous- and pyro-techniques should not be in competition with each other, because both of them have their position in the partitioning and transmutation strategy.

Regarding **the scaling up**, aqueous-techniques are more advanced and much more developed than pyro-techniques, so the step forward, in view of technical applications, is also more advanced. For pyro-techniques, we are at the stage now that we cannot really go to an industrial scale although in this conference we have seen that there are some parts of the process which are already developed on a larger scale.

There is no T without P. We should try to have a closer collaboration between those people who develop, for instance, the fuels or targets for the transmutation processes. It is very important that from the beginning, when we develop a new fuel, that immediately we think about the techniques we can apply for the partitioning, because only if those two aspects work closely together, then we can come to a good result.

J. Laidler (ANL, USA)

With regard to the concept of separating cesium and strontium for the purpose of reducing the heat load in the repository, is this a worthwhile step to incorporate in our processes or is it not cost-effective?

N. Takaki (JNC, Japan)

JNC has evaluated the effects of removing cesium and strontium from high-level liquid waste, and the results show that we can obtain **some benefit in form of a reduced waste volume and thus the size of the repository**. We are not sure **whether the benefit compensates the cost increase** by introducing new separation process.

J. Laidler (ANL, USA)

In the USA, we have done a similar study and found that **by removing the actinides** – all of the actinides including the uranium, technetium, iodine and Cs/Sr – **we increase the repository capacity**

by a factor of forty. This means, in case of the Yucca Mountain repository capacity, that it then becomes the single repository for the entire nuclear era for even hundreds of years, if we operate for hundreds of years. **The issue is how we store this Cs/Sr.** Presently we are considering storing it on the surface for a period of 300 years until it has decayed. The issue is that it is a significant heat source that we have to deal with. We are looking at various options.

Fuel development issues

S. Pillon (CEA, France)

We need to focus all our activities on only one or two of the most promising candidates, because the fuel development activities demand a lot of time and people. The problem is also due to the reactors. We have a limited number of reactors for irradiation testing and not enough space in the reactor. For example, the PHENIX reactor is now fully booked for irradiation tests and we have to select and limit the number of fuels to test as much as possible.

H. Aït Abderrahim (SCK-CEN, Belgium)

The situation in the USA and in Europe is different. The USA has Yucca Mountain, but in Europe, we do not have anything similar. Moreover, European countries have very dense populations and they have different waste management policies. **P&T is absolutely needed in Europe.**

Merit of P&T, Waste after P&T, Collaboration with the waste management community, and International collaborations

T. Mukaiyama (JAIF, Japan)

We can discuss the further merit or the necessity of P&T only after waste form after P&T or a way of disposal becomes clear.

J-H. Ahn (UCB, USA)

Ten years ago, I think partitioning and transmutation was regarded as kind of a competitor to geological disposal. But now I think people don't think that way any more. It's part of more larger system of the nuclear power and I think that it should be that way. Still, I think that there is some kind of mis-communication or misunderstanding between the two communities. I have been thinking what was the reason or reasons for such mis-communication, and recently I came up with one idea and that is probably because the measures of geological repository performance we use in the geological community and you use in this community are quite different.

The radiological toxicity curve is decreasing with time and crossed by uranium toxicity. If you use that curve and show that to the geological repository community that means that you don't want to communicate with them because that does not include the geological repository performance at all, as that radiological hazard is the potential hazard of the spent fuel or the waste from the P&T before the disposal. If you would like to communicate with the geological community properly, you need to include that. On the other hand, we have also problems – one of the problems was that we did not have a proper model for the performance assessment of the geological repository. Let me show some examples. Usually we model the repository as a collection of many individual canisters, and we usually model a single canister first and then multiple that results by say *n* canisters. So we did not see the effect of mass reduction properly and in addition to that, in the repository performance assessment, we usually use the radio exposure dose rate as the performance measure. As you may know, the radiological exposure dose is based on the concentration of radionuclides in the ground water basically, whereas in this community most efforts have been devoted to decreasing the mass of the radionuclides in the waste. There is a big discrepancy or gap in the terms of the model development between the reduction of the mass and the effect of the radiological hazard in the downstream 20 km from the repository. There have been no good models so far, and I think that was one of the reasons why we couldn't communicate with each other very well. So I think the keen and urgent issue is to develop a good measure – actually we need multiple measures to view the repository performance and some of them should be based on the mass of the radionuclides, which should be disposed of in the repository, and some should be based on the concentration. For example, the heat generation is heavily dependent on the mass and concentration of the radionuclides in the waste form, but so far we have been looking at the radionuclide concentration in the ground water only. That's I think the major discrepancy. **We could develop good measures for the repository performance which could join or connect the effect or efforts of the partitioning and transmutation studies.**

If we were to continue with our nuclear energy for a long period of time, we need to expand the repository capacity and I heard many times in this conference that the repository capacity should be expanded, and more waste should be accepted by a repository. If we have more waste, the impact should be increased, but this will probably not be allowed by the public in the future. We need to go to more waste but less impact in the repository or from the repository. And for that, we have fortunately three kinds of technology. One is P&T. This is the most important part of the technology. In addition, we can do something by changing the repository design and the layout, and we can also redesign the pre-closure scheme like interim storage or separation of Cs/Sr and store that for a long time. By the combination of these technologies, we can improve the waste characteristics and improve the material and space utilisation in the repository. And I think this is the desired future – I call it the new regime and we need to move on from the nuclear legacy now to the new nuclear regime, which has much less impact on the repositories, with help of P&T technology and other repository technologies.

E. Gonzalez (CIEMAT, Spain)

I would like to add some comments on this topic. One thing, at least for me, that looks curious in this meeting is the **absence of the bodies responsible for waste management**. I'm not so aware of the situation in Japan and in the United States, but in the case of the European countries, this is quite a common. But I think **we should involve them in the discussions, which will force in a way the closer discussion of the communities related to the repository and the community that is looking on the waste production part of the nuclear cycle.** On the other hand, the very last final conclusion of the NEA report on fast reactors and ADS was that before you reflect on whether it is worth or not to do P&T, **we have to evaluate the impact on the final waste repository.**

V. Bhatnagar (EC)

On behalf of the European Commission, we have been thinking about these problems and the reality of the communication gap between the P&T community and the geological disposal community, and also the waste management agencies. In this respect a future programme that we are preparing now is looking towards the proposals in the cross-cutting regimes meaning that people of both communities should be involved. Some proposals that will study the impact of P&T on realistic geological disposal should be suggested. So I think that there is a need for more communication and possibly common meetings in which both communities are present and then they can understand and maybe then they will see the importance of P&T. So I think **we have to work together and we should not see these two communities as competing with each other but rather working together and I think that will help the situation.**

A. Stanculescu (IAEA)

As you know, we try to set up co-ordinated research projects around the technical scientific issues that are of interest to our member states. The important thing is that we include developed/developing countries. A co-ordinated research project has to be shared amongst all participants and they have to agree to commit themselves to resources, which then have to be shared in the member states in order to achieve these results, which have to be shared by everybody. On the first day, I mentioned that we are planning **a co-ordinated research project benchmark exercise on P&T ADS technology based on experiments**, not an analytical exercise but experiment related.

Now, I would also like to make a few comments, the first one is related to what Dr. Osugi said. He was proposing a network. Well, again in my presentation on Monday, I presented the **ADS research and development database,** which is something that could be one of the mechanisms for this network and I would also strongly encourage people to solicit input to this database. It is a working instrument on the Internet. It is open to everybody. You need a password, you need login information, but you just have to request it. Everybody can get it and provide data.

Now the last comment I wanted to make is related to what Dr. Mukaiyama said and his suggestion to include the geological community. I agree, but I don’t necessarily see a problem. I mean what the geological community will tell us is how to translate risk into hazard. First of all, I’m not sure that the public opinion, that you have on your viewgraph on top, does care if it is hazard or risk. If we think that they don’t care, we have to ask ourselves – do we want to spend the money to make the case that we reduce not only the hazard but also the risk. I want to stress that **we have to involve the geological community, but we have to involve the people who have the spent fuel.** They have to tell us who is responsible and who has to manage the spent fuel and I guess in many cases it’s the government, but it’s also the utilities.

T. Mukaiyama (JAIF, Japan)

If we can find another way of waste form production and another means for placement of waste in a repository site, then the current design of the repository will be much different after P&T. So I should say **the performance of P&T should be evaluated based on the advanced waste form concepts**, and not based on the evaluation of the current design of repositories. So we should develop some kind of a better waste form for most short-lived and long-lived nuclides.

Concluding remarks from the panel discussion chairmen

J. Laidler

I'm afraid the time is drawing late and we must come to a close. I want to thank you for your participation. It is very important to have a free and open expression of opinions and in a forum like this, there are not unacceptable opinions. It is important for everyone to express themselves and I thank you for doing that. So let's bring this session to a close; there are some further remarks from the chairman.

T. Mukaiyama

Thank you. You know Jeju is a place where the honeymooners come. This is a place where we think about the next generation, we have a very nice place for discussing the future. This is my final message. Thank you very much for participation.

Closing remarks

David Hill (ORNL, USA)

It falls on me to wrap up this information exchange meeting. This is the 7th meeting. I would like to add my personal thanks to Dr. Takehiko Mukaiyama, to Dr. Massimo Salvatores for the work that initiated this series of meetings and really rekindled interest in this subject again. They achieved something which is great, and it is up to us now, the community working in partitioning and transmutation and in the fuel cycle more general, to carry that forward.

I would also like to compliment the NEA as an organisation. It has sponsored seven of these meetings, it has supported the working party on partitioning and transmutation and other working parties which deal with related issues, and that has also been important. To the NEA, that abstract entity, I think we all owe a debt of thanks.

I support something Jim Laidler said – open debate and free debate is important. That's why we come to these meetings, more so in fact than just to listen to papers. I was very encouraged by the debate over the last couple of hours. There's a divergence of views based on, really, a divergence of national circumstances, but I think some themes came through. We always need to be questioning the assumptions behind what we do and making sure that we are answering the right questions. The community is small; the level of investment compared to the scale of the problem is small, which means that international co-operation at every level is mandatory.

Much has been done. That's obvious. You have seen the papers here this week. But there's still a lot to do. I noticed two, three or four times in different presentations and in poster sessions, that people emphasised the importance of what they are doing is providing the motivating force for drawing young people. We need viable motivated projects that will draw in the motivated students that will become the future of this programme. That was very pleasing for me personally and again I think it's a credit to all of you.

I thanked the NEA as an abstract entity and I need on behalf of you all to thank the organisers of this meeting, starting with the general co-chairs, who are Luis Echavarri, the Director General of NEA, and Chung-Won Cho, the Director General for Nuclear Energy of MOST, the organising chair, Chang-Kue Park, the Senior Vice President of KAERI, and I also thank the scientific chair of this meeting, Phillip Finck from Argonne, who put in all the work and unfortunately, at the last minute, was unable to attend, and the scientific advisory committee – I won't name all of you - you know who you are but everybody who contributes to reviewing and assessing papers, adds their little bit to the community.

I think that this meeting has been impeccably organised. What I want to add is the genius of the person who chose this spot, such a beautiful spot to have a meeting.

This was an information exchange held every two years. The next information exchange meeting, the 8th, has provisionally been decided to be held in Las Vegas, USA, approximately this time of year, two years ahead. The dates are not chosen. The University of Nevada, Las Vegas, is intimately involved in partitioning and transmutation studies. The Senate of Nevada has a keen interest in this subject. So I think that we can be sure of a welcome there and Dr. Laidler, my colleague from Argonne, will be acting as chair of that meeting. We'll get information out as soon as appropriate. Finally, I would just like to thank all my colleagues here on the panel, but mostly all of you for coming here, for participating in what has been an outstanding meeting. I hereby declare this meeting closed, and I will see you in Las Vegas.

Annex 1

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Printed in France.