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**Thematic Network on Advanced Options for
Partitioning and Transmutation
(ADOPT)**

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PU: public

RE: restricted to a group specified by the partners of the ADOPT project

CO: confidential, only for partners of the ADOPT project

M: Management, **S/T:** Scientific/Technical reports, **MT:** Mid-term, **nnn** = 36

ABSTRACT

In Europe there is a strong interest to explore the potential scientific, technical and industrial possibilities of Partitioning & Transmutation of high level waste. Integrating the total European efforts as efficiently as possible would be very beneficial and would speed up the development and put the European R&D at lead in this field. The **Advanced Options for Partitioning and Transmutation** thematic network has been established during FP5 to review and monitor 14 projects funded by the EC in the field of P&T, namely: PARTNEW, CALIXPART, PYROREP, FUTURE, CONFIRM, THORIUM CYCLE, PDS-XADS, n-TOF-ND-ADS, HINDAS, MUSE, SPIRE, TECLA, MEGAPIE-Test and ASCHLIM. The final reports of these projects can be found at the web address: http://www.cordis.lu/fp5-euratom/src/lib_finalreports.htm. The specific objectives of ADOPT were:

- § To promote consistency between P&T FP5 projects and national programmes;
- § To define rules for information dissemination and access to national R&D programme data;
- § To review results of the P&T FP5 projects and avoid duplications;
- § To identify gaps in the overall programme;
- § To inform the members about the ongoing activities in P&T and ADS outside the EU; namely within IAEA, OECD-NEA, USA, Japan, Korea, former CIS countries and primarily through the ISTC projects.

Based on this effort the partners associated in this thematic network have summarized their recommendations on how to shape the P&T future programmes within Europe towards the industrial deployment of P&T by implementing the building blocks for P&T:

- The realisation of an experimental ADS that can be partially loaded with MA that can be put in service around 2015-18;
- The realisation of an advanced hydrometallurgical reprocessing pilot unit able to treat at least 1 ton of spent fuel per year that would be ideally developed around 2015;
- The realisation of a pilot plant for producing advanced fuel heavily loaded with MA with a capacity of few tens of kg per year;
- And finally the development of a pyro-chemical reprocessing pilot unit able to treat few kgs per year of transmutation fuel to be installed close to the experimental ADS.

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GLOSSARY

Acronym	signification
A316L	Austenitic Stainless Steel
ADOPT	Thematic Network on Advanced Options for Partitioning and Transmutation
ADS	Accelerator Driven System
ADT	Accelerator Driven Transmutation
AEA-T	AEA Technology (UK)
appm	Atom Part Per Million
BOR60	Fast neutron reactor in Russia (RIAR, Dimitrovgrad)
BR2	Belgian Reactor 2
BTP	Bis-triazinylpyridine
CERCER	Ceramic-Ceramic Fuel
CERMET	Ceramic-Metallic Fuel
CFD	Computational Fluid Dynamics
CIS	Confederation of Independent States (former USSR)
CMPO	CarbamoylMethyl Phosphine Oxide
COSAN	Cobalt bis (dicarbollide) Anion
CW	Continuous Wave
DHR	Decay heat removal
DIAMEX	DIAMide Extraction
DMDOHEMA	dimethyldioctylhexylethoxymalonamide
DPA	displacement per atom
EM10	Martensitic Steel (10% Cr)
ENDF	Evaluated Nuclear Data File
ETWG	European Technical Working Group on ADS
EUROFER	Low Activation Steel
FP	Fission Products
FR	Fast Reactors
GEANT	Montecarlo computer code for high energy particles transport simulation
Gen.IV	Generation IV
GSI	Gesellschaft für Schwerlonenforschung
HAW	High Active Waste
HFR	High Flux Reactor (Petten, NL)
HLM	Heavy liquid metal
HLW	High Level Waste
HPPA	High Power Proton Accelerator
ISI	In-Service Inspection
ISTC	International Science and Technology Centre, Moscow (Russia)
KWO	Kernkraftwerk Obrigheim GmbH (nuclear power station)
LBE	Lead-bismuth eutectic
LES	Large Eddy Simulation
LINAC	Linear Accelerator
LLFP	Long-Lived Fission Products
LME	Liquid metal embrittlement
LWR	Light Water Reactor
MALAB	Minor Actinide LABoratory
MASURCA	Maquette SURgénératrice Cadarache
MCNPX	Monte Carlo N-Particle eXtended
MSA	Multiplication Source Approach
MSM	Modified Source Multiplication
MYRRHA	Multipurpose hYbrid Research Reactor for High-tech Applications
NMR	Nuclear Magnetic Resonance

P&T	Partitioning and Transmutation
PHENIX	Sodium Fast Reactor (Marcoule, France)
PIE	Post Irradiation Examination
PNS	Pulsed Neutron Source
PTA	Post Test Analysis
PUREX	Plutonium and Uranium Refining by EXtraction
PWR	Pressurised Water Reactor
QS	Question sheets
R2	Studsvik Research Reactor (Sweden)
SANEX	Selective ActiNides EXtraction
SINQ	Swiss Spallation Neutron Source
T91	Martensitic Steel (9% Cr, 1% Mo)
TBP	Tri- <i>n</i> ButylPhosphate
TRU	TransUranic elements
VELLA	Virtual European Laboratory for Lead Alloys
VOF	Volume of Fraction (CFD Technique for tracking free surface)
XADS	eXperimental Accelerator-Driven System

1. INTRODUCTION

Presently the European Union relies for 35% of its electricity on nuclear fission energy leading to the annual production of 2500 t/y of used fuel, containing 25 t of plutonium, 3.5 t of minor actinides (MA, namely Np, Am, Cm) and 3 t of long-lived fission products (LLFPs). This MA and LLFP stocks need to be managed in appropriate way. The used fuel reprocessing followed by the geological disposal or the direct geological disposal are today the envisaged solutions depending on national fuel cycle options and waste management policies. Required time scale for the geological disposal exceeds our accumulated technological knowledge and this poses problems of public acceptance. The Partitioning and Transmutation (P&T) could be the strategy that would relax the constraints on the geological disposal, and reduces the monitoring period to technological and manageable time scales. Therefore a special effort should be made to develop P&T in general and the usually associated ADS transmuters in the frame of ADOPT activity, in order to assess the technical and economical feasibility of this complementary waste management option.

Despite the diversity between the European Member States concerning nuclear power and envisaged fuel cycle policy ranging from the once through fuel cycle without reprocessing up to the double-strata fuel cycle ending with the ADS as the ultimate burner, the P&T and ADS development is an R&D topic that requests an integrated effort at the European level and even worldwide. In addition, the combination of P&T and ADS technologies would allow meeting the objectives of countries which decided on phasing out of nuclear energy as well as of countries favouring the continuity of the nuclear energy development towards the deployment of new fast spectrum systems.

After a decade of exploratory research, it is time to put research in the position of being able to quantify indicators for decision-making, such as the proportion of waste to be channelled to this mode of management, but also issues relating to safety, radiation protection, transport, secondary wastes, costs, and scheduling. These elements, worked out on the basis of the extensive knowledge already acquired and an overall system approach including existing PWR, projected FR and ADS installations in scenario studies, must be delivered by the EU institutions working on the P&T research, largely represented by the ADOPT community. By covering all the necessary feasibility assumptions, this approach will result in identification of the costs and the benefits of partitioning and transmutation for European society.

In this sense, the ADOPT network deliverables include:

- The identification of the different options for implementation of the P&T technologies in nuclear waste management considered in the EU national policies, and their common R&D interest;
- The identification of the scientific and technological issues to be resolved to:
 - Assess the cost/benefit of P&T to waste management;

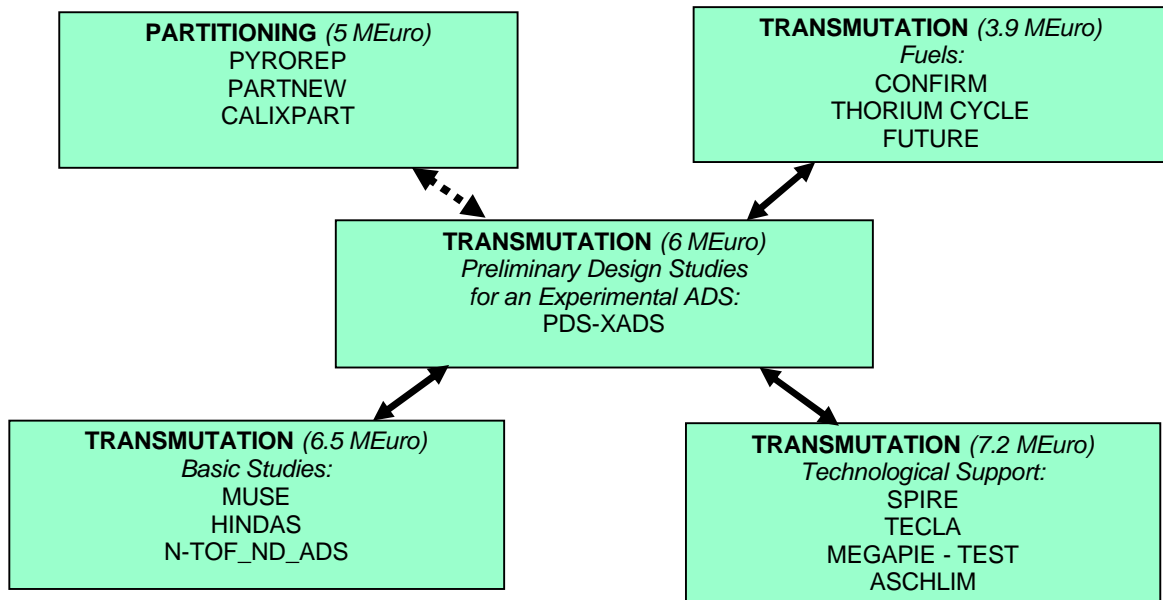
- Develop the components of P&T nuclear cycles (ADS, fuel fabrication and reprocessing plants etc...);
- Prepare the industrial deployment of those components.
- A proposal for the P&T research activities for the coming EU Framework Programmes, and promoting a set of driving projects that allows to target the EU resources and provide milestones.

The vision mentioned above must be complemented by a progressive and collective technical evaluation of the scientific difficulties. The knowledge available today and at the end of the FP5 projects is and will be already important; nevertheless, the task now is to evaluate and gain a better understanding and control by focusing the effort over the different R&D topics required for this assessment, namely: partitioning of HLW both via aqueous and pyro-reprocessing, development of advanced fuels heavily loaded with MAs, ADS design addressing the key points of the ADS components : such as the accelerator development, the proof of feasibility of both window and windowless spallation targets, the sub-critical core design based on LBE whereas the gas cooled option should be gaining from the critical gas reactor development, the siting and licensing approach of an European experimental ADS, the delivery of still needed nuclear data for achieving a reliable design and the consolidation of the engineering knowledge for the pre-selected structural materials and coolant technology.

A first global vision on ADS development and deployment in Europe entitled "A European Roadmap for Developing Accelerator Driven System for Nuclear Waste Incineration" has been produced by the European Technical Working Group (ETWG), chaired by Prof. C. Rubbia in April 2001 [1]. Representatives of Austria, Belgium, France, Germany, Italy, European Joint Research Centre (JRC), Portugal, Spain and Sweden participated to that effort and concluded that the ADS can be considered as a specific transmuter system in the single or double strata fuel cycle scenarios.

The "Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles" report [2] recently prepared under the hospices of the OECD Nuclear Energy Agency by a panel of international experts clearly demonstrated the advantage of this positioning of ADSs with respect to critical cores for concentrated management of waste. Hybrid systems perform as excellent dedicated minor actinide incinerators and offer the required flexibility for transition scenarios. This report also indicates that the meaningful reduction of the radiotoxicity of waste (at least a factor of 100) requires multi-recycling of fuels in which fuel losses to waste are to be very low (less than 1%).

The present report gives an overview of the achievements within the different areas covered by the 14 projects of the five clusters of ADOPT namely PARTITION, BASTRA, FUETRA, TESTRA and PDS-XADS in the 5th Framework Programme (see figure below). The report defines the objectives to be confirmed or reached to enable decisions about a transmutation option by ADS during the debate on waste management and gives an action plan that represents an updated vision by the ADOPT members of the ETWG ADS roadmap.



2. ACHIEVEMENTS IN FP5

2.1. PARTITION

During FP5, 3 projects were launched related to the domain of the partitioning of actinides. Two separation domains were considered: hydrometallurgy with the CALIXPART and PARTNEW projects and pyrometallurgy with the PYROREP project. The executive summaries of the final reports of these projects are presented below. These projects have been all successfully completed at the end of 2003 and the cluster gave birth to the Integrated Project EUROPART selected for funding following the first call for proposals in FP6.

Hydrometallurgical processes (PARTNEW, CALIXPART)

The final disposal of the vitrified high active waste issuing the reprocessing of nuclear spent fuels in an underground repository is a complex problem mainly related to the fact that these waste contain long-lived radionuclides with high radiotoxicity and this for a very long period of time, *i.e.* thousand to million years. A possible solution to this problem is not to incorporate these long-lived radionuclides into the vitrified waste. After separation (Partitioning), before the vitrification step, the long-lived radionuclides can be destroyed (Transmutation) into short or medium lived or stable nuclides by nuclear means. This is the so-called Partitioning-Transmutation strategy (P&T) under study in several countries. Among the long-lived radionuclides to be removed from the High Active Waste (HAW) (*i.e.* the aqueous raffinate or concentrate issuing the PUREX process), the minor actinides (MAs), Np, Am and Cm are the most important to eliminate. The partitioning of the neptunium (Np) can certainly be done by the PUREX process, which is not the case for Am and Cm, which exist at the oxidation state +III in the spent fuel aqueous dissolution liquor and which possess very low affinity for tri-*n*-butylphosphate (TBP), the extractant of the PUREX process.

Because of the laws of chemistry, the chemical separation of Am and Cm from the HAW is more easily carried out in two steps, first by co-extracting them with the lanthanides at the oxidation state +III, and then by separating the actinides

from the lanthanides. A more innovative approach is to perform the direct extraction of the Am and Cm in one step from the HAW, but this requires synthesising more selective extractants. The advantage of the second approach is that it should produce less secondary waste. Nevertheless, hydrometallurgical processes must be developed for both approaches, which can be used at the industrial scale and should therefore be based on organic extractants able to withstand the extreme conditions of the HAW (very acidic and very radioactive media).

The PARTNEW project followed the two step route for the partitioning of minor actinides. Its main objective was to study and define efficient solvent extraction hydrometallurgical processes for the partitioning of the trivalent Am and Cm ions from the HAW and for the Am(III)/Cm(III) separation. The research carried out in this project was in continuity with that performed in the previous framework programmes. The consortium of laboratories involved within PARTNEW included: 1/ CEA-DEN, Marcoule (France), 2/ CEA-DSM, Saclay (France), 3/ University of Reading, Reading (U.K.), 4/ Chalmers University, Göteborg, (Sweden), 5/ EC-JRC-ITU, Karlsruhe (Germany), 6/ ENEA, Saluggia (Italy), 7/ PoliMi, Milano (Italy), 8/ FZK-INE, Karlsruhe (Germany), 9/ FZJ-ISR, Jülich (Germany), 10/ CIEMAT, Madrid (Spain) and 11/ Universidad Autonoma de Madrid, Madrid (Spain).

The working programme of the PARTNEW project addressed 5 topics:

- Basic and process development studies of the DIAMEX process for the co-extraction of actinides and lanthanides;
- Basic and process development studies of the SANEX process (separation of the actinides from the lanthanides) with N-polydentate ligands;
- SANEX basic and process development studies with *bis*-(substituted-phenyl)-*di*-thiophosphinic acid + neutral ligand synergistic mixtures;
- SANEX basic studies with new S-bearing ligands;
- Am(III)/Cm(III) separation: basic and process development studies.

Numerous progresses were achieved for the basic understanding of the solvent extraction chemistry of actinides and lanthanides at the oxidation state +III. They are based on experimental results as well as on theoretical computations using quantum chemistry and molecular dynamic models. Concerning process developments, the main achievements are the following:

- The DIAMEX process, based on the use of the DMDOHEMA malonamide, which is sufficiently robust to hydrolysis and radiolysis, is mature for industrial application, even for the treatment of high active concentrates;
- The SANEX process has been investigated for different classes of extractants and synergistic mixtures; the best performances for actinide/lanthanide separation have been obtained with the bis-triazinylpyridine (BTP) extractants; however, this process cannot be proposed at present for industrial development due to the insufficient stability of the BTP molecules;

- Two extraction systems based on the DMDOHEMA malonamide and on the (CIPh)₂PSSH + TEHP synergistic mixture are promising for the development of Am(III)/Cm(III) separation processes.

The aims of the CALIXPART project were to prepare extracting molecules able to selectively extract in one step the trivalent minor actinides (Am and Cm) from acidic high active raffinates issuing the PUREX process. The research programme of this project was more basic than that of the PARTNEW project. It included synthesis of organic extractants and determination of their extraction properties, but no process development. The participants to the CALIXPART project were: 1/ CEA-Cadarache (France), 2/ ECPM-Strasbourg (France), 3/ J. Gutenberg Univ. Mainz (Germany), 4/ Katchem Ltd (Czech Rep.), 5/ Univ. Parma (Italy), 6/ Univ. Liège (Belgium), 7/ IIC (Czech Rep.), 8/ Micromod GmbH (Germany), 9/ Univ. A. M, Madrid (Spain), 10/ CIEMAT (Spain), 11/ NRI (Czech Rep.), 12/ Univ. Twente (Netherlands), 13/ Univ. L. Pasteur (ULP), Strasbourg (France).

A total of 160 extractants were synthesised, such as calixarenes, cavitands, tripodal compounds, beads or dendrimers bearing different ligating sites like soft and hard donor groups, CMPO, picolinamide, malonamide, glycolamide, COSAN, TTFA... The extraction properties of the compounds synthesised were tested and the promising ones were submitted to stability tests towards hydrolysis and radiolysis. The structures of the extracted species were elucidated by Nuclear Magnetic Resonance (NMR) spectroscopy and the hydration state of the complexed ions was determined by luminescence studies. Some key factors involved in the efficient and selective extraction of cations by suitable ligands were modeled by computer simulations.

The results obtained with the most promising compounds prepared within CALIXPART show the importance of: i) the solubility of the macroligands in the organic solvent(s), ii) the extraction capacity of the ligands, iii) a possible high scale synthesis of the ligands. In addition, it should be noted that the ligands should resist efficiently to hydrolysis and radiolysis.

Research on hydrometallurgical processes will be continued within the EUROPART Integrated Project in FP6.

Pyrometallurgical processes (PYROREP)

The main objectives of the PYROREP project were to:

- Determine the practicalities of separating uranium, plutonium and minor actinides from fission products (FP) using pyrochemistry in a molten chloride or fluoride system;
- Obtain basic data to allow conceptual design and assessment of reprocessing processes suitable for fuels and targets;
- Consolidate and revive European expertise in pyroprocessing.

The participants to the PYROREP project were: 1/ CEA-Marcoule (France), 2/ AEA-T (U.K.), 3/ BNFL (U.K.), 4/ CIEMAT (Spain), 5/ CRIEPI (Japan), 6/ ITU (E.U.), 7/ NRI (Czech Rep.), 8/ Univ. Valladolid (Spain).

Within the scope of the PYROREP project, substantial progress was made by working teams. Many basic data values concerning the behaviour of fission

products and actinides (U, Pu and Am) in molten salts and metals were measured for the first time or confirmed in both fluoride and chloride media.

The main R&D focus of the PYROREP project was on the separation step, which represents the core of the future pyrochemical separation process(es). In fluoride media, the investigation of reductive salt/metal extraction yielded very promising results for both actinide recovery and fission product decontamination factors. To investigate electrorefining of fuel materials, several electrorefiners have been built in different EU laboratories. For electrolytic processes in chloride media it has been shown that, from the strict standpoint of actinide/lanthanide separation, an aluminum cathode would provide better results than a cadmium cathode, although the latter could be used if it is not indispensable to recover and separate the actinides from the lanthanides with very high efficiency. Conversely, recovering the separated actinides from an aluminum cathode appears to be more difficult than for a liquid cadmium cathode which can easily be evaporated. Development work should be carried out on the use of an aluminum cathode to take advantage of these potentially interesting results.

The data acquired to date are sufficient to begin designing and quantifying preliminary schemes for reprocessing processes. From the standpoint of a fuel cycle policy based on Partitioning and Transmutation (P&T), effective implementation will require not only a very high actinide recovery factor (typically 99.9%) but also sufficient FP decontamination to recycle less than 5% of the initial negative reactivity of the FP with the actinides. This criterion should also be confirmed and/or qualified by taking into account not only the neutronic criterion but also the FP content recycled in the burner system and the risk of creating a holdup loop for some FP in the cycle. The system studies clearly show that the required performance cannot be obtained by a single separation stage. In each case at least two and perhaps three separation stages based on different separation principles must be implemented (electrorefining plus reductive salt/metal extraction in one case, or volatilization of some FP in a reducing medium followed by digestion of noble metals by a metal phase and reductive extraction in the second case). It is still necessary to demonstrate experimentally by combining all these process steps that the announced performance can be achieved.

An/FP separation, which constitutes the core of the process, will probably be applied to a variety of different fuels (oxide, metal, nitride, carbide, or molten fluoride) and should therefore logically be the primary focus of attention. However, An/FP separation must be preceded and followed by equally important steps designed to dissolve the elements in the molten salt upstream, and to recover the finished products downstream. These steps depend to a greater extent on the nature and type of the fuel, and must be investigated in greater detail in the future as the fuel specifications are defined.

Pyrochemical processes generate metal and salt waste flows of a substantially different nature than the waste currently produced by aqueous processes. A major effort will be necessary in the future to optimize the management routes for this waste - particularly for chlorinated salt waste, which is incompatible with the glass matrices used today - either by dechlorination or by developing dedicated containment matrices such as sodalite.

Unlike enhanced aqueous reprocessing processes that can be implemented with technology comparable to that used in today's reprocessing plants, the deployment of pyrochemical processes would require considerable technological R&D that must be undertaken as soon as the fuel specification for the future systems is sufficiently defined. The research in the domain of pyrometallurgy is continued within the EUROPART Integrated Project in FP6. Today the effort could focus on developing the continuous salt/metal contactors that will be necessary regardless of the type of fuel and the separation technique finally adopted.

2.2. BASTRA

Nuclear data, evaluation results

Several strategies are being considered in the EU and worldwide to implement P&T methodology in their nuclear waste management. The different strategies require different transmutation devices including critical reactors and ADS, fast to thermal spectrum with different coolants, several fuel matrix and MA contents, and homogeneous and inhomogeneous MA burning. This situation increases the relevance of the basic nuclear data of a large number of isotopes and in many cases of higher energy ranges. A wide nuclear data measurement and evaluation campaign is required to complete our basic knowledge of the neutronics, allow to make precise evaluations of the different options proposed for the nuclear cycles including P&T, and to optimize and evaluate the viability and performance of the corresponding transmutation devices. This campaign has been initiated in the FP5 with the projects HINDAS (High and Intermediate energy Nuclear Data for ADS) and n_TOF-ND-ADS (neutron time-of-flight Nuclear Data for ADS) and complemented with additional measurements in EU national programs and in other world regions, notably Russian Federation, USA and Japan, and needs to be completed during the FP6.

Reactions at energies below 20 MeV (n_TOF-ND-ADS)

Besides the large variety of proposed P&T strategies and transmuters, all of them have a few common features: all use fuels with large enrichment on minor actinides, they all aim to reach very large fuel irradiation (in many cases integrated over several recycling steps) and all rely on neutron fission for most of the neutron production (95-100% in nearly all cases). The energy of fission neutrons hardly exceed 20 MeV and well proven codes are able to perform very detailed and precise simulations of the neutronic behaviour and safety parameters of nuclear systems assuming there are precise nuclear data libraries in the standard ENDF format. As a consequence one of the highest priorities for the nuclear data activities has been to improve the accuracy of the present libraries that actually limit the final accuracy of the available simulation codes, with new measurements and evaluations of all available and new data.

The basic nuclear data, at the same time, should completely determine the evolution of the isotopic content of the actinides in the transmutation fuel and, ultimately in the final wastes loaded to the repositories. It should also be noted that these data would be useful for the development of new generation nuclear devices designed for energy production as well.

In FP5, this activity was performed within the framework of the n_TOF-ND-ADS (n_TOF) project, at CERN and IRMM. The n_TOF project has set-up a new

neutron TOF facility at CERN, Geneva, which provides the highest instantaneous neutron flux for this kind of facilities. n_TOF also includes a very long flight-path (200 m) and extreme shielding configuration that have reduced the ambient background level by one order of magnitude with respect to existing standards and have provided excellent energy resolution and a wide energy range (up to 250 MeV). All these characteristics make n_TOF specially suited for measurements of cross sections of radioactive and/or rare materials, and in general for measurements of low cross sections. This is the case of most of the isotopes requiring new measurements for P&T evaluations. The n_TOF project included measurements and evaluations of capture and fission cross sections of many long-lived actinides (Np, Pu, Am and Cm) and fission products (Sm, Zr and Tc), some capture and (n,2n) cross-section of coolant materials (Pb and Bi) and fuel matrix potential materials (Th and Zr). The measurements at the n_TOF facility have been complemented within the EU with some additional experiments performed in France and Greece. It is important to point out here that, only a small fraction of the isotopes measured at n_TOF and elsewhere (in the USA and the Russian Federation there are relevant activities on new measurements and evaluations) have been fully evaluated within the framework of FP5 projects.

As it is the case for nuclear fuels design, the complete production of the required evaluated libraries is a long and difficult process that requires sustained effort and time. Some of the remaining needs after FP5 activities in this energy range are the data for minor actinides with half-lives ranging from weeks to few hundred years. In particular, measurements of inelastic, (n,xn) and elastic reactions on all major isotopes present in the core, integral measurements validation for the more difficult measurements of the actinide cross section and the complete evaluation and incorporation to the standard libraries of all these data are called for the FP6 activities in this field.

Reactions with energies above 20 MeV and Spallation reactions (HINDAS)

Most of the P&T strategies with independent MA transmutation (double strata), are proposed to take place in subcritical systems, ADS, that require intense neutron sources, only possible using the spallation process induced by the external accelerator. The incorporation of a spallation source in a critical or subcritical core introduces particles (neutrons and charged particles) of energies well above 20 MeV and reaching 1 GeV. Although they represent a small fraction of the total fluence, the high-energy particles have a strong impact on some specific aspects of the ADS design, like the proton beam window, damage to structure close to the spallation target, total ADS power, shielding and radioprotection, and generation of new waste in the target.

Until very recently, the simulation of the reactions in the full energy range has been based on models rather than libraries. However, at present the extension of the neutron libraries to energies close to 200 MeV in combination with transport codes traditionally used below 20 MeV can provide a better description of the physics of nuclear system in this energy range. Above 200 MeV only models can handle, at present, the number of open channels and complexity of reactions induced by neutrons and charged particles.

This energy range has been covered by the HINDAS FP5 project that has combined measurements at different energies in several installations in Europe

(France, Germany, The Netherlands, Belgium and Sweden). The measurements provide directly usable information at a few energy points for some of the most characteristic isotopes. HINDAS has simultaneously developed highly improved models that allow to interpolate in energies and to extrapolate to other isotopes of the fuel, spallation target and structural materials. These models are being introduced at present in the most used neutral and charged particles transport codes (MCNPX, GEANT4). With these upgraded codes, it will be shortly possible to simulate with sufficient precision the neutron and charged particle transport from their production energy down to 20-200 MeV, where data libraries and standard model-free codes continue their simulation with even higher accuracy. The completion of the nuclear data libraries in the range from 20-200 MeV requires additional theoretical and experimental work to be completed during FP6.

The spallation process in the target generates radioactive residuals that constitute a new hazard of the ADS operation. Although partially similar to the fission fragments, these spallation products include in addition new isotopes of short and medium lives, and being embedded in the liquid Pb or Pb/Bi of the target, they represent specific risks and might require dedicated radioprotection and waste handling procedures. The HINDAS experiments at GSI have provided data that show that the mass distribution of spallation residues is accurately reproduced by the latest developed models, while the distribution of isotopes for a given Z is subject to imperfections that a complementary experimental program would reduce. The study program on spallation is therefore currently well advanced and the objective for FP6 is to produce validated models with acceptable uncertainties (< 20%).

Another major concern specific to ADS is the damage of the charged particles and neutrons involved in the spallation process in the beam window and surrounding structural materials, determining the life of these ADS elements. HINDAS has also addressed this problem both experimentally as theoretically, paying particular attention to the gas producing reactions. A detailed model of these nuclear reactions, for which the validity of the experimental results will be verified, will enable us to calculate the different production rates of neutrons and hydrogen or helium isotopes. However a major effort is still necessary to understand and describe the production of composite particles by models, given the fact that these composite particles may contribute up to 50% of the gas production in structures. The target for FP6 is to be able to complete these models and data base and to include them in the neutronic programmes.

Physics of ADS reactors (MUSE)

The neutronics of ADS reactors is currently being studied by two complementary approaches:

- Simulation from neutron programs taking account of the energy and spatial distribution of neutrons originated from spallation and then multiplication in a sub-critical reactor comprising a spallation module at its centre;
- The experimental approach carried out in Cadarache with MUSE experiments, coupling the MASURCA critical mock-up for several different sub-criticality configurations with a 2.5 or 14 MeV neutron generator. This

generator outputs 10^7 neutron pulses within $0.7 \mu\text{s}$ and was used to study the dynamic properties of such a sub-critical reactor.

Different measurement techniques for the determination of kinetic parameters and in particular the reactivity were investigated in the framework of the MUSE project.

The main experimental results obtained by the different partners showed that the reactivity level for an ADS (with $k_{\text{eff}}=0.95$) can be calibrated with an accuracy of the order of 10%. In MUSE, the correction induced by the MSM (Modified Source Multiplication) factor with regard to the simple MSA (Multiplication Source Approached) method remains very small, of the order of 5%. This small correction is probably due to the quite homogeneous MUSE core and the averaging many different core detectors in the MSA method which reduces the overall spatial effect.

Based on the measurements performed in the MUSE project and the envisaged conditions of a future ADS the applicability of the different methods towards future application in an ADS were investigated. It was concluded that a combination of techniques will be needed to provide an accurate and robust monitoring of the reactivity.

The monitoring of the reactivity is achieved through an in-depth philosophy of calibration and validation. The current-to-power indicator provides a simple and on-line reactivity indicator, which is regularly checked. A cross-check can be performed at beam trips (imposed or not) with an ADS source jerk technique or a Pulsed Neutron Source (PNS) fitting technique such as the kp-method (prompt Multiplication method). An absolute determination of the reactivity level can be obtained by use of PNS based techniques.

As the on-line monitoring of the sub-criticality level is not achieved during the MUSE project due to the non-CW mode of the GENEPI, it is highly recommended to foresee during the FP6 an experimental programme making use of a CW excitation accelerator to address this fundamental need of the ADS.

2.3. PDS-XADS

Previous studies showed that a fast neutron spectrum allows maximising the transmutation of minor actinides (MA), because of both the better fission efficiency compared to the neutron capturing rate, and the potentially high level of neutron flux.

A core dedicated to the fission of the MA should be designed in order to minimise its self-production of actinides. Such a core has very low delayed neutron fraction and Doppler coefficient. Therefore, its control in a critical configuration would be difficult to achieve. This difficulty can be resolved by using the core in a sub-critical mode and controlling it by an external neutron source, namely a spallation source, to be generated by means of a high power proton beam directed on a spallation target located in the centre of the sub-critical core. This combination of a sub-critical core, a spallation target and a high power proton accelerator is called Accelerator-Driven Systems (ADS).

The demonstration of the practicability of transmutation on an industrial scale requires operating at a European level, an experimental ADS (XADS) which will demonstrate the coupling of the accelerator, the neutron spallation target and the

sub-critical core. Complementary to the demonstration of the basic phenomena involved in the ADS technologies, the preliminary engineering design studies of the XADS have to be performed in order: (i) to select the most promising technical concepts, (ii) to address the critical points of the whole system, (iii) to identify the Research and Development (R&D) in support, (iv) to define the safety and licensing issues, (v) to preliminary assess the cost of the installation, and then, (vi) to consolidate the road mapping of the XADS development. This was the main mission of the PDS-XADS project. PDS-XADS stands for Preliminary Design Study of an eXperimental Accelerator Driven System.

Accelerator

CEA/CNRS teams have already been working for several years on a proton accelerator with a power of several MW. The selected concept was of a linear accelerator (LINAC), operating in continuous beam mode equipped with superconducting accelerating cavities above a certain energy. During the FP5 project PDS-XADS, this effort was supplemented by those of IAP_Frankfurt University, INFN (Italy), IBA (Belgium), Framatome (France), Ansaldo (Italy), FZJ (Germany), UPM (Spain) and ITN (Portugal) to focus the efforts on the specific requirements for the high power proton accelerator needed for the ADS application, namely:

- Investigation of LINAC and cyclotron types with the main emphasis on the XADS requirements;
- Examination of the XADS accelerator characteristics: reliability, availability, stability, power control & maintainability;
- Definition of the R&D needs to achieve the above defined objectives;
- Choice of the reference accelerator type for XADS and for a long-term extrapolated industrial transmuter;
- Definition of the road mapping of the ADS-class accelerators.

These comparative studies clearly showed that, the LINAC is the only concept capable of satisfying essential requirements defined by the XADS specification, namely:

- Extreme reliability, with only a few unplanned interruptions of the beam per year;
- Extrapolation in energy and current towards an "industrial" ADS.

The PDS-XADS WP3 group main technical answers can be summarised as follows:

- For the Superconducting LINAC:
 - No limitation in energy and in intensity;
 - Highly modular and upgradeable design, thus applicable to the industrial transmuter;
 - Excellent potential for reliability, as it can allow the fault-tolerance design approach;
 - High efficiency, allowing optimisation of operation cost.

- For the Cyclotron:
 - It has attractive construction cost due to the compactness;
 - The required parameters for the XADS are at the limits of feasibility of the as quoted "dream machine" by PSI;
 - The compactness of the device becomes a drawback when addressing the fault-tolerance design to improve the reliability as a Cyclotron is not modular.

Thus the final findings of this FP5 effort and in complete agreement with findings of the NEA report on HPPA [2]:

- **Cyclotrons of the PSI type** should be considered as the natural and cost-effective choice **for preliminary low power experiments**, where availability and reliability requirements are less stringent;
- **CW linear accelerators must be chosen for demonstrators and full scale plants**, because of their potentiality, once properly designed, in term of availability, reliability and power upgrading capability;
- Main issue is the reliability to be supported by a R&D programme for qualification of the key components.

Spallation target: Design and material issues

Design issues

At the heart of an Accelerator Driven System (ADS) is the spallation target. It is the neutron source providing primary neutrons that are multiplied by the surrounding sub-critical core. The primary neutrons are produced by the spallation reaction of heavy target nuclei under impinging high-energy protons generated by a suitable accelerator.

The amount of spallation neutrons depends on the initial energy of the incident particle and on the atomic number of the target nuclei. Due to the high Z efficiency, a heavy metal such as lead-bismuth (Pb-Bi), lead (Pb), mercury (Hg), uranium (U), tungsten (W) or tantalum (Ta), is the most appropriate solution for the target.

Moreover, because of the very high power density one arrives at during the spallation process (several hundreds of kW per litre for proton beam powers of several MW); a liquid metal remains the only option permitting to remove the heat by convection. The use of a heavy liquid metal (HLM) target also significantly reduces the damage caused by intense radiation to the target itself and the structural materials.

However, the use of HLM gives rise to problems related to erosion, corrosion and liquid metal embrittlement (LME) of structural materials which are in direct contact with the liquid metal at high temperature and high fluid velocities, to the confinement of (volatile) spallation products and the separation between the proton beam vacuum and the liquid spallation target.

Lead-bismuth eutectic (LBE) is today the reference target material for ADS. Because of the significant reduction of Po-210 (α -emitter) production, Pb could be regarded as advantageous over LBE, if it would not have the essential disadvantage of a higher melting point (327 °C compared to 123.5 °C) which puts severe constraints to the structural materials. For LBE, the Po release problem is mitigated by the fact that Po

forms a bond with Pb to form meta-stable Pb-Po which has an emanation rate which is about 1000 times lower than Po itself.

Mercury (Hg) has also been considered as spallation target material because of its low melting point (-38.9 °C) and the absence of the Po-210 problem. However, its high volatility would seriously complicate the confinement of the radio-active Hg and its low boiling temperature would make its use in ADS difficult due to the high working temperatures.

With regard to the separation between the proton beam vacuum and the HLM, two types of spallation targets can be considered: the window target where a physical separation is made by a solid window and the windowless target where the HLM is in direct contact with the beam vacuum and the proton beam directly impinges on the liquid metal.

Configurations using a metallic beam window have the problem of the window cooling, cyclic thermal loading under creep conditions, the very corrosive environment, and the radiation damage induced by the protons and fast neutrons in the window material. It is therefore likely that the beam window will have to be replaced at least every 5-6 months.

A windowless target poses the problem of vacuum compatibility: evaporation from the surface should be avoided to not jeopardize the beam vacuum and to retain radioactive spallation products within the bulk material. Another issue is the definition and the stability of the free liquid metal surface in normal and transient (e.g. beam trip) conditions. These problems can be solved by a proper design of the target and lower beam guide (limiting the surface temperatures (< 450 °C) and in this way the evaporation and absorbing/trapping what rests) and a feed-back loop setting the level of the free surface at a pre-defined position.

The problem of jeopardizing the beam vacuum and release of radio-active spallation products should also be taken into account for a window target in the not unlikely event of rupture of the beam window. Safety measures should be taken both in the window and windowless designs.

For the cooling of the ADS spallation target, two options can be considered: cooling by means of the sub-critical reactor primary system coolant or cooling via an independent loop. In order to limit the window operating temperature (< 650 °C), it is likely that the target with window needs an independent loop which allows lower coolant temperatures. In the case of the windowless target configuration, the target can be cooled by the primary coolant because the window integrity is no longer an issue. However, an independent cooling loop gives more flexibility as far as control during transient operations, such as start-up and shut-down.

The HLM target containing the spallation products has to be kept confined within the target unit, separated from the primary coolant, in order to prevent contamination. In case of a gas cooled ADS, the unit has to be high pressure resistant. For both HLM and gas cooled systems, it needs to be designed as a removable unit, because its life is anticipated to be shorter than the reactor lifetime due to the intense radiation exposure, the high local thermal stresses and the cyclic fatigue. The structural materials for the target unit should be compatible with the HLM and able to resist to the mechanical loads on the target at the relevant operating temperatures and under intense proton and/or neutron irradiation.

Material issues

The reference spallation target material in the current designs of accelerator driven systems is liquid lead-bismuth eutectic (LBE). As discussed above, the eutectic has clear advantages over other candidates (e.g. Pb and Hg), both regarding operation temperature and confinement of radioactive products. However, LBE is potentially highly corrosive on most common construction materials due to the high solubility of the alloying metals, mainly Ni and Fe, in LBE.

The process of liquid metal corrosion is initiated by the interaction of the liquid metal with the surface of the material. This damages the protective outer layer and thus exposes the alloying elements in the bulk to solution in LBE. In addition, there is the possibility of the reaction of the material with non-metals that are dissolved in the LBE. The presence of a fast liquid metal flow, in contrast to stagnant lead bismuth eutectic, increases the corrosion speed because of the increased diffusion rate and the contribution of erosion. Furthermore, mass transfer processes of the dissolved material along temperature gradients in the vessel, where compound elements are dissolved in the hot zones and deposited in cold parts, maintain the corrosion. The mechanism also poses an operational hazard due to accumulation of sludge in critical parts like e.g. the heat exchangers. Liquid metal corrosion changes the structure and appearance of the materials surface leading to a possible deterioration of the heat transfer efficiency. Finally, the corrosion will obviously influence the mechanical properties of the materials.

The specific conditions in a spallation target with regard to material corrosion and degradation are even more severe. Firstly, the presence of high energy protons and neutrons produce isotopes via spallation and fission of the target material. These spallation products can modify the chemical composition of liquid metal and consequently the corrosion potential in a very significant way. In addition, the attack on structural materials and a possible target window is enhanced by the thermal load due to internal heating by the proton beam and the radiation burden coming from the hard high intensity proton and neutron field with the latter causing irradiation embrittlement and swelling. In view of these considerations it is clear that the reference materials for the construction of a spallation target must be chosen with due care. The selected substance should meet the following criteria:

- A proven manufacturing process should be available for all components required;
- The material must have the right physical characteristics to be employed in the construction of nuclear components;
- The material should have sufficient strength and be capable to withstand thermal-mechanical stresses and loads;
- The material must have good resistance to LBE corrosion, irradiation by a hard proton and neutron spectrum and possible synergies by the combination of both effects.

At high temperatures (>500 °C) unprotected or uncoated high-nickel austenitic steels are known to be susceptible to severe corrosion in LBE. Ferritic and low-alloy steels, on the other hand have, in principle, a higher resistance to liquid

metal corrosion because of the absence of alloying elements that have a large solubility in LBE. At lower temperatures however, high chromium austenitic steels show better resistance because of the higher stability of the chromium oxide protective layer. The current state of corrosion research indicates that for a mid-term exposure to fast flowing LBE (2 m/s) the operational temperature limits are about 450 °C and 550 °C for unprotected ferritic/martensitic and austenitic steels, respectively. Adding a proper coating, including in-situ oxidation increases these temperatures to 530-550 °C and 600-650 °C, respectively. In highly irradiated parts there is also a minimum requirement for the temperature since results from the SPIRE project indicate that hardening and embrittlement under helium production would be reduced significantly above 400 °C.

It should be noted that in almost all situations an active control of the oxygen concentration in the liquid metal is of paramount importance. The concentration range is defined by the requirements that it must be sufficiently high to allow a stable Fe-Cr-oxide layer to be formed while on the other hand the precipitation of oxides, formed with Pb or removed from the metal surface by erosion, should be avoided.

Further R&D efforts with respect to the materials choice for ADS spallation targets must be aimed at the understanding of the physical and technological aspects of corrosion/erosion behaviour of structural (and window) materials that are exposed to flowing lead bismuth eutectic under irradiation of the hard intense mixed proton and neutron spectrum. On the one hand, investigations should be concentrated on the nickel free 9-12 % Cr type of ferritic/martensitic steels, work that may benefit from the development of low-activation martensitic steels in the fusion material programme. On the other hand, high chromium / high nickel austenitic steels should be considered as well because of their high-temperature strength. In most of current design projects involving a megawatt ADS spallation target, T91 (9 % Cr, 1 % Mo with traces of V, Nb, N, Si and Mn) and SS 316L (16-18 % Cr, 10-14 % Ni, 2-3 % Mo) have been selected as reference materials for both types of steel, respectively, because of the availability of some data from irradiation tests in fission reactors. To optimise the integrity of the materials used in the spallation source the following topics should be covered.

- Susceptibility to LBE corrosion, liquid metal embrittlement and fatigue.

As was already mentioned briefly above, present state of research into the reference materials shows that LBE corrosion should not pose a problem in the relevant temperature range for ADS operation provided that proper control of the oxygen concentration in the LBE is established.

The data on liquid metal embrittlement (LME) are not conclusive. Experiments on SS 316L did not show any LME in the relevant temperature range. For T91 there is some concern for LME to occur in situations predetermining the embrittlement. This may point to a possible synergy between the effects of irradiation/He-formation damage and LME.

Fatigue experiments on T91 have shown that normal cycle fatigue is not significantly altered by the presence of LBE. Low cycle fatigue on the other hand, is affected by LBE. Data taken at 375 °C using a 1-10

Hz cyclic load between 50 % and 150 % of the yield stress have shown a lifetime reduction of 25-30 % in LBE as compared to the same experiment in air. This result is independent of the frequency.

An important concern in this research that focuses on the validation of reference materials for use in structural components of an ADS spallation source is that the influence of the presence of LBE depends on the morphology of the material surface after manufacturing of the component. This means that in principle not only samples with a standard surface but also "realistic" components (after forging, drawing, rolling, machining, welding, etc.) should be investigated. Furthermore, all experiments have been performed using "pure" lead-bismuth eutectic while in the real situation, other elements, in particular spallation products, may be present. In view of these uncertainties the development of protective coatings and surface treatment to augment the corrosion resistance is highly relevant. Finally the tools required to guarantee the assumed conditions of oxygen control must be developed. This argumentation leads to the following, non exhaustive list of research issues that need to be addressed:

- Long time scale stability of oxide layers and scales that are formed on the reference materials by pre-oxidation in air;
 - Influence of manufacturing process on the surface morphology and corrosion susceptibility;
 - Chemical-physical effects of inhibitors in LBE;
 - Influence of spallation products on the corrosion of reference materials in LBE;
 - Development of protective coatings to augment corrosion resistance;
 - Development of an integral oxygen control system with the inclusion of stable and reliable oxygen sensors.
- Susceptibility to radiation

The susceptibility of the reference SS 316 L alloy has been investigated extensively via experiments performed in fission reactors while also some data on T91 are available. Measurable material characteristics that are most relevant to structural design analyses are the tensile stress strain curve, ductility (and the ductile-to-brittle-transition temperature) and cycle fatigue.

- Displacement (dpa) hardening/embrittlement

Present data indicate that irradiation hardening embrittlement under irradiation occurs for both reference materials, in particular for irradiation below 350 °C. The temperature dependence is due to annealing effects in the lattice. Experimentally, the reduction of final elongation under tensile tests, which acts as a measure for the ductility, is found to depend on the irradiation temperature. It seems to reach a maximum for irradiation at 250 °C but data between 250 °C and 400 °C are scarce. Yet, even at the highest doses (up to

50 dpa) there is still some ductility (5-6 %). To fill the gap between 250 °C and 400 °C, a new irradiation at 325 °C has been committed in the fast neutron reactor BOR 60 (Russia).

- He/H hardening/embrittlement

While being exposed to the radiation field, the structural materials are involved in the spallation reaction, giving rise to a range of new isotopes in the metallic matrix. Helium and hydrogen are among the most produced and both cause material hardening and embrittlement. The material degradation due to the presence of alien elements is in principle independent and supplemental to the contribution coming from displacement damage. The concentration of the induced elements in the lattice depends on the production rate and their mobility in the matrix up to the out gassing surface. This is the reason why helium, although it is produced less than hydrogen, is expected to be more damaging. The mobility factor is, together with the annealing effect, responsible for the observed temperature dependence. As before, low temperature can cause higher susceptibility. The temperature range indicated above for displacement damage is valid here as well.

- Swelling & creep

Investigations in the field of advanced fast reactors and nuclear fusion technologies form the basis of the knowledge of swelling and creep behaviour of T91 and SS 316L under irradiation. Actually, the basic reason for selecting T91 as the martensitic steel reference material is the improved behaviour concerning swelling and creep effects under irradiation as compared to the behaviour of austenitic steels like SS 316L under the same conditions. Irradiations at 400 °C, up to 49 dpa, have shown that swelling is small (<0.01%/dpa) for T91 while for SS 316L much higher values have been measured. It should be noted however, that for a high energy (600-1000 MeV) mixed proton neutron spectrum, the nuclear reaction chain is quite different and its effect on swelling and creep must be investigated.

- Susceptibility to LBE/radiation synergy

Up to now, there is no clear evidence on the effect of the synergy between the degrading effects on the structural material caused by exposure to LBE and those originating from proton/neutron irradiation. Solid information can only be obtained by performing irradiation experiments of materials exposed to LBE. These studies are planned within the EUROTRANS project in FP6 and also in fully prototype target tests as MEGAPIE.

Concept (Window- Windowless) issues

As mentioned above, an important distinction in current designs of megawatt spallation targets for ADS is the separation between the window and windowless design approaches. In the first option, a physical separation between the accelerator beam line and the target zone is done by a metal window. The

window forms a cut off between the beam line vacuum and the target material and defines the position and shape of the target surface.

The most difficult technical challenge in this design option is to ensure the integral stability and reliability of the metallic window under very high harsh conditions. These combine cyclic thermal loads, exposure to potentially highly corrosive liquid LBE and a very hard and intense mixed proton/neutron field including direct impingement of the accelerator beam. Consequently, window embrittlement is indeed a major concern.

Irradiation damage calculations were performed within the PDS-XADS project for the window target option in the gas cooled reactor. These indicate that for the envisaged 600 MeV*6 mA proton beams impinging on a LBE target, the target window will suffer irradiation damage of about 210 dpa per year. The bulk of this value (about 85 %) is due to neutrons. It should, however, be taken into account that He effects (embrittlement, void swelling and creep) are yet to be added to the analyses. Nevertheless, if one uses an estimated operation limit for existing ferritic/martensitic steels of about 80 dpa, as was done in this assessment, it turns out that the window should be replaced at least every 4-5 months.

Identifying and testing suitable materials for use in the spallation target window is one of the important tasks in the SPIRE project that has been undertaken. Preliminary results indicate that the ferritic/martensitic steels (like T91) seem to be adequate. In addition, oxide dispersion strengthening, that is expected to increase the window lifetime is being investigated. In any case, definite assessment must await the final analyses of the materials after full completion of the irradiation program.

In the windowless design option the absence of the physical barrier implies that the beam line and target material share a common vacuum and that confinement of volatile spallation products must be incorporated as an integral property of the vacuum system. The target material itself is kept in place by gravity while the target surface is defined by the free liquid metal flow.

In principle, vacuum compatibility of the interface between the beam line and the target is achieved when the proton beam can reach the target material without too much interference. The value of about 10^{-3} - 10^{-4} mbar for the maximal pressure that is tolerable above the target surface is determined by the rate of plasma formation. The latter occurs from the interaction of the proton beam with the gases and vapours that are emanated from the spallation target. The main difficulty in this respect is that plasma formation has a positive feedback because the electrons and ions in the plasma have enough energy to induce desorption of atoms from the beam line wall. These will, in their turn, contribute to the plasma formation and a run-away effect could take place. Intense plasma will cause sputtering on the structural materials, giving rise to an additional thermal load on the beam line walls and may eventually leads to beam clogging. The need to avoid plasma formation thus implies that the vacuum pumping speed, including geometrical limitations must be sufficient to reach required pressure under the given gas load.

The most important contributors to the atmosphere above the target material are the out gassing of dissolved elements, liquid metal evaporation and emanation of volatile spallation products. Experiments combined with theoretical calculations

on this topic performed at SCK•CEN in Mol, Belgium, and at the university of Milan, Italy, have shown that at 400 °C, out gassing of LBE can be reduced to a level where it is comparable to the liquid metal evaporation rate. On the other hand the production rate of spallation products is not sufficient to cause any difficulties as far as the vacuum interface problem is concerned.

Nevertheless, the absence of the target window removes the containment barrier for the radioactive spallation products that is otherwise present. For this reason a closed vacuum system must be foreseen. A possible solution is a scheme in which the vacuum above the target is maintained by a set of cryopumps in order to minimise the amount of moving parts in the spallation target. Periodically, each of the cryopumps is regenerated by a turbo pump that is backed by a small molecular getter pump. The latter may then be treated as radioactive waste. The device may possibly require some initial cooling because of the amount of radioactive materials that are concentrated in the getter pump. It should be noted here that for safety reasons, also in the case of a window design a closed vacuum pumping system should be foreseen. In order to reach a proper design of the vacuum system, the liquid metal evaporation and deposition, the emanation rate of volatile spallation products and the gas dynamics of the beam line geometry have to be investigated.

A last function of the target window that is lost due to its omission is the shaping of the target surface. In a windowless spallation target the surface is formed by the free flow of the LBE through a properly designed nozzle. In order to avoid excessive evaporation at the target surface, surface temperatures should be kept low (< 450 °C for LBE). Consequently, the target nozzle should be designed in such a way that the convective removal of the deposited heat is sufficient to prevent overheating. Heat deposition in recirculation or stagnant zones should be minimised, as it would lead to the formation of hot spots. This is done by excluding or minimizing these zones through the design of the liquid metal flow guide. In addition, the time averaged proton beam profile can be tailored in order to avoid them. Along the same line, emanation of HLM droplets from the surface should be prevented by design. For a vertical target flow – which is the most sensitive for the creation of recirculation zones and droplets – a possible mitigation tool is adding a few percent of swirl to the flow for stabilisation.

R&D programmes in support of the target design are grouped in the TESTRA cluster of ADOPT network and will be summarized further in this report.

Learning from the FP5 activities

Various designs have been studied during the FP5 project PDS-XADS and one can conclude the following:

- Design accommodate different target styles (window or windowless, liquid or solid);
- LBE reactors can accommodate liquid LBE target with both window and windowless concepts;
- Gas cooled XADS relies on liquid LBE window target with solid target as back-up solution;
- Different engineering variants have been developed to account for specific requirements;

- For the LBE-cooled XADS and MYRRHA, the Windowless Target Unit option presents more merits in term of less Reactor Roof activation, longer lifetime and reduced need of material qualification (to be further developed and supported by R&D: CFD/Vacuum system/pumps);
- For the Gas, the solid Target cooled by He seems the most coherent choice and shall improve the window integrity and maintenance aspects.

ADS Primary System Design

Preliminary design studies of the XADS would allow to select the most promising technical concepts, to address the critical points of the whole system (i.e. accelerator, spallation target unit, reactor housing the sub-critical core), to identify the research and development (R&D) in support, to define the safety and licensing issues, to preliminary assess the cost of the installation, and then, to consolidate the road mapping of the development of the European XADS.

Concerning the reactor housing the sub-critical core, three concepts have been identified: a small core (about 20 - 40 MW) cooled by lead-bismuth eutectic (LBE); a larger (around 80 MW) LBE-cooled concept and a gas-cooled concept. The main achievements of the design of the primary systems of the three concepts are summarized hereafter.

Large LBE XADS achievements

- A main vessel with relatively small thickness can be designed, in spite of the significant mass of contained lead-bismuth eutectic coolant, if the plant is provided with horizontal seismic supports.
- The design of a windowless target configuration which exempts from the need to develop and test materials able to withstand irradiation from high energy protons. The effort on the windowless target design has brought to develop a configuration with a quite smaller proton beam pipe cross sectional area, yielding significant benefits in terms of reduced materials activation above the reactor cover plate and hence reduced dose rates in the surrounding region.
- The demonstration, by means of safety analysis that, under abnormal and accident conditions, the adopted plant configuration:
 - Provides an adequate subcriticality margin (according with design requirements) also for very low probability scenarios;
 - Maintains maximum temperatures below values compatible with materials structural capability as well as, based on current knowledge, limitation of corrosion.
- Specific safety issues associated to the LBE coolant such as control of oxygen activity, purification plugging risks, corrosion and In-Service Inspection (ISI) basic technology are to be evaluated more in depth and supported by R&D programmes.
- LBE Technological issues like ISI equipments/repair/maintenance of the components to be further assessed.

Large Gas Cooled XADS achievements

The Large gas cooled XADS has been started from scratch at the beginning of the PDS-XADS FP5 project thus its development is not as advanced as the LBE system. Nevertheless, a serious progress has been accomplished to allow to list here the main achievement as follows:

- Primary system feasibility : no showstopper identified but,
- There are main issues to be addressed in more depth before being able to draw any conclusion concerning this concept, namely:
 - For the reactor vessel and internals: guaranteeing the reactor thimble integrity through the right material selection and therefore their a priori characterization, the thermal-hydraulics assessment of the cooling of the reactor, the assessment of the structural mechanics and their lifetime assessment for predicting their replacement;
 - For the decay heat removal (DHR) system: feedback from transient and reliability studies needs to be further assessed;
 - Development of the design at the end of the FP5 PDS-XADS is still at a conceptual stage and needs more detailed assessment and optimization;
 - Radiation protection around beam line is also here a concern like in the LBE concepts;
 - Reliability and quickness of the measurement instrumentation to shutdown the accelerator could be more demanding in the case of the gas system due to the lack of the thermal inertia existing in the LBE option;
 - Mitigation of severe accidents in case of depressurization is to be addressed.
- Optimization routes identified :
 - Use of advanced cladding material;
 - Solid target with window above the roof to improve window lifetime and simplify its replacement.

Small LBE XADS (MYRRHA) achievements

The Small-scale XADS (MYRRHA) has been conceived from the very beginning as an experimental facility and thus its operation, inspection and maintenance have been conditioned by this objective and consequently affected the design of the facility. An experimental irradiation facility has generally a short operation cycle in order to allow loading and retrieval of irradiated devices containing the various experiments on very regular and flexible manner. An availability rate of 65 % is targeted for the experimental Small-scale XADS (MYRRHA). To achieve this level of availability it is decided from the very beginning to operate the facility thanks to a robotic (remote handling) approach due to the high radiation level and potential α -contamination in the reactor hall. All these considerations led to more innovative engineering options as compared to the large LBE cooled XADS especially when considering the much higher intended power density in the core

for fulfilling the irradiation objective. The main achievements of the Small-scale LBE XADS (MYRRHA) are:

- Core cooled by forced convection;
- Less forgiving than the large LBE but acceptable behaviour in transient conditions with enough grace time for acting;
- Small diameter for the spallation target and interlinking design;
- Fuel inserted from underneath the core support plate for not interfering with the experimental device loaded from the top of the core support plate;
- Provision for irradiation devices (19 irradiation positions in the core – including ones for MA-based test fuel elements – are made accessible through the reactor lead allowing to have irradiation conditions independent of the MYRRHA core conditions);
- Engineering options : Standing vessel / Flat bottom (but this is not mandatory and is left open for later decision);
- Extensive use of remote handling for limiting the shut-down periods between the working cycles that are limited to 3 months with shut-downs in between of one month. Therefore the cooling time is too limited to consider operators intervention.

Definition of the Needed R&D in Support to the Design Activity

The PDS-XADS project has also generated a series of R&D question sheets (QS) resulting from the open questions encountered by the different work packages (WP). These QS's are intended to guide the research community acting in the framework of ADOPT to better focus its activity in the FP6 towards the needs expressed by the design teams of the European experimental ADS. These QS are available through the ADOPT thematic Network (<http://www.sckcen.be/adopt>) now transferred under the EUROTRANS web-site: <http://www.fzk.de/eurotrans>

2.4. FUETRA

In FP5, three projects (shared-cost actions) are still underway within the FUETRA cluster with the aim to study the feasibility of design and fabrication of fuels or targets for transmutation of minor actinides:

- FUTURE (uranium-free oxide fuels design, fabrication and characterization),
- CONFIRM (Pu nitride fuels irradiation, Am nitride fuel fabrication and characterisation),
- THORIUM CYCLE (Th-Pu mixed oxide fuel fabrication and irradiation).

The three projects have been extended due to the difficulties encountered with the irradiation programmes. The main achievements of the various projects are listed below.

FUTURE

The FUTURE project main objective is to design dedicated fuels for an Accelerator Driven Transmuter based on the well-known oxide technology. At this stage, a reference 800 MWth ADT core, cooled with LBE metal has been

designed for this purpose. Different TRU oxide based fuels are being studied: composite fuel such as (Pu, Am)O₂ diluted in MgO, Cr, W or Mo or solid solution such as (Pu, Am, Zr)O₂. (Pu, Am, Th)O₂-based fuel is thought as a backup solution if U or Th free fuel performances are not satisfying. The main achievements are:

- Various CERCER and CERMET U-free candidate fuels have been assessed on the basis of thermal-physical properties, general feasibility and core safety criteria namely: fabricability, margin to melt, coolant void worth, reactivity loss and burn-up performance, and finally the fission probability;
- Dedicated core safety studies of ADS loaded with these uranium-free candidate fuels have been completed to lead the safety criteria results;
- As a result of this down-selection, two CERCER materials with MgO and ZrO₂ and one CERMET candidate with ⁹²Mo are found to be worth undergoing further investigations;
- The fuel development studies confirm the easier fabricability of the TRU-oxide fuels compared to the nitride or metal alloys fuels. The nitride fabrication process is more complex than that of oxide, requiring an additional step of oxide nitridation. The efficiency of the reaction of nitridation is limited by the process temperature kept below the temperature of vaporisation of AmN (1500°C). As regards metal, the fabrication of ingot is difficult because of the high volatility of Am. To limit significantly Am losses during heat treatment, heat and cooling treatments must be rapid and the batch size limited. In both cases, controlled atmosphere (without oxygen and humidity) are necessary to avoid oxidation. The easier fabricability of Am-based oxide has been fully demonstrated through the preparation of the Phénix and HFR irradiation tests. Significant improvements in terms of process simplification, compactness and robustness are possible.

CONFIRM

The objective of the CONFIRM project is to investigate a uranium free fuel for ADS compatible with PUREX reprocessing. The activities being undertaken to meet these objectives are:

- Modelling, fabrication and characterisation of (Pu, Zr)N & (Am, Zr)N;
- Fabrication of 4 (Pu, Zr)N pins and irradiation to above 10 % fission in TRU;
- Safety analysis of nitride fuels: nitride dissociation and ¹⁵N recovery.

As of today, the main results achieved are:

- For fabrication of (Pu, Zr)N, the removal of excess of carbon using H₂-N₂ instead of Ar-H₂ was decided to avoid the formation of ZrC;
- Pellets of (Pu, Zr)N with oxygen impurities below 0.4 % have been fabricated at PSI using powder pressing methods;
- 4 pins of (Pu, Zr)N have been fabricated at PSI and were transported to Studsvik in December 2004. In October 2004, Studsvik decided to shut

down the R2 reactor, and hence the irradiation is being moved to HFR in Petten;

- The thermal conductivity of (Pu, Zr)N measured at CEA is slightly higher than the values previously predicted by AEA-T;
- It has been shown that using N₂ atmosphere for sintering should provide improved stability of AmN;
- ITU has fabricated (Pu, Zr)N pellets from Sol-Gel prepared zirconia spheres using the carbon integration method. This method looks promising for the Pu-based nitride fuel fabrication but at present seems more difficult for the MA based fuel.

THORIUM CYCLE

The goals of the THORIUM CYCLE project are to supply key data for application of Th-cycle in LWR's. In particular, it includes the study of:

- The behaviour of Th-based fuel and extended burn up through an irradiation experiment of 4 short fuel pins (UO₂, ThO₂, (Th-Pu)O₂) up to 55 MWd/kgHM in HFR, and an irradiation experiment of 1 short fuel pin ((Th,Pu)O₂) to 35 MWd/kg HM in PWR (KWO in Obrigheim);
- The core calculations for Th-based fuel, including code-to-code validation, sensitivity check for significant isotopes ²³²Th and ²³³U, and the calculation up to 80 – 100 MWd/kgHM for Pu/Th fuel.

The achievements of the THORIUM CYCLE project are as follows:

- HFR irradiation:
 - Problems with Na coolant are resolved;
 - Irradiation underway (initially foreseen to finish in 2003 but has been delayed due to the Na coolant problem), PIE upcoming;
 - Good behaviour of pins during the ongoing irradiation based on the on-line monitoring.
- KWO irradiation:
 - Licensing of experiment in commercial PWR demonstrated to be feasible;
 - Irradiation underway (in 2003 two irradiation cycles were completed leading to an accumulated burn-up of 23 MWd/kg HM, 3rd cycle completed in 2004 and 4th one in 2005 leading to a final BU of 37 MWd/kg HM);
 - Good behaviour of (Th,Pu)oxide pin based on profilometry examination between irradiation cycles;
 - It will be difficult to conduct any PIE during the FP5 programme.
- Th-based Core Reactor physics:
 - Full core calculations are completed;
 - (Th,Pu)O₂ full core seems to be feasible.

2.5. TESTRA

The TESTRA (Technological Support for Transmutation) Cluster is formed by the four projects (i) **TECLA**, (ii) **SPIRE**, (iii) **MEGAPIE-TEST** and (iv) **ASCHLIM**. These projects are established in support of the window target design: SPIRE for the window material selection and characterisation under irradiation, TECLA for the behaviour of the same material when exposed to LBE and the mitigation of the induced corrosion and MEGAPIE-Test consist of a design of a 1 MW pilot experimental target using HLM as a spallation material.

The main objectives of the TESTRA cluster are: (i) characterisation of materials in terms of corrosion and irradiation resistance, (ii) thermal hydraulic investigations of Heavy Liquid Metals (HLM) (iii) assessment of Computational Fluid Dynamics (CFD) codes, (iv) validation of ADS components to be used in LBE environment and (v) development and comprehensive testing of a HLM spallation target.

An outstanding result of the TESTRA cluster is the success in designing, building and operating Heavy Liquid Metal facilities with well equipped laboratories, which can be used for the various purposes previously mentioned. This important patrimony puts Europe as frontrunner in the field of heavy liquid metal technology.

The main achievement of the four FP5 projects of this cluster are summarised hereafter:

TECLA

The TECLA project was addressing mainly the compatibility of the structural material in contact with the LBE and the mitigation of the corrosion problems in combination with the irradiation embrittlement. The main results obtained within this project are:

- Threshold limit of 550 to 650 °C, above which the oxide layer becomes non-protective for the European steels tested (T91, EM10, EUROFER, A316L);
- Aluminized coatings protect austenitic and martensitic steels up to 550 °C. This needs to be tested now at large scale and complex geometries and later on demonstrate its compatibility with combined effect of exposure to LBE and radiation;
- A new generation of oxygen sensors together with an oxygen control system is available and applied to the operating loops;
- Development and qualification of advanced HLM measurement techniques, such as pressure difference, local velocity, and wall heat flux are achieved;
- Performance and assessment of heat transfer experiments and validation of heat transfer and turbulence models in CFD codes have been started and need further development;
- Performance and assessment of a single-effect experiment to prove the operability of a solid beam window;
- Thermal-hydraulic design and qualification of a closed spallation target has been accomplished;

- Future Needs: Long-term performance of selected steels in flowing Pb-Bi, assessment of mechanical properties in presence of liquid metal and irradiation, development of oxygen control system for large pool design ADS relevant systems.

SPIRE

The SPIRE project was addressing mainly the behaviour of the structural materials ferritic/martensitic pre-selected steels for use for the spallation target window or for the structure of the core in the vicinity of the spallation neutrons source under neutron and mixed (p, n) irradiation conditions. The main results obtained within this project are:

- Irradiation under proton/neutron mixed spectrum (SINQ) leads to an increase of hardening with decreasing the irradiation temperature ($T < 300$ °C) with an acceptable ductility for the investigated conditions (dose ~ 12 dpa, He < 1000 atom-part per million (appm));
- To optimise the lifetime of the spallation target, the in-service temperature range would be: 350 °C $< T < 500$ - 550 °C;
- Based on the reactor irradiation results, at $T < 350$ °C, hardening and embrittlement induced by the irradiation could reach a prohibitive level. At $T > 500$ °C, besides irradiation effects, corrosion, thermal creep and creep-fatigue contribute to define the upper limit of in-service temperatures. Therefore combined experiments are needed to assess fuel cladding materials and window materials;
- Future Needs: complete data for reference martensitic steels and other materials foreseen, such as coatings or high temperature resistance materials.

MEGAPIE Test

The MEGAPIE (**MEGA**watt **P**ilot **E**xperiment) project is a joint initiative of six European research institutions (PSI, CEA, FZK, CNRS/Subatech, ENEA and SCK CEN), joined in the meantime by the EU through the FP5 project MEGAPIE Test and DoE (USA), JAERI (Japan) and KAERI (South Korea). The objectives of the MEGAPIE project are to design, build, operate and assess a HLM spallation target using Pb-Bi, having about 1 MW of proton beam power. The project takes advantage of the existing spallation neutron source SINQ at PSI and presently based on a solid target.

MEGAPIE has a window target cooled by a pumped bypass flow of LBE next to the main LBE cooling flow. An electromagnetic pump has been selected for this purpose. The structural material for the target is martensitic steel (T91) for the lower, active part. For the upper part, austenitic (316L) steel is used.

The project initiated by assessing the feasibility of the HLM target under realistic operating conditions, in order to construct the spallation target module and its ancillary before operating it in SINQ accelerator complex for a period of 6 months in 2006 and later on perform the out-of-pile testing of beam window region via Post-Irradiation Examination. The main results obtained within this project are:

- In collaboration with the International MEGAPIE Initiative, the design of MEGAPIE spallation target is finalised, which includes technical drawings,

neutronic, thermo-mechanical and thermo-hydraulic specifications of each relevant component, the safety report and licensing;

- Geometrically 1:1 scaled water and LBE experiments to investigate cooling of beam window have completed and lead to optimised lower target geometry;
- Electromagnetic pumps for driving the LBE circulation in the target have been newly designed and successfully tested;
- The spallation target is currently being assembled;
- Next Steps: Integral out-of-pile testing in 2005/2006, irradiation phase presently foreseen in 2006 and finally PTA and PIE are to be completed after irradiation.

ASCHLIM

The ASCHLIM project objective is the Assessment of the applicability of existing computational fluid dynamics (CFD) codes (commercial ones such as STAR-CD, FLUENT, CFX, FLOW-3D or Labs ones such as TRIO_U (CEA), FLUTAN (FZK) and others) to HLM thermal-hydraulics especially in the fields of turbulence, free surface and bubbly flow based on benchmark experiments across Europe. The main results obtained within this project are:

- Concerning the turbulence and heat transfer modelling: the Reynolds analogy is generally overestimated in the approach using a constant turbulent Prandtl number. Higher order models are to be used when turbulence anisotropy is important. Wall functions have to be adapted to HLM applications;
- Free surface modelling: all codes and techniques are in principle capable of modelling the global behaviour of a windowless configuration. Strong discrepancies are observed for the turbulence intensity between the experiment and the CFD analyses. Best free surface modelling techniques are available in research codes, but these codes lack an adequate turbulence modelling;
- Bubbly flow modelling: drag laws used in CFD need development for HLM applications. Available models are generally based on spherical bubbles. Bubble shape and diameter should be measured in HLM experiments. Direct Numerical Simulation in combination with basic experiments to describe flow around a single bubble would be the recommended approach;
- Future Needs: fundamental benchmark experiments for specific physical model development such as combination of VOF (Volume of Fluid) for free surface tracking and LES (Large Eddy Simulation) for high turbulent flow treatment and code validation.

One of the main achievements during FP5 of the TESTRA cluster through all Europe is the creation of a complementary combination of test facilities in various countries such as Germany, Italy, France, Sweden, Belgium, Spain and Switzerland. It would be of paramount interest to integrate those facilities in the next future in a Virtual European Laboratory for Lead Alloys (VELLA). This can be

a good proposal for an Integrated Infrastructure Initiative (3I) to be submitted for the last call of FP6.

3. NEED FOR AN EXPERIMENTAL ADS IN EUROPE AND ITS OBJECTIVES

Separation and transmutation of long-lived nuclides aims to reduce the radiotoxic inventory of high level waste to be disposed of. The main contributors to the long-term radiotoxicity of the waste are plutonium and the minor actinides (MA) such as americium (Am) and curium (Cm). Many studies done in the last few years have shown that by removing 99.9 % of the actinides the radiotoxicity of the waste could be reduced by more than a factor of 100. The resulting waste would become less radioactive than uranium ore after more or less one thousand years, thus decreasing the monitoring period of a geological repository.

In order to perform the transmutation of americium and curium in a safe and effective manner, these nuclides should be fissioned in accelerator driven systems (ADS) through repeated recycling. In principle critical reactors, thermal and fast, can be used to fission these actinides, however, addition of minor actinides to the nuclear fuel deteriorates safety parameters crucial for the performance of the critical reactors. The situation is different for subcritical systems. An ADS does not rely on the presence of a Doppler feedback for safe operation, and may hence operate with uranium free fuels. Thus, the elimination rate of long-lived radiotoxic nuclides can be maximised, and the cost penalty for performing the transmutation task can be minimised. The implementation of accelerator driven systems could therefore enable nuclear utilities to take larger responsibility for waste streams produced by them, leading to a reduction in the environmental debt left to future generations. The ratio in terms of transmutation efficiency of MA in ADS system as compared to critical fast reactor is ~10 (135 g/GWh in an ADS loaded with MA Inert Matrix Fuel compared to 12 g/GWh if a FR with a conversion ratio of 0.25). On top of that one should take into account the reduction of the MA loaded fuel transport between the production site and the burning sites in case of the choice of critical reactors.

In order to develop and test the technology for commercial deployment of accelerator driven systems, an experimental facility is required. This facility should in pilot scale prove the feasibility of operating a sub-critical reactor driven by a high intensity accelerator. It is needed to demonstrate the long term applicability of corrosion control in lead-bismuth cooled reactors.

It should further provide the fast neutron environment necessary for developing minor actinide based transmutation fuels. After the planned shut down of Phenix in 2008, no fast neutron irradiation facility will be operational in the EU, and hence the construction of a fast neutron experimental ADS is essential for the task. The availability of a fast neutron spectrum will finally be mandatory for development of more irradiation resistant structural materials that can increase the operational lifetime of commercial ADSs or new generation of critical reactors to be deployed in the future.

An experimental ADS can be also conceived with less demanding working condition in terms of facility rate availability (50 to 70 %) as compared to the one that would be envisaged for an industrial transmuter (70 to 90 %). Such a reasonably but nevertheless acceptable availability rate would allow to

accommodate the beam trips expected for the first-of-kind machine to be deployed. This will then allow improving the accelerator performance progressively towards the performances to be achieved for the industrial ADS.

Ideally, the experimental ADS would become available as soon as possible after the shutdown of Phénix reactor in France. Considering the time needed to design, engineer and test the components, the engineering design phase should at least start in the FP6 period, in order to start operation of the facility between 2015 and 2018.

Moreover, the ADS dedicated research can be considered as a development of modern technology in the area of nuclear engineering that can serve several purposes, the most important of all are:

- § Relaxation of the constraints for the nuclear fuel and the reactor core design without increasing the risk of accidents;
- § Opening of new possibilities for treatment of the LWR spent fuel when it becomes fuel for ADS whereas it was waste in existing nuclear systems;
- § Keeping alive and moreover improving expertise in nuclear industry in Europe in particular in the field of fast spectrum technology - a vital asset for a safety operation of existing nuclear systems, and developing new generation critical reactors if such a decision would happen;
- § Widening the demands for technology solution to other high technology areas of the industry.

A vital development of a new research area like ADS research requires experimental verification of the theoretical research and the consolidation of the design choices.

In case of ADS we need to explore new areas of engineering and to experimentally verify the physics in the work regime not exercised yet. Construction of an Experimental ADS will allow us to:

- § Experimentally verify the coupling of a reactor with an accelerator at real power level;
- § Define the difficulties in system operation and maintenance, and address them within this experimental facility to be ready for an optimum solution when implementing the ADS industrial prototype;
- § Establish and optimise efficient operational procedures for start up, shut down, restart that would be needed for the industrial ADS;
- § Organise excellent research facility in order to refine the nuclear design of commercial ADS as a safe and socially accepted solution to the nuclear waste problem;
- § Have in a second stage a fast spectrum irradiation facility for material and fuel research for ADS, for new generation of critical reactors and for fusion reactor thanks to the even harder spectrum close to the spallation target;
- § Boost the research and development of the high current accelerator and improve its economics allowing for lowering the capital cost of future ADS;
- § Develop the associated technology that will be of value for the ADS as well as in other nuclear energy sectors such as for fission critical reactors as

well as for fusion reactors. This concerns the robotics development in high radiation environment and under HLM, the development of ultrasonic visualisation, the improvement of HLM technology and physics understanding and the development of new structural materials and advanced fuels that are also of interest for the Gen.IV reactor deployment. All these technological developments can be part of the cross-cutting R&D programme for the Gen.IV reactors.

4. UP DATED AND DETAILED ROADMAP FOR THE XADS

4.1. ETWG roadmap for ADS in Europe

The roadmap presented in the April 2001 ETWG report entitled “**A European Roadmap for Developing Accelerator Driven Systems for Nuclear Waste Incineration**”, assumes that a major financial investment would have been made as early as 2003, which was the scheduled year of the beginning of the FP6 (255 M€ over 4 years for R&D, engineering for the Detailed Preliminary-Design and the beginning of construction). This financial investment has not yet been reached even when integrating the EC effort for P&T (31 M€) and the national efforts one can reach a total effort of 100 M€ including generic support R&D. This is certainly not enough as compared to the reasonable estimates of the ETWG. The reason for such a delay as compared to the ETWG planning given below in Table 1 is due to the fact that the option of high level waste transmutation via ADS is not yet fully accepted by all European nuclear countries or at least a majority of them as the most appropriate way of doing it. Indeed, transmutation through critical fast reactors is an alternative option to the ADS route but this will request a rapid deployment of a large number of fast reactors and accepting the contamination of a major part of the reactor park with MAs that one is willing to eliminate. Besides this situation one should mention that in Europe there are many fuel cycle scenarios in application ranging from the once-through scenario up to the double-strata one. There are also various policies regarding nuclear energy ranging from the continuous development up to the phase out policy. Therefore, the emergence of a regional, at European level, HLW management policy accommodating these various scenarios and political choices will be the most appropriate approach leading to the need of deployment of the ADS for the transition period between the thermal reactors era and the fast reactors era. The date by which these prerequisite factors are now more likely to be achieved is the year 2008, corresponding to the completion of the present FP6 EUROTRANS and EUROPART (completion date in 2006) integrated projects that are better integrating the activities covered during FP5 by the ADOPT projects.

Table 1. TWG schedule for development of an experimental ADS and for the associated transmutation technology in Europe

Year 2000+	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	20	30	45
	5 th FP		6th FP				7th FP											
ADS (Phase 1)																		
Basic & Supporting R&D																		
Choices of Options																		
Design and Licensing																		
Construction																		
Low power testing																		
Full power testing																		
Operation																		
ADT (Phase 2)																		
Conversion																		
Operation																		
Prototype																		
Industrial Deployment																		

4.2. Updated Roadmap For ADS Development in Europe

The updated roadmap given in Table 2 takes into account the outcome of the FP5 PDS-XADS project as well as the other FP5 ADOPT projects related to advanced fuel development, material and HLM technology and nuclear data that have led to start the FP6 integrated project EUROTRANS. There is a period of 4 years corresponding to the duration of the EUROTRANS project where potential show stoppers towards the deployment of an experimental ADS (labelled ADS (Phase1) in the ETWG roadmap or XADS in the PDS-XADS FP5 project and later on industrial ADS) should be addressed, namely:

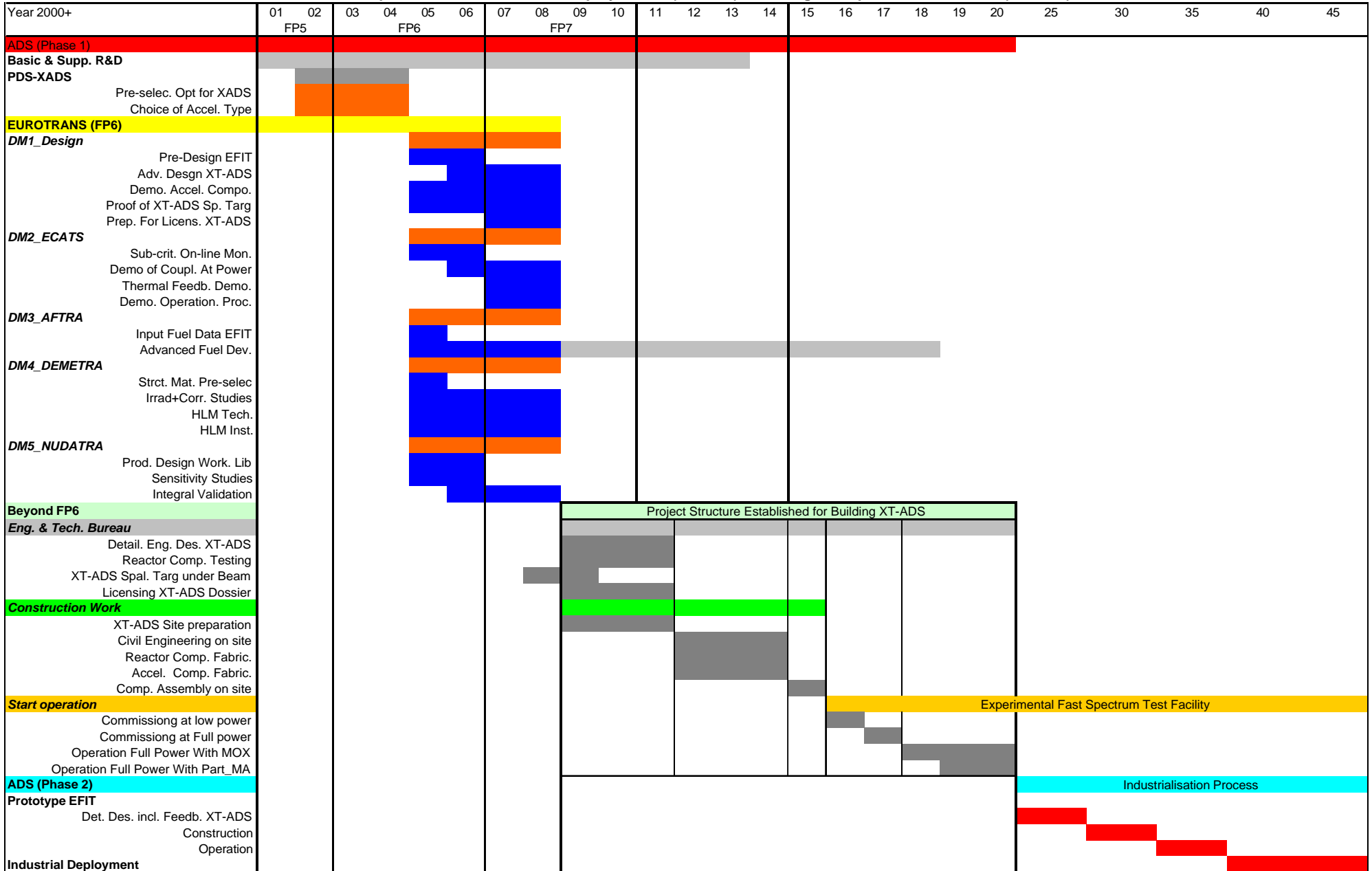
- In basic technological research, the material selection problem for the internal core structures as well as for the spallation target module and fuel cladding in contact with LBE;
- In HLM technology, the problems of LBE conditioning and filtering in pool design conditions;
- The development of the needed instrumentation for LBE quality monitoring in order to guarantee a safe and efficient operation of LBE cooled ADS (O₂-Meters, ultrasonic visualisation under LBE, HLM Free surface monitoring, sub-criticality monitoring, LBE velocity field measurement);
- Demonstration of key accelerator components, namely the reliable operation for periods of 3 months of the injector, the building of both SC and normal conducting intermediate section of the LINAC, the construction and testing of a spoke cavity that would bring the proton beam to an energy level of circa 100 MeV and from there on the development, building

and testing of a cryomodule based on niobium elliptic cavities for the high energy section;

- Full design of the spallation module based on the windowless concept (most promising of achieving high performance core) from the neutronic, mechanical and thermal-hydraulic point of view including vacuum aspects;
- Achievement of the coupling of the ADS components (accelerator, spallation module and a sub-critical core) at realistic power that would allow to study the thermal feedback reactivity, the on-line subcriticality monitoring and control at various k_{eff} values;
- Last but not least the design of the experimental ADS (now labelled XT-ADS in the EUROTRANS project) should be well advanced at the end of the EUROTRANS project (Spring 2009) in order to be in a position to discuss with the licensing authorities on a serious basis;
- Prior or in parallel to the advanced design of the XT-ADS, a conceptual design of a modular industrial ADS unit would be addressed in order to make out of the XT-ADS a test bench as much as possible for the technological choices of the industrial scale system.

At the end of this still generic development period one should enter a project dedicated structure for the construction of an experimental ADS that would last for 10 years for bringing the project to the full power operation of this facility. It will include a first 3 years period for detailed engineering design of the facility, demonstration and testing of the reactor components and putting under beam the already established design of the spallation and finally preparing the construction site and the licensing file. The next period of 4 years would be dedicated to the construction of the components at the production site and the civil engineering at the facility site during 3 years and the fourth year would be dedicated to the assembly on site of the reactor as well as the accelerator components. In 2016 the facility will be then undergoing the commissioning tests for reaching the full operation stage somewhere at the beginning of 2018. The facility will be already able to accept MA loaded assemblies. From then on the facility can be operated as an irradiation facility and for gaining feedback experience to the designer of the industrial ADS prototype EFIT that would be constructed during the period 2025-2030. After a maximum of 10 years of operation of this prototype the deployment at industrial scale would be possible which is the needed time frame also for having the deployment of the advanced reprocessing as well as the heavily MA loaded fuel.

Table 2 : Updated Schedule for ADS Deployment (Phase 2) including an Experimental XT-ADS (Phase 1)



5. ELEMENTS INFLUENCING THE ADS STRATEGY

Besides the technological challenges listed above which can influence the ADS development as a technological endeavour, there are other elements that can impact seriously the ADS development. Among others, these elements are given below.

5.1. Advanced Separation deployment

The deployment of advanced reprocessing, following the PUREX process and aiming at the separation of the MAs Np, Am and Cm from the HLLW stream with an efficiency better than 0.1 % and even of the separation of some LLFPs such as ^{135}Cs , ^{99}Tc , or ^{129}I , could impact heavily on the development of the P&T strategy as a whole and not only on the ADS development. Indeed, as of today the Atalante facility in Marcoule has various labs and hot-cells, where advanced aqueous reprocessing with the above mentioned efficiency can be achieved. However, the maximum treatment capacity of this facility is about 15 kg of spent fuel in the largest hot-cell. This kind of test can be run in a few weeks or months on an exceptional basis, because of the exploitation regulations of the facility, and therefore it cannot be repeated continuously. Thus this will be a very limiting factor for the deployment of the transmutation strategy in general and the transmutation via the ADS route in particular if there is no unit able to produce the feed for ADS prototype. This could be obtained by the deployment of at least an advanced reprocessing pilot-scale unit able to treat 1 ton of spent fuel per year. In average 1 metric ton of UO_2 spent fuel with an average burn up of 60 GWd/t_{HM} contains 889 g of Np, 926 g of Am and 193 g of Cm. The deployment of such a pilot-scale unit should be happening in 2015 to be in line with the updated roadmap given in Table 2.

One should mention that the challenges here are not only of technological nature but also strategic, industrial and commercial ones.

5.2. Advanced Fuel Fabrication

Besides the need for continuing the progress of the development and studying the behaviour of the advanced fuels as it has been done in the FUETRA Cluster projects during FP5 and as it is foreseen in the domain AFTRA of the EUROTRANS integrated project of the FP6, one should also consider seriously the production capabilities available today. Indeed, before envisaging the use of these advanced fuels in large quantity even in a small-scale experimental ADS such as XT-ADS, one should be able to produce a reasonable quantity of such advanced fuel in a reasonable time. Indeed, for instance if we consider the full core loading of ~500 kg of HM to be Am oxide and with the present day capabilities of MALAB at ITU, it would take 2500 years for producing such a core loading. Indeed, the present day capabilities of the MALAB are limited to 150 g/batch for Am and 5 gr./batch for Cm. But the main limitation will be due to the oven capacity used for the pellet sintering in ideal conditions one can reach 50 pellets/week x 40 weeks/years = 2000 pellets (if one speaks about CERMET $(\text{Pu,Am})\text{O}_2+\text{Mo}$ this would correspond to 200 grams Am/year. At best these capacities can be doubled by taking adequate measures.

Thus it is obvious that MALAB is an important tool for the progress of the advanced fuel technology and research development but can not be used as a production unit even at pilot. This means that for being in line with the roadmap developed above we need the deployment of a pilot unit production able to handle few tens of kg at the horizon of 2020.

5.3. Gen IV Fast Reactors Deployment

In the NEA/OECD comparative study of the MA transmutation capabilities of Fast reactors and ADS [3] it has been shown that both critical reactors and ADS can transmute MA efficiently if fast spectrum systems are considered. The only difference is the amount of burning units needed per installed capacity as for the critical reactors the amount of MA in the core will be limited to maximum 5% and even to 2% [4] when one takes into account the uncertainty margins due to nuclear data on the operational safety parameters of the critical reactor. It is also mentioned in various fuel cycle scenarios including fast reactors deployment that if Gen. IV fast reactors deployment would happen around 2030 then the need for ADS can be questioned. Nevertheless, when it comes to the efficient burning of MA the comparative studies show clearly the higher efficiency of ADS [5]. These considerations of time schedule deployment of the Gen. IV reactors as well as the ethical problem of subjecting nuclear workers to the MA hazard by dispersing them in a large number of sites through the burning in critical reactors should be addressed in a cost/benefit approach but also in terms of feasibility with a public opinion opposed to the nuclear material transport. This can be answered partly by the RED-IMPACT FP6 project.

6. CONCLUSIONS

The ADOPT Thematic Network has gathered the main European actors active in the field of P&T and ADS development. It allowed a close interaction among the 14 FP5 project coordinators in the fields of partitioning, nuclear data related to the fuel cycle and ADS development, material research and heavy liquid metal technology for ADS development, advanced fuel development for transmutation and ADS design studies. Through the very successful “International Workshop for P&T and ADS Development” held in Mol (B) on October 6-8, 2003 [6], it allowed a worldwide reviewing of the ongoing activities in these fields of P&T and ADS.

A preliminary roadmap has been sketched by the ADOPT members in 2 phases, the first one leading to the realisation and operation of an experimental ADS and a second phase going far beyond up to the industrial deployment of the ADS technology.

Based on these interactions the ADOPT efforts shaped the next stage of the European activities towards the integrated project EUROPART for the partitioning activities and the integrated project EUROTRANS that will serve as a triggering project for answering still open questions for considering the P&T deployment at large scale. The realisation of the basic building blocks for P&T would consist in:

- The realisation of an experimental ADS that can be partially loaded with MA that can be put in service around 2015-18;

- The realisation of an advanced hydrometallurgical reprocessing pilot unit able to treat at least 1 ton of spent fuel per year that would be ideally developed around 2015;
- The realisation of a pilot plant for producing advanced fuel heavily loaded with MA with a capacity of few tens of kg per year;
- The fourth building block should also be considered, namely the development of a pyro-chemical reprocessing pilot unit able to treat few kg per year of transmutation fuel to be installed close to the experimental ADS.

The appropriate frame for such developments and infrastructure realisations should be worked out by the partners involved in the P&T FP5 and FP6 projects taking into account the international environment in order to strengthen the European position within the Gen.IV International Forum, to answer the legitimate question of high level waste management and to contribute to the energy independence of Europe.

7. REFERENCES

- [1] “A European Roadmap for Developing Accelerator-Driven Systems (ADS) for Nuclear Waste Incineration”, Report compiled by ENEA, Roma, Italy, ISBN 88-8286-008-6, April 2001.
- [2] Proceedings of the 3rd OECD/NEA Workshop on High Power Proton Accelerator, Santa Fe (NM), USA, May 12-16, 2002.
- [3] OECD/NEA Report “Accelerator Driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles”, Report N° NEA#03109, ISBN 92-64-18482-1, (2002).
- [4] M. Salvatores, G. Palmiotti, G. Aliberti, G. Youinou, “Innovative Nuclear Energy Systems and Related R&D Challenges”, ND2004, International Conference on Nuclear Data for Science and Technology, Santa Fe (NM), USA, 26 September – 1 October, 2004.
- [5] M. Cappiello, “The Potential Role of Accelerator Driven Systems in the US”, ICR10-RPS’2004, Funchal, Madeira Island (Portugal), 9-14 May 2004.
- [6] W. Haeck, G. Van den Eynde, Th. Aoust, H. Aït Abderrahim, P. D’hondt (Eds), “Proceedings of InWor’2003, the International Workshop on P&T and ADS Development” on cd-rom, BLG-959, ISBN 9076971072, SCK CEN, Mol, Belgium, October 6-8, 2003.

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