RESEARCH AND DEVELOPMENT ON ACCELERATOR-DRIVEN SYSTEMS IN THE EURATOM FIFTH AND SIXTH FRAMEWORK PROGRAMMES

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Abstract

A fast subcritical reactor coupled to a particle accelerator is a concept of transmutation system that would allow large quantities of minor actinides to be burned efficiently. The research on transmutation encompassing accelerator-driven systems (ADS) is a part of the EURATOM research and development programme that lies within the area of partitioning and transmutation (P&T) of long-lived radionuclides in nuclear waste. P&T 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 the research work in this area is to determine practical ways of reducing the amount and/or hazard of the waste to be disposed of. In FP5, there are 13 projects in this area with a total budget of about 69 M€ of which the EU contribution is about 28 M€. In FP6, the research in this area, with a EU contribution of about 30 M€, strengthens the work that has been carried out in FP5 with a view to building a European Research Area (ERA) in this field. This has lead to integrating all EU activities on partitioning into one integrated project, and the same is planned for the transmutation activities. Moreover, a targeted project concerning the impact of P&T on waste management has also been initiated. International co-operation in the area of P&T with non-EU countries (such as Canada, USA and Japan), 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]. To maximise its impact, FP5 has focused 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 had emerged. National research programmes have been undertaken to a large extent independently of one another.

The primary objective now is to achieve greater co-operation among member states' research strategies and a mutual opening-up of programmes. To this end, 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 toward making 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-focused research priority areas principally by using new research implementation instruments such as Networks of Excellence (NoE) and Integrated Projects (IP).

- Structuring the ERA through 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" are to help exploit the full potential of nuclear energy, both in the long and short term. Its development and exploitation are to be undertaken in a sustainable manner while combating 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.

The paper briefly recalls the goals of P&T, including ADS, its position in the framework of management and disposal of radioactive waste. The research projects on P&T that are being funded in FP5 are then briefly described. A brief sketch of the P&T research work programme of FP6 is also given where once again the focus is on 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].

The implementation of the key action on nuclear fission, comprising 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, was made through targeted calls for proposals. 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€ of which the EU contribution is 28 M€.

Partitioning and transmutation (P&T) and accelerator-driven systems (ADS)

Spent fuel and high-level waste contain a large number of radionuclides, from short- to long-lived. 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 and of 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 subcritical 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 is still at the research and development (R&D) stage. Nevertheless, it is generally accepted that the techniques used to implement P&T could considerably alleviate the problems linked to waste disposal.

There has been a renewal of interest in P&T worldwide [5], including Japan, Korea, Europe, China and the USA. In Europe, the most notable idea is that of the 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, Czech Republic, France, Germany, Italy, Spain, Sweden as well as in Switzerland. P&T activities are also pursued in Russia.

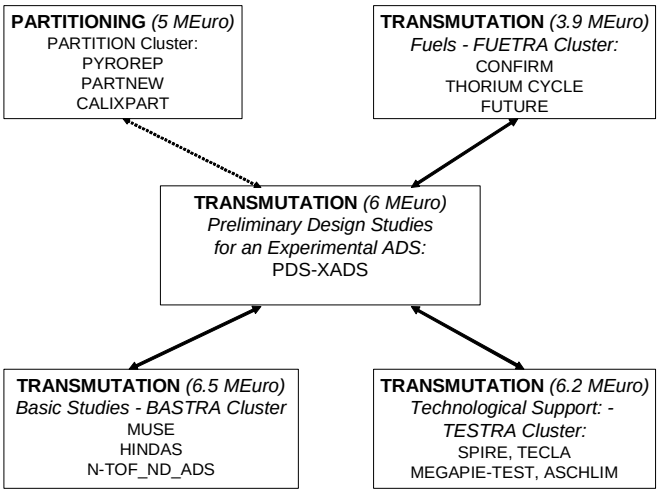
The interest for P&T in the EU is reflected in the increase of funding in this area over the successive EURATOM Framework Programmes, 4.8, 5.8 and about 28 M€ for the Third, Fourth and Fifth Framework Programmes respectively. In the Sixth Framework Programme (2002-2006), the indicative budget for P&T is about 30 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 hydrometallurgical 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 subcritical 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 re-grouped. 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 concerns chemical separation of radionuclides (PARTITION) and three deal with 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 the ADOPT network



ADOPT network

The objectives of the 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 subcritical core is a first step for demonstrating the practicability of this type of transmuter on an industrial scale. The aim of the PDS-XADS project (see Table 1) is to produce a 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, subcritical core, primary system) will allow identifying the most promising solution which could be studied in detail during the next phase of design activities.

FP5 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 electro-refining, investigate the possibility of separating actinides from lanthanides. Materials compatible with corrosive media at high temperature will be selected and tested.

Table 2. PARTIONING 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 (using the DIAMEX processes), then separated from the lanthanides (using the 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.

FP5 transmutation projects

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 subcritical 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 subcritical system with different coolants (such as sodium and lead). Cross-comparison of codes and data is foreseen. Experimental reactivity control techniques related to subcritical 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.

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 subcritical neutronics validation	CEA (F)	13	01-10-00 49 m	2.0
HINDAS	High- and intermediate-energy nuclear data for ADS	UCL (B)	16	01-09-00 39 m	2.1
n-TOF-ND-ADS	ADS nuclear data using time-of-flight facility	CERN(CH)	18	01-11-00 49 m	2.4

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 the 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 39 m	2.5
MEGAPIE-TEST	A megawatt heavy liquid metal spallation target experiment with proton beam	FZK (D)	17	01-11-01 61 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 *AS*sessment of *C*omputational Fluid Dynamics Codes for *H*eavy *LI*quid *M*etals (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.

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 the 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 ^{14}C 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 the 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 64 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.

In the area of management of radioactive waste, 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. Combating the decline in both student numbers and teaching establishments by a better integration of European education and training in nuclear safety and radiation protection is another important aim.

The detailed work programme of EURATOM FP6 has been adopted by the EC [8]. 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 subcritical systems (ADS) is proposed [9].

Two calls for proposals have been made in December 2002 and November 2003 respectively, where the so-called new instruments (such as Integrated Projects) are used as a priority. 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. Specific Targeted Research Projects (STREPS) are sharply focused on research and technological development designed to gain new knowledge either to improve or develop new products, processes or services or to meet other needs of society and Community policies.

Studies on the impact of P&T on waste management

RED-IMPACT project

Partitioning, transmutation and conditioning (P&T/C) and waste reduction technologies, if implemented properly and in full consultation with the geological disposal community, are expected to significantly reduce the burden associated with radioactive waste management and disposal. P&T is likely to ease the final repository requirements and it will also contribute to the sustainability of nuclear energy in those countries that pursue this source of energy.

The objectives of this three-year RED-IMPACT project (total budget 4 M€ including an EC contribution of 2 M€) are: (i) to assess the impact of P&T on geological disposal and waste management, (ii) to assess economic, environmental and societal costs/benefits of P&T (iii) to diisseminate results of the study to stakeholders (scientific, general public and decision makers) and get feedback during the course of the study and (iv) to iterate and refine the work based on stake-holders' feedback to achieve the full impact of this study on the implementation of the waste management policy of the European Community.

Partitioning

EUROPART project

The research work in this project (total budget 10.3 M€ and EC contribution 6 M€) concerns the partitioning (chemical separation) of actinides that are contained in the nuclear wastes issuing from the reprocessing of nuclear spent fuel. The selected elements for partitioning are the so-called minor actinides (MA) but in the case of the treatment of dedicated spent fuels or targets the actinides to be separated also include U, Pu and Np. The separation techniques are hydrometallurgy and pyrometallurgy.

In hydrometallurgy, the research is dedicated to the study of partitioning methods mainly based on the use of solvent extraction methods including the development of An co-conversion methods for fuel or target preparation. The research in pyrometallurgy concerns the development of An partitioning methods, and the study of the basic chemistry of transcurium elements in molten salts. Conditioning of the wastes and system studies are also included. Processes for possible industrialisation of partitioning strategies will also be defined.

Transmutation

For this subject matter, the proposal is currently undergoing the evaluation and selection procedure. The objective of the required work is the evaluation of the industrial practicability of transmutation of high-level nuclear waste in a fast neutron burner and development of the necessary basic knowledge and technologies. The focus of research should be on system analysis for an accelerator-driven system (ADS), including more advanced integrated design, cost evaluation of the whole system and safety and licensing issues. Moreover, the work should improve the basic knowledge and technologies required for improving the reliability of high-energy accelerators for ADS applications, coupling of the ADS components (accelerator, spallation target and subcritical core), material and coolant technologies, advanced fuels and targets and basic nuclear data.

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 scientific co-operation. It is an inter-governmental organisation grouping the European Union, Japan, the USA, Norway and 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) was established in 1995; the EU, Canada, the USA, Georgia and Uzbekistan are involved.

Five topics have been identified by the ISTC Contact Expert Group (CEG) for 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 the BASTRA cluster with related ISTC projects and the PARTITION cluster with related ISTC/STCU projects.

Conclusions

Research activities in the field of partitioning and transmutation under the EURATOM Fifth Framework Programme are nearing completion. The research projects have been re-grouped 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 is 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. Two calls for proposals have been launched in FP6 making the ERA a reality. One partitioning project and one project on impact studies have begun. The

project on transmutation is undergoing the evaluation and selection procedure. 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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