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Impact of P&T on the Final Repository.

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Impact of partitioning and transmutation on the final waste management

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1. Introduction

Nuclear energy generates 30% of the electricity of the EU, at a competitive price, without production of CO_2 or other greenhouse effect gases, and contributing to reduce the energetic dependence from third countries and from the carbon based fuels. Its characteristics, which will be further enhanced in the future generations of reactors, perfectly match the requirements of reduction of emissions, security of supply and competitivity, defined by the EC as the priorities for the future energy supply in the EU. However different countries in Europe make a different evaluation of the cost and risk of nuclear energy versus its benefits, and we can find in Europe countries that have a clear policy to maintain or increase the present nuclear installed power, others planning to reduce or phase out the electricity generation from nuclear fission and countries considering to initiate in the coming years their nuclear industry. In addition, these policies might in some countries change with time or as a function of the future evolution of its economical and political environment.

Independently of the political decision of continuation or phase out nuclear energy, all countries using nuclear energy to generate electricity are facing the question of the final management of its spent nuclear fuel and other high level radioactive wastes, HLW. The disposal in stable deep geological formations has been proven to be a technically viable solution to handle the already available and future HLW. However the Deep Geological Disposal has not been fully implemented in any country, although Finland and the USA have approved its construction and identified, at least, one accepted site for the facility. Other countries like Sweden and France are also close to identifying an emplacement, but most countries have still not selected a site.

Many countries have defined their present policy for waste management as the direct disposal of spent fuel, eventually after some interim storage near surface for 40 to 150 years. However there are two arguments that are driving large interest on searching viable variants and alternatives to the direct geological disposal: the long term sustainability of nuclear energy and the minimization of the long term legacy of hazards for future generations.

From the sustainability point of view, the spent fuel of the present Light Water Reactors, LWR, contains very valuable materials, typically 95% of the Uranium of the fresh fuel and Plutonium with as much energy potential as 25% of the fissile part (^{235}U) of the fresh fuel. There are several reactor concepts, particularly Fast Reactors, but also the new generation of thermal LWR, that are able to use these components of the spent fuel to generate large amounts of electricity. These reactors will fission this new fuel to generate energy, transmuting it from long-lived actinides to fission fragments with largely reduced radiotoxicity and, most of then, of much shorter half-life. Some of these reactors are also able to use higher actinides (Np, Am and Cm) bringing further the utilization of the energy potential and the minimization of wastes from the spent fuel. A continuous recycling of the actinides (U, Pu and minor actinides), that can be implemented combining reprocessing technologies with some advanced reactor concepts, allows to multiply the amount of energy extracted per ton of mined Uranium by a factor between 30 and 100. It should be noted that, according to the most recent estimations [1], the Uranium resources at acceptable exploitation cost might be only enough for 60 to 200 years, with the technologies of the reactors presently in operation. Recycling will make these resources sufficient for several thousand years, making these components of the spent fuel high valuable resources.

The Geological Disposal designs can warranty for hundred of thousands of years that, under normal evolution scenarios, the dose to the public from HLW will be minimal, below the regulatory limits for general public and largely smaller than the dose from the natural radiation in the same area. The reduction in actinides will reduce the heat load at medium and long term, reducing the required

disposal size and/or the number of disposal sites. In addition, the minimization of the finally disposed actinide inventories has a positive value by itself by reducing the consequences of very low probability accidents. For example, the risk of the irradiation of personnel and proliferation of materials will be minimized becoming negligible after few hundred years in all circumstances, including voluntary or accidental human intrusion in the disposal site. It will also eliminate any risk of criticality contributing to a potential simplification of the final storage of the HLW.

In order to reduce the amount of long lived radioactive materials sent to the final disposal a process of separation and recycling, typical of many other industries, has been proposed. This methodology is generically described as Partitioning and Transmutation, P&T. The first step is to separate, or partition, the spent fuel into different components according to its final use or disposal requirements. Different options are considered for combinations but the basic components are:

- The irradiated Uranium, with large mass and volume, low specific radioactivity and thermal load and large energetic potential;
- The transuranium actinides, very small fraction of the total, very radioactive, with very long half-lives and high thermal load, high energetic potential and proliferation attractive;
- Some selected short lived fission fragments, the Cs and Sr, that include the isotopes (^{137}Cs and ^{90}Sr) producing most of the thermal load of the spent fuel for the first hundred years; they are very radioactive during 300 years but of low activity and mass afterwards,
- Some selected long lived fission fragments, the I and Tc, they represent the largest contribution to the radiotoxicity at very long term after the actinides and are some of the main responsibles of the dose at long term from the geological disposal; they are a small fraction of the total and very low specific radioactivity and thermal load,
- The rest of fission fragments, very radioactive and with relevant thermal loads at very short times, but after hundred years they have small specific radioactivity and thermal load;
- The activated structural materials and other intermediate level wastes, of high volume, low specific thermal load and an specific activity that can be low or medium depending on technological choices;

After this partitioning some of these groups will be recycled in normal or advanced reactors (including subcritical ADS). In these reactors the actinides (U, Np, Pu, Am, Cm, …) are fissioned becoming fission fragments or converted in other actinides, this is described saying that they had been transmuted. The spent fuel from this transmutation normally still contains significant amounts of actinides and it is necessary to repeat the Partitioning and Transmutation steps several times. In addition, the parasitic transmutation of the selected long-lived fission fragments could be done by neutron capture in these advanced reactors. The present studies indicate that very large reduction factors (typically 1/100) can be expected for the actinides and long-lived fission fragments.

As a consequence of its potential benefits, large R&D initiatives on P&T had been launched worldwide with large participation of the EU. The Omega project at Japan; the Accelerator Transmutation of Waste, ATW, Advanced Accelerator Applications, AAA, and Advanced Fuel Cycle Initiatives, AFCI, at the USA; a large Partitioning and Transmutation program in the EU, and similar initiatives in Russia and South Korea, efficiently coordinated in several NEA/OCDE working groups and IAEA projects, had developed these new concepts. In parallel, the Generation IV [2], GNEP and other initiatives for the preparation of the medium term future of nuclear energy had incorporated these concepts in their strategies.

This document will summarize the rationales and added value of these Partition and Transmutation technologies for the waste management and how they could introduce variants or modify the approach to the final disposal of the HLW, and the consequences for the final repository. Additional

information on the potential utilization of P&T at the EU and planning for the development of this technology can be found in [20], that has strongly inspired the present document.

2. Background on Partitioning and Transmutation

According to recent global energy scenario surveys [2][4][5][6], the increase in energy demand from emerging countries, the increase on cost of gas and oil and the need of limiting the emission of greenhouse effect gases will result in a world nuclear installed capacity equal or higher to the present park. Indeed [4] predicts that the world nuclear capacity would range between 1300 and 2000 GWe in 2050 and [5] estimates an installed nuclear capacity of 1000 GWe by the same date.

A standard light water power reactor of 1 GWe discharges about 23 tons of actinides each year; cumulatively 900 tons in 40 years lifetime of the reactor [7][8]. One ton of spent fuel of average burnup of 40 GWd/t contains about 10 kg of Pu and 1.5 kg of the other transuranium elements, mainly neptunium, americium and curium, which are called the minor actinides (M.A.). These transuranium elements are not only long-lived radiotoxic substances but also major heat sources which affect the performance of the repository. It is predicted that without partitioning and transmutation of transuranium elements, *"repository availability may be the major constrain to nuclear energy"* [6]. The amount of spent nuclear fuel accumulated in Europe, is estimated as 37000 tons for year 2000 with additional 2500 tons of spent fuel being produced every year [7].

A scientifically proven and technologically available solution for this spent fuel is its disposal in deep stable geological formations. Many countries including many from the EU have selected in the last decades the direct disposal of spent fuel as their final solution for these wastes, however none has still built the Geological Disposal and so no spent fuel had so far been directly disposed. The spent fuel generated so far are stored in the power plants (spent fuel pools or dry storage containers) or in centralized interim storage plants. Still in the EU several countries like France, Belgium, the Netherlands, Germany and UK are or have been reprocessing part of their spent fuel.

The amount of spent fuel and HLW already available and to be produced by the future exploitation of the nuclear power plants, calls for the evaluation of any possible technological solution that might minimize the burden of their final disposal. In this contest, a large R&D effort has been developed in the EU, and other countries, to evaluate and develop a complete set of partitioning and transmutation solutions. The EU effort has been coordinated around the different R&D framework programs, FP, with special increase in the number of projects and resources in the FP5 and FP6. A brief summary of these activities in the FP4 and FP5 can be fount in [10]. Most of these projects concentrate on specific technology development or basic data measurement and evaluation for specific processes involved in the P&T technologies like partitioning technologies (aqueous or pyrochemical), transmutation reactors, subcritical systems and spallation targets, fuels, structural materials and nuclear data for transmutation systems. Complementary the global evaluation of feasibility, performance, R&D needs and implications of the different options for the implementation of P&T in advanced fuel cycles had been performed in the framework of NEA/OCDE expert groups and WPPT (Working Party on Partitioning and transmutation) and WPFC (Working Party on scientific issues of advanced Fuel Cycles), and in IAEA projects. A comprehensive summary of most relevant projects, with detailed review of antecedents and a very complete list of references can be found in [7][11][12][13][14].

The first comprehensive report with a consensus of the possible performance and role of P&T as a waste management technology was [12]. This study however only evaluated the modification of inventories and expected consequences. The implications on the actual waste management and the potential benefits in the final geological disposal had been studied first in [13] and their evaluation is the objective of FP6 project RED-IMPACT, that is including additional realism on the studies by

including considerations on the impact of intermediate level wastes, ILW, and the transition process from present situation towards the advanced fuel cycle.

The main conclusions of these three reports will be summarized in this chapter.

Advanced fuel cycle scenarios

There are many possible new fuel cycle elements and combinations that had been proposed to implement the advanced technologies of P&T, each of these configurations is call a fuel cycle scenario. In first approximation the critical parameter is the mass flows for the different actinides in the fuels or targets of each reactor included in the fuel cycle. Every single study has defined a new set of scenarios depending on the particular topics to be highlighted, however many conclusions are sufficiently generic to be valid for wide families of similar scenarios. A good set of scenarios, from [12], that has been taken as starting point in many other studies is shown in Figure 1.

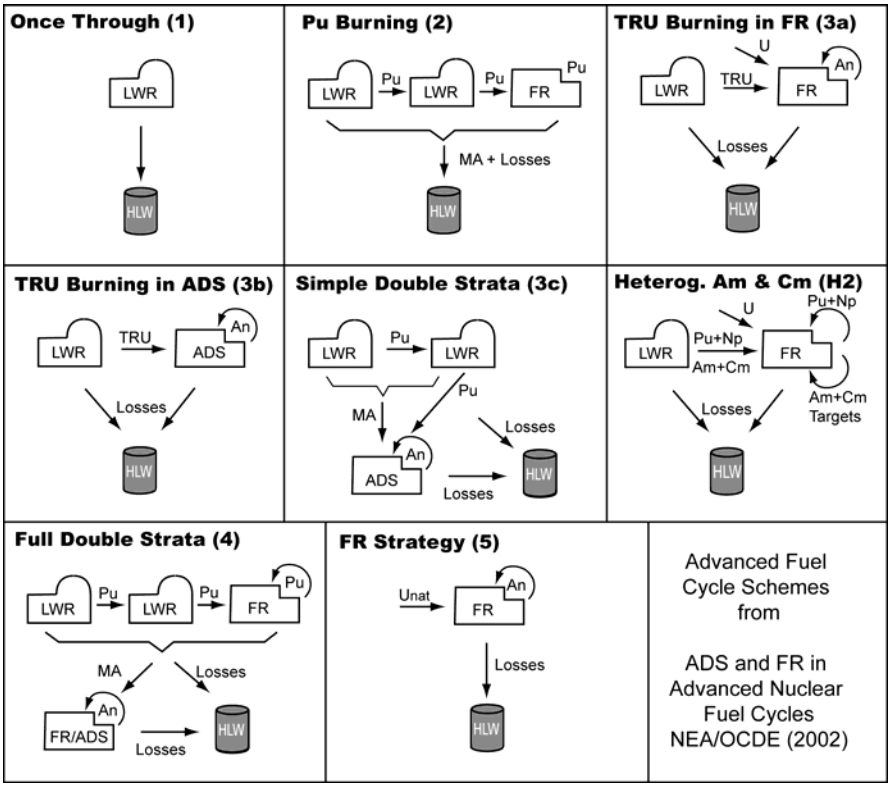

Figure 1: Advanced fuel cycle scenarios from [12], including Light water reactors, LWR, fast critical reactors, FR, and accelerator driven subcritical systems, ADS. The figure indicates the mass flows of Plutonium, Pu, Uranium, U, transuranic elements (Np, Pu, Am, Cm,…), TRU, minor actinides (Np, Am, Cm, …), M.A., and all the actinides (TRU+U), An.

Between these scenarios there are, on one hand, those that transmute all the transuranic elements, TRU, and on the other hand those that only recycle Pu (2), as in the simple closed cycle. Then we can identify scenarios that are based in a more or less complex single stratum (3a, 3b and 5), where the transmutation and the generation of electricity is done in the same reactors, and double strata scenarios (3c and 4) where the electricity generation is performed in reactors with clean fresh fuel (only U and Pu) and there are a small number of transmutation systems dedicated to the minor actinides plus any remaining Pu. Another important element is the combination of systems with fast and thermal neutron spectrum and the selection for the TRU or minor actinide transmutation of critical reactors or subcritical ADS. Finally there is also discussion about the homogeneous transmutation of minor actinides within the reactors fuels or their “heterogeneous” loading in

specific transmutation targets (H2). Although not shown in this scheme the selection of the fuel nature and the reactor, recycling, and fuel fabrication technologies have also important influence on the scenario feasibility and performance.

Partitioning and Transmutation expected performance

The potential benefits of the P&T technologies depends first of all on the capacity of the different technologies and scenarios to reduce the inventories of critical components of the final high level wastes as compared with the spent fuel of the open cycle. This performance was studied in detail at [12] for the eight different fuel cycles described in Figure 1, and with particular attention to the advantages or difficulties of using different types of fast spectrum systems, fast critical reactors, FR, and Accelerator Driven Subcritical systems, ADS.

In the corresponding NEA/OCDE expert group was agreed, by consensus, that the principle of sustainable development requires the fuel cycle of future nuclear energy systems to be closed for plutonium as well as minor actinides to ensure the production of fission energy with limited amounts of natural resources (i.e. uranium) and long-lived radioactive waste. It also requires a safe and cost-effective nuclear energy production. The resource efficiency and waste reduction goals together can ultimately only be reached by the introduction of advanced reactor systems with a significant fraction of fast reactors. For well-known reasons, however, a massive substitution of existing LWR-based by such advanced reactor and fuel cycle technology is not a realistic near-term scenario.

P&T which could address the high-level radioactive waste issue at mid-term and prepare the ground for a more resource-efficient nuclear energy system in the future, may become an attractive and appropriate intermediate strategy on the way to the ultimate goal of the sustainable nuclear energy system. In this context, the accelerator-driven system (ADS) can play an interesting role as a minor actinide or transuranics burner. The interest in such burners is, of course, coupled with the P&T system and might diminish with an increase in the fraction of fast reactors in the park because, in a FR-dominated reactor park, the role of the ADS might be assumed by the FR, although requiring some modifications, and the choice will be based only on still uncertain economical advantages.

The principal conclusions from this study that provide arguments to evaluate P&T added value and which could influence P&T policy development are:

- While P&T will not replace the need for appropriate geological disposal of high-level waste, the study has confirmed that different transmutation strategies could significantly reduce, i.e. a hundred-fold, the long-term radiotoxicity, Figure 2, of the waste and thus improve the environmental friendliness of the nuclear energy option. In that respect, P&T could contribute to a sustainable nuclear energy system.
- Very effective fuel cycle strategies, including both fast spectrum transmutation systems (FR and/or ADS) and multiple recycling with very low losses, would be required to achieve this objective.
- Multiple recycle technologies that manage Pu and M.A. either together or separately could achieve equivalent reduction factors in the radiotoxicity of wastes to be disposed. The study shows that pyrochemical reprocessing techniques are essential for those cycles employing ADS and FRs where very high M.A.-content fuels are used.
- In strategies where Pu and M.A. are managed separately, ADS can provide additional flexibility by enabling Pu-consumption in conventional reactors and minimizing the fraction of dedicated fast reactors in the nuclear system.

- In strategies where Pu and MAs are managed together, the waste radiotoxicity reduction potential by use of FRs and ADS is similar and the system selection would need to be made based on economic, safety and other considerations.
- Fully closed fuel cycles may be achieved with a relatively limited increase in electricity cost of about 10 to 20%, compared with the LWR once-through fuel cycle.
- The deployment of these transmutation schemes need long lead-times for the development of the necessary technology as well as making these technologies more cost-effective. The full potential of a transmutation system can be exploited only if the system is utilized for a minimum time period of about a hundred years.
- Further R&D on fuels, recycle, reactor and accelerator technologies would be needed to deploy P&T. The incorporation of transmutation systems would probably occur incrementally and differently according to national situations and policies.

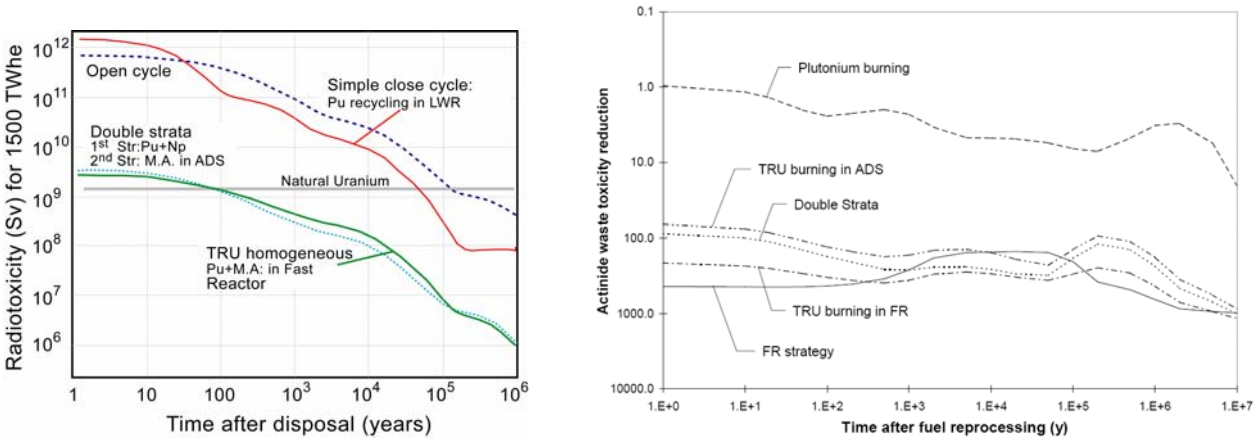

Figure 2: Evolution of the radiotoxicity of the spent fuel in the open fuel cycle and HLW in advanced scenarios from [7] and gain on radiotoxicity as a function of time in advanced fuel cycles from [12].

Impact on the HLW final disposal

After the evaluation of the reduction of inventories, it was realized that one of the main consequences will be the effect on the geological disposal of the HLW. A new NEA/OCDE was performed where the previous study was complemented by studying the possible conditioning of these HLW, and evaluating the effect of the P&T technologies in the HLW final disposal. This calculation included the evaluation of thermal loads, disposal volume of the repository required for the HLW and performance assessment with estimation of the dose to the representative person from the most critical group. The study also improved the economical assessment paying particular attention to the uncertainties and sensibilities on unknown parameters to provide the appropriated understanding of the potential financial implications of implementing the different advanced fuel cycle options. Of particular relevance was the study of complementing the actinide transmutation with the separation of the short lived fission fragments, Cs and Sr, responsible of most of the thermal load at the reference disposal time.

The main conclusion from this expert group was that advanced fuel cycles offer possibilities for various strategic choices on uranium resources and on optimization of waste repository sites and capacities, while keeping almost constant both the radiological impact of the repositories and the financial impact of the complete fuel cycle. In this sense it should be possible to design for acceptable costs innovative nuclear reactor cycles, which at the same time spare resources and make the most efficient use of the foreseen geological repository sites.

The main conclusions from this expert group relevant to understand the added values of P&T are:

- As to the natural uranium demand, the reduction potential of advanced LWR strategies is about 10%, compared with the once-through fuel cycle. A significant (40%) uranium saving can be achieved with the DUPIC fuel cycle, where spent fuel is reused in CANDU heavy water reactors. Higher savings are possible by incorporating fast reactors into the park. And an all-FR strategy will allow the uranium demand to be reduced by more than two orders of magnitude.
- Since the actinides are mostly recovered, minor actinide management techniques, in fact, always reduce the total decay heat of the waste. While the heat reduction at normal disposal time (50 years) is modest (at most 70%), schemes with minor actinide management show a significant reduction potential at longer times. A tenfold reduction could be achieved by prolonging the cooling time from 50 to 200 years.
- Separation and temporarily storage of Cs and Sr can reduce the number of vitrified HLW canisters 25-40%. The interim storage time needed varies from 12 to 32 years depending on the waste loading. Additional cost of Cs/Sr separation and Cs/Sr interim storage results a 5-10% increase in total cost.
- Removing and sequestering Cs and Sr in a separate area of the repository or another facility, would allow a further substantial increase in the drift loading of the repository, up to a factor of 43 in comparison with the direct disposal case for 99.9% removal of Pu, Am, Cs, and Sr.

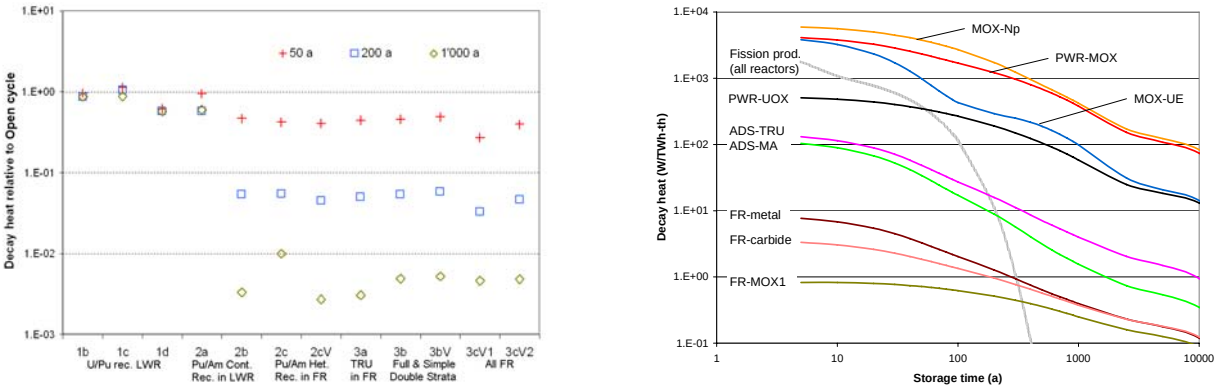

Figure 3: Thermal load from different scenarios in [13]. Ratios respect to direct disposal in the open cycle and the long-term evolution of decay heat from actinides in waste

- Generally, the high level radioactive waste arising from the advanced fuel cycle scenarios generates less heat than the LWR spent fuel. In case of disposal in hard rock, clay and tuff formations the maximum allowable disposal density is determined by thermal limitations. Especially in the case of a fully closed fuel cycle, the considerably smaller thermal output of the high level waste at the considered cooling time of 50 years allows a significant reduction in the total length of disposal galleries required. Separation of Cs and Sr allows further reduction in the HLW repository size. For example, in the case of disposal in a clay formation the required length of the HLW disposal galleries is reduced by a factor of 3.5 when comparing the waste from the fully closed fuel cycle compared to once-through fuel cycle, and by a factor of 9 when Cs and Sr are separated. Extending the cooling time from 50 to 200 years will result in a reduction of the thermal output of the high level waste and, consequently, of the required size of the repository. In the case of advanced fuel cycles this reduction is a factor of about 30.

- In the case of disposal in rock salt the heat generation of the disposed waste contributes to a fast salt creep and void volume reduction. Therefore, a lowering of the thermal output of the high level waste forms needs an optimization of the waste packages and of the disposal configuration.
- For all considered repositories the maximum dose resulting from the disposal of the high level waste from the various considered fuel cycles scenario does not significantly change from one scenario to another. They are differences most often favorable to advanced fuel cycles as a consequence of the reduction of inventories and denser repositories configurations, but the differences are always small. However, the activity of the high level waste arising from advanced fuel cycles decreases faster than that of the reference fuel cycle. This can considerably limit the eventual consequences of less probable repository evolution scenarios, such as future human intrusions, that might strongly perturb the functioning of the HLW repository.
- Using the mass flow of pure plutonium as a simple indicator for the proliferation risk, the schemes can be divided into groups with high (2a, 2b, 2c, 2cV- scenarios with continuous Pu recycling, 3b – full double strata), low (1b – single pass Pu recycling, 3bV – simple double strata) and no flow (all other schemes). Increases in proliferation resistance may be coupled with technical or economical drawbacks.
- All reactor parks including LWRs produce significant amounts of residual uranium. The use or long-term storage or disposal of this uranium has to be considered as an integral part of the waste management.
- Large amounts of the LILW-LL are expected from the reprocessing activities. However, the uncertainties are very large because no real or experimental data on all the secondary waste flows exist.
- Total electricity costs are dominated by reactor investment costs and, therefore, do not vary widely between different advanced fuel cycles schemes. Fuel cycle costs vary between cycles by factor two but are significantly affected by uncertainties on unit costs for advanced technologies and processes.
- The price of natural uranium has a significant effect in LWR cycles and in particular in once-through cycle, whereas the effect is much slighter in cycles involving advanced reactors due to the low consumption of natural uranium. The portion of waste management costs including repository in the total electricity production cost is so low that we could ignore uncertainties in those waste management steps. The Monte Carlo simulation considering large uncertainties of the unit costs illustrates that we can not deny the possibility that the advanced fuel cycle options would cost less than the once-through fuel cycle option.

Similar conclusions had been reached in a number of studies of the Separations and Transmutation criteria to improve utilization of a geologic repository applied to a repository similar to the one proposed at Yucca Mounting [21]. In these studies, the main conclusion is that the repository capacity, defined by the different thermal limitations of the repository after the shutdown of the forced cooling, can be multiplied by a facto of 5 if Pu and Am are recycled, by a factor 40 if Pu, Am, Sr and Cs are recycled and by a factor 91 if Pu, Am, Cm, cs and Sr are recycled.

Impact on the Deep Geological Disposal

Both NEA/OCDE studies had been continued within the FP6 RED-IMPACT project. This project has included the evaluation of the intermediate level wastes, ILW, more complete evaluation of the waste streams including structural materials and fuel impurities activation as well as the activation of all the specific components of the ADS (spallation target structural materials and coolant activation, spallation products activation,…). Also the level of details in the Cs & Sr handling

scenarios and the performance assessment, including in this case the handling of the ILW, has been improved. Finally RED-IMPACT has made a large effort to evaluate the transition process from the present European situation to hypothetical future scenarios.

Although RED-IMPACT has still not presented its final report, the results obtained so far allow reaching the following conclusions relevant for understanding the added value of P&T:

- Thermal power is a critical characteristic of HLW as it strongly affects the required repository volume (gallery length). In scenarios where Pu or M.A. are largely included in the HLW, after the 50 years cooling time the contributions from actinides dominate the thermal load of the HLW and consequently the evolution of HLW thermal power is rather slow and takes about 1000 years to reduce by a factor 10 and about 10000 years for a factor 100. On the other hand, for scenarios with full Pu and M.A. recycling, fission fragments (mainly ^{90}Sr and ^{137}Cs) dominate the thermal power for 300 years in the waste streams and so, the total thermal power for these scenarios is reduced by a factor 10 in only 100 years and by more than a factor 100 at year 300 after unloading.
- These reductions show the possibility, for scenarios with full Pu and M.A. recycling, of large gains in the reduction of the thermal load to the repository and on its associated capacity by delaying the disposal time 100 to 200 years more. Similar reduction on the HLW thermal power can be gained at shorter times by separating the Sr and Cs from the HLW. In fact, when Pu and M.A. are recycled, the heat from the actinides plus 1% of these fission fragments, at the reference disposal time of 50 years, is only 2% of the total. This effect combined with the minimization of fissile materials, might help reducing the volume of the repository for granite and clay formations.
- RED-IMPACT has shown that without specific Cs and Sr management, the HLW disposal gallery length can be reduced in factors that range from 1.5 to 6 for the granite and clay formations. If Sr is removed and Cs disposal is delayed by 50 additional years (disposal time was set as 50 years), then an additional factor 4 can be obtained in some of the geological formations, bringing the reduction in the disposal gallery length to a factor 13. Higher reduction factors are not excluded if the Cs disposal would be delayed longer.
- RED-IMPACT results show that there is small or no advantage from P&T on the dose to the average member of the critical group from the normal evolution scenarios of the geological repository. This is expected because the main component for the dose in these scenarios is produced by fission fragments and activation products. Large difference is found on the different estimations for the margins on the dose from regulatory limits to the predicted normal scenario releases. Different geological formations and even different estimations for the same type of formation show up to three orders of magnitude of difference for the estimated dose from the HLW. The dose from the HLW remain, for all scenarios, several orders of magnitude lower than the regulation allowed dose and largely smaller than the natural dose. On the other hand, P&T have a significant positive reduction on the dose to the reference group in the low probability human intrusion scenarios.
- Indeed, there might be a moderate degradation of the dose depending on the retention of the ILW and the ^{129}I and the characteristics of the matrix used for the immobilization of these wastes streams. For the evaluated clay formation, the dose from both ILW and ^{129}I in advanced fuel cycles is smaller than the one from HLW so their contribution is negligible. However for the evaluated granite formation, the dose from ILW and/or from ^{129}I might become up to one order of magnitude larger than from the HLW in advanced fuel cycles reducing the margins to the regulatory limit.
- On the other hand, RED-IMPACT has identified that the ILW might seriously compromise the advantages of P&T for the repository in some geological formations and for large reactor

parks. In these conditions, sending these materials to the geological disposals might require significant space and might generate additional dose that counterbalance the advantages of the HLW minimization. The main contributors to the ILW maximum doses are the possible impurities in the cladding and structural materials, particularly ^{14}N that could be activated to ^{14}C. If this dose could become a significant hazard, the use of low activation steels and a stronger specification of the impurities content could possible limit the problem. In any case, new repository concepts and, eventually, new legislation might be needed to properly handle the ILW, without handicapping the P&T advantages.

- The time dependent studies have shown the importance of a correct and sufficiently anticipated policy of P&T to take full benefit of the advantage of these advanced cycles. In particular, it is important to start early enough the reprocessing to have accumulated sufficient TRU, Pu or M.A. by the time it is needed in the transmutation plants, without requiring strong peaks in the utilization of the reprocessing and fabrication plants. However, this will result in significant stocks of Pu and M.A. separated or in Pu/M.A. rich fuels fabricated in advance. The studies also show that reaching equilibrium composition is a very slow process and that reducing significantly the waste inventories in scenarios on reduction of nuclear power will require very long times, although regional cooperation might reduce this periods of time to the lifetime of the transmutation plants.
- In addition, the transition scenarios have also shown the relevance of waiting till the appropriate technology is available. For example, the use of standard reprocessing technologies that will send all M.A. to the HLW glasses, will not be acceptable in scenarios of reduction of the nuclear energy installed power, where the M.A. inventory reduction is one of the main objectives. If this was done, the inventory of M.A. immobilized in the glasses will limit the possible reduction on TRU mass to less than a factor 10 instead of the factor 100 reachable if the all the M.A. are transmuted before their storage. These considerations depend on the scenario, and this practice will be much more acceptable in the case of continuous or increased nuclear installed power.

3. Specific Rationales and Added Value of P&T for different scenarios of Nuclear Energy deployment

Added value of P&T for a sustainable energy production from Nuclear Fission

The long term sustainability of nuclear energy requires in a continuous way to maintain or improve the safety, efficacy and economical competitivity, from the technical point of view, and to gain public acceptance and proliferation resistance from the social point of view. In addition it has two technical conditions whose relevance increase with the envisaged duration of the nuclear power exploitation: to find sufficient fuel (at reasonable prices) and to be able to handle the continuous generations of radioactive wastes, particularly the HLW. P&T, in its generic sense, is mandatory for these two conditions.

The presently identified Uranium resources with the present technology and the year 2004 nuclear electricity generation will be exhausted in 85 years [1]. This time can be reduced by the increase of Uranium demand foreseen from the increase of its deployment in emerging countries or can be increased if we take into account all the conventional resources. In total a range of 60 to 270 years is the present projection of U availability, with the second figure implying much larger prices. Indeed the price of Uranium in the market has strongly increased in the last years by more than a factor 5, Figure 4 [8].

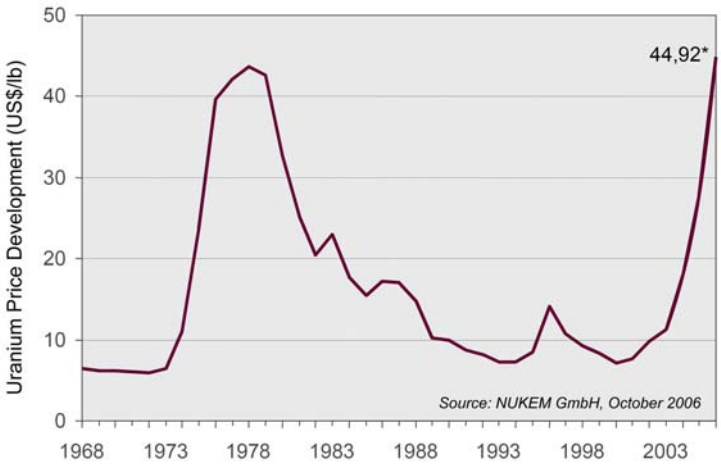

Figure 4: Evolution of the Uranium price [8].

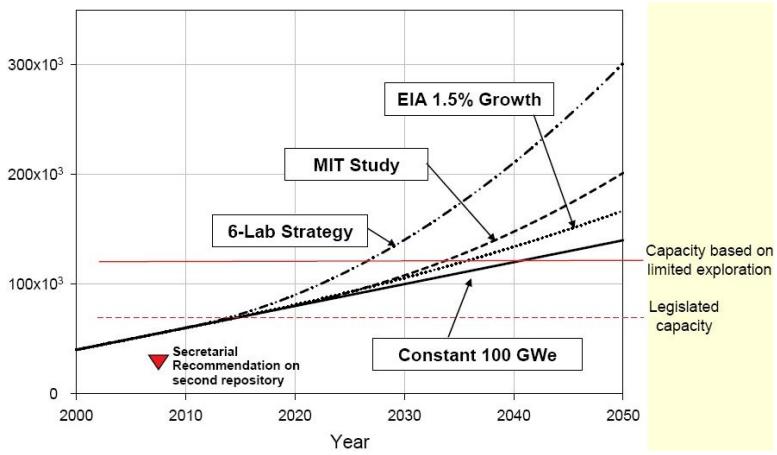

Figure 5: Spent nuclear fuel (metric tons) as a function of time in the USA, for different prospective studies and scenarios.

P&T provides a new technology to the nuclear fuel cycle, based on of fast nuclear reactors and recycling of actinides, that will make the presently identified Uranium resources worth 2500 years. In addition, this technology will turn the spent fuel from the present reactors from waste into valuable fuel, extending even further the possible exploitation period of nuclear fission energy.

Countries committed to the continuous utilization of nuclear fission and with a large park of nuclear reactors would face a continuous production of radioactive wastes and a continuous grow in the number of repositories needed. For example, the amount of spent nuclear fuel accumulated in the USA as a function of time is displayed in Figure 5 for different evolutionary scenarios considered. As for Europe, the existing figures for year 2000 [7] indicate an accumulated amount of 37000 tons with additional 2500 tons of spent fuel being produced every year.

The assessment of the number of geological repositories needed to accommodate the spent nuclear fuel in geological repositories varies with the different scenarios and solutions adopted for the fuel cycles and with the implemented radioactive waste and fuel management policies. As an example, Figure 6 provides an estimation of the number of repositories needed in year 2100 in the U.S.A., for different scenarios and corresponding amounts of cumulative spent nuclear fuel. The reference indicate that only one repository is need with P&T, whereas as much as 5-22 could be required with the direct disposal policy, or otherwise that a repository able to receive the spent fuel of 50 years of open cycle, could accept the HLW of advanced fuel cycles with P&T, corresponding to 250-1000 years.

Nuclear Futures		Existing License Completion	Extended License Completion	Continuing Level Energy Generation	Continuing Market Share Generation	Growing Market Share Generation
Cumulative spent fuel in 2100 (MTiHM)		90,000	120,000	250,000	600,000	1,500,000
		Existing Reactors Only <-----		-----> Existing and New Reactors		
Fuel Management Approach		Number of Repositories Needed (at 70,000 MT each)				
----> No Recycle	Direct Disposal (current policy)	2	2	4	9	22
	Direct Disposal with Expanded Repository Capacity	1	1	2	5	13
Recycle <----	Limited Thermal Recycle with Expanded Repository Capacity	1	1	1	3	7
	Repeated Combined Thermal and Fast Recycle	(requires new reactors)		1	1	1

Courtesy of K. McCarthy

Figure 6: Estimated number of geologic repositories in the USA, for the different scenarios of the cumulative spent fuel in 2100.

Both Fast reactors and Double Strata scenarios with Fast ADS can be useful for these countries. The choice will probably be based on the technological development and financial considerations at the time of deployment. The reutilization of energy and the extension of the value of fuel resources from less than 100 years to several thousands can also be achieved by the simple closed fuel cycle with continuous recycling of U and Pu only. P&T could complement this sustainability axis, reducing the final wastes and the size or number of the repositories at mid and long term.

Added value of P&T for a country reducing the nuclear reactors park or phasing out nuclear

A country reducing the nuclear reactors park or phasing out nuclear will have to cope with the legacy of spent fuels, and the need to define a safe and acceptable strategy to manage them, essentially based on the implementation of a geological repository. P/T offers the potential to reduce the burden on a geological repository, in terms of waste mass and volume minimization, and in terms of significant reduction of the heat load and of the potential source of radiotoxicity.

Indeed for a country phasing out nuclear, P&T will allow to reduce the inventory of long lived radioactive materials by a factor 100 in activity, heat load, radiotoxicity and transuranium actinide elements mass, by 200-300 years after the final disposal of the reduced HLW. This will bring proliferation risks from the repository to the fuel cycle and consume all the energetic resources for electricity production. In this way, the responsibility on the final use of the energy contained in the transmuted actinides and the prevention of its possible proliferating application will be assumed by the present generation, that has the appropriate technology and know how. The reduction of long-lived radioactive isotopes also will strongly reduce the consequences of any remote and very low probability accident that brings people close to the HLW. Indeed, with P&T the HLW radiotoxicity inventory will be restored to the level of mined uranium in 300-1000 years instead of the one million years needed for the spent fuel to reach the same level.

In addition, the P&T will allow reducing the thermal load at disposal time and eventually reducing the required disposal gallery length and the specifications of the final storage site. The very large uncertainties on the cost of the new technologies do not allow concluding if the significant cost reduction on the geological disposal will be compensated by the additional cost of the other elements of the advanced fuel cycles. A reduction on the dose to the public is not to be expected, but it is also not needed as any, properly designed, Deep Geological Disposal site will bring the dose well within the allowed limits for general public and largely under the natural background.

The fastest way to reduce the actinides inventories in the fuel cycle, for a fixed installed power, is to use inert matrix (or low fertile content) transmutation fuel loaded with all the transuranium elements. Fast ADS systems allow using such extreme fuels. However if a country decides to phase-out independently it will find that using P&T by approximately as much time as the nuclear energy was deployed the reduction on the transuranium actinides and radiotoxicity inventory will be limited to something like a factor 4. Otherwise, if the inventories reduction factors have to reach 20-50 the required P&T time might become 2-3 times longer than the operation of present nuclear power plants [15]. This trade-off can be avoided using a regional approach to implement P&T for a country reducing the nuclear park.

Several studies within the WPFC/NEA/OCDE have shown that a "regional approach" can be beneficial to support the deployment of P&T strategies aiming at waste minimization. In fact, to benefit from the recognized potential of these strategies, it is necessary to develop sophisticated technologies for the fuel cycle and to develop new facilities for fuel reprocessing and fabrication and innovative reactor systems. It does not seem probable for countries which have a stagnant or are phasing out nuclear energy, to cope with this major endeavor in isolation.

In [16], both ADS-based transmutation and critical fast reactor based transmutation were considered. The first scenario considered was related to the deployment of a number of ADS shared by two countries with different policies with respect to nuclear, but both committed to waste management and reduction. The ADS did use the Plutonium of country A, which has a spent fuel legacy (approximately 120 tons of Pu and 20 tons of M.A.), and did transmute the minor actinides of the two countries. The Plutonium of country B, committed to a continuous use of nuclear energy (e.g. with a nuclear power park producing ~400 TWhe), is continuously recycled in PWRs.

The main objective of this scenario was to decrease the stock of spent fuel of country A down to ~0 at the end of the century, and to stabilize both Pu and M.A. inventories of country B, Figure 7. The comparison of the number and pace of deployment of the ADS in the regional approach and in the case of ADS deployment by the country A and country B in isolation indicates the significant benefits of the regional approach. Moreover, if the country A had pursued P/T in isolation, despite the relevant deployment of facilities (for reprocessing, fuel fabrication and ADS), at the end of the century ~20% of the initial spent fuel legacy inventory would have not been transmuted. This residual inventory should either be sent to the repository, limiting in a significant way the benefits from the investments in P/T technologies, or be transmuted in additional cycles of dedicated ADS leading to a much longer period required for the phase-out period.

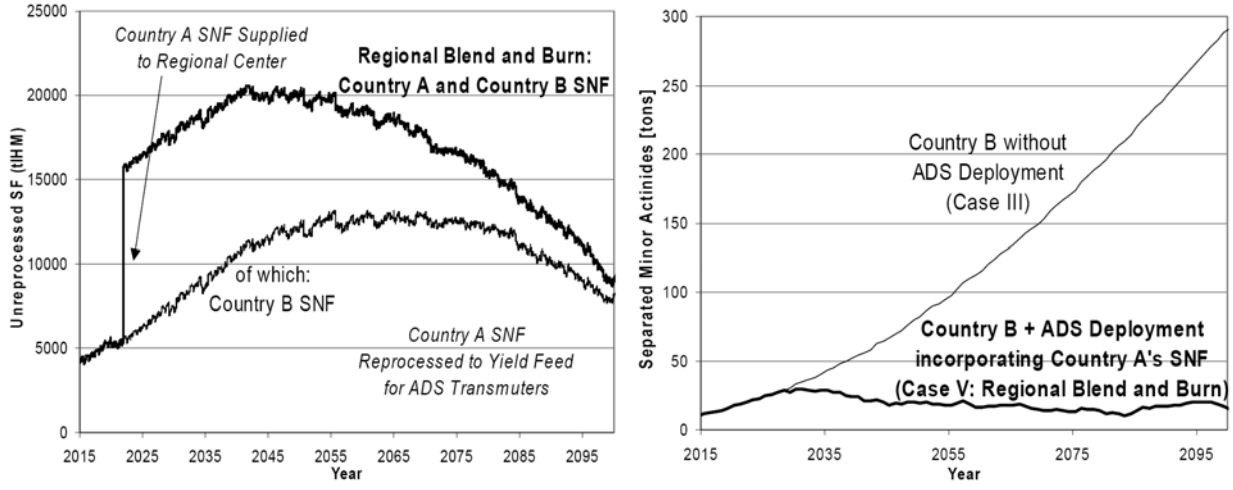

Figure 7: Results of regional scenarios with ADS deployment. Spent nuclear fuel, SNF, and separated minor actinide inventories.

The second scenario considered the deployment of fast reactors in country B. These fast reactors are deployed with the Plutonium of the two countries and recycle all the minor actinides. The main objective of this scenario was again to decrease the stock of spent fuel of country A down to 0 at the end of the century and to introduce Gen-IV fast reactors in country B, starting, e.g., in 2035.

It was shown, Figure 8, that the deployment of fast reactors in country B is not jeopardized by a shortage of Plutonium if the TRU inventory in the spent fuel of country A is reprocessed and used. Moreover, the increase in minor actinide content in the fast reactor fuel, due to the higher minor actinide content in the spent fuel of country A, has no significant impact on the feasibility of the fast reactors in country B. These results confirm the potential interest of regional approaches to the fuel cycle and a regional approach should help to outline a strategy on how to share facilities and fuel inventories to optimize the use of resources and investments in an enhanced proliferation-resistant environment at the European level.

The increase in repository capacity provided by the P&T technologies together with an even closer cooperation at EU level in the radioactive waste management, that might eventually require modifications in the regulatory and legal framework, could significantly reduce the number of final repositories in the EU by grouping the HLW of several countries in one common deep geological disposal facility.

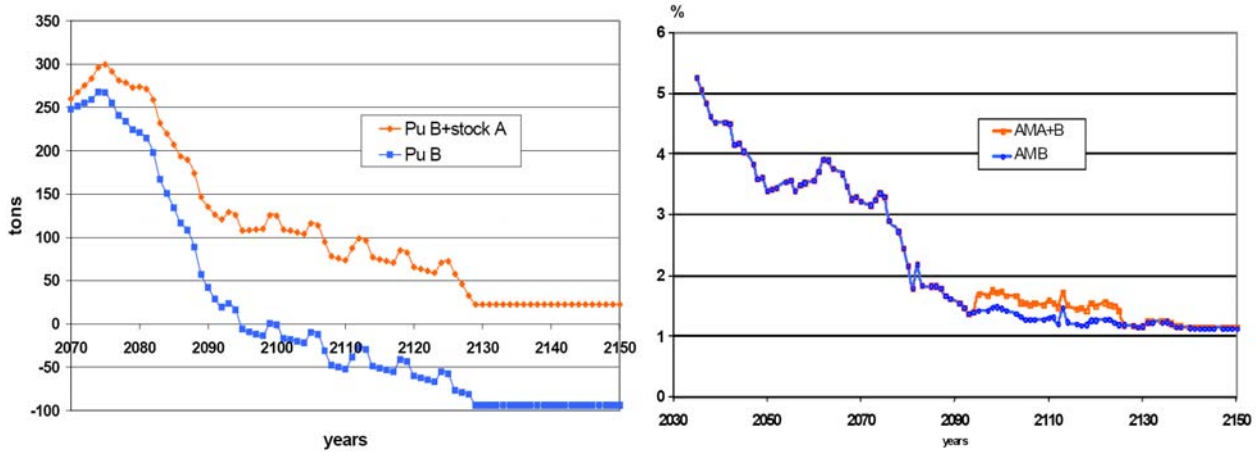

Figure 8: Impact of a regional approach on the deployment of fast reactors in a selected country.

Added value of P&T for a country without installed nuclear energy

High level wastes and their final disposal in a long term repository as well as proliferation risks are always quoted as critical issues which strongly dominate public opinion. As such, countries without installed nuclear capacity but in the process to reconsidering their energy policy and domestic energy mix due to severe concerns on environmental protection and climate changes on one hand, and security of supply and high energy costs on the other hand are often recalcitrant to put forward and support nuclear energy as a viable option vis-à-vis public acceptability.

As already stated P&T can provide large reduction of the TRU mass inventory and, as a consequence, of: radiotoxicity, fissionable materials, time required to reach acceptable risk levels and, at large, requirements of the final waste repository. Therefore P&T development up to full demonstration of feasibility and effectiveness can provide elements to policy makers in order to successfully propose nuclear energy in the country.

Furthermore, P&T is a challenging R&D field with significant synergies and common areas of development with other advanced beneficial technologies such as nuclear fusion, radioisotopes production, nuclear medicine, etc. and leads to spin-offs in the fields of accelerators, spallation

sources, liquid metal technology, etc.. This is also consistent with the European Research Area policy for synergism among research programs and activities in the EU.

In addition P&T is an exciting area of investigation which can draw new generations and maintain and develop competence in the currently stagnating field of nuclear energy research; it may be also seen as a training ground for young researchers.

Finally, countries without installed nuclear energy may have nuclear industries interested in developing new nuclear systems – both critical and subcritical - which exhibit high performances as far as waste minimization through fuel recycling and/or TRU transmutation. P&T technologies also prepare industry to contribute in new reactor development and help to retain and distribute nuclear experience and know-how.

4. Technological choices and R&D&i needs

Fast vs. Thermal Spectrum

The transmutation performances of different systems can be compared on the basis of transmutation physics characteristics.

The variation of transmutation behavior with energy spectrum is illustrated in Figure 9. The fission/absorption ratio is compared for dominant actinides in the PWR and SFR (Sodium Fast Reactor) spectra. The fission/absorption ratios are consistently higher for the fast spectrum SFR. For fissile isotopes (U-235, Pu-239, and Pu-241) over 80% of fast neutron absorptions result in fission, as compared to 60-80% in the PWR spectrum. In addition, the fast spectrum fission fraction can rise to 50% for fertile isotopes as observed for Pu-240 in Fig. 1, while remaining low (<5%) in a thermal spectrum. Thus, in a fast spectrum, actinides are preferentially fissioned, not activated into higher actinides. This implies that fast systems are more “efficient” in destroying actinides because fewer neutrons are lost to capture reactions before eventual fission. Furthermore, higher actinides (Americium, Curium, etc) continue to build-up with LWR recycle. These higher actinides tend to be more radioactive and can be problematic for fuel handling and fabrication in closed fuel cycles.

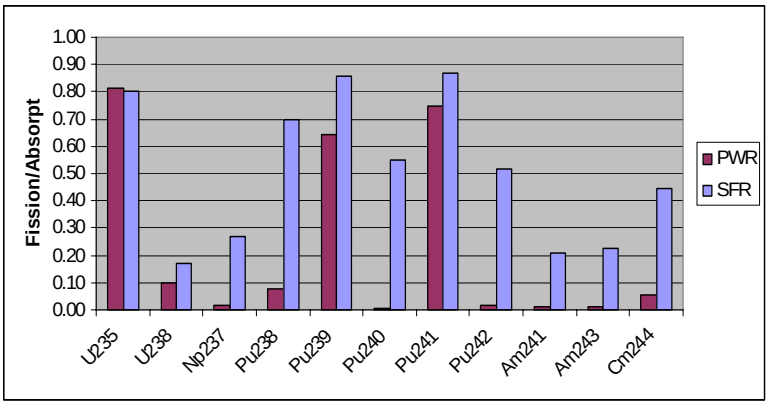

Figure 9: Comparison of Fission/Absorption Ratio for PWR and SFR.

For resource utilization and sustainability goals, it is useful to compare the overall neutron “balance” of the transmutation process. The neutron balance, that depends on the fuel composition, the neutron spectrum and the reactor geometry, has to be sufficient, in any feasible reactor, to provide and maintain the criticality (or subcriticality level) during the required fuel burnup.

As shown in Figure 9, the fission probability is higher in fast reactors, in addition the number of neutrons per fission is higher and there are more (n,2n) reactions and so, in general, all of the fast reactor systems (harder neutron spectrum) exhibit a significantly more favorable neutron balance compared to the thermal systems.

This effect that has been evaluated in [17] [18] is particularly important when the M.A. of the LWR spent fuel (Np, Am and Cm) are loaded in the new fuel, as the change in fission/absorption ration between fast an neutron spectra is larger. This implies that the use of TRU fuel in LWRs requires the addition on fissile isotopes (with an economic penalty) and that the amount of M.A. should be kept low, reducing the transmutation performance.

Conversely, the fast reactors and fast subcritical ADS have a significant positive neutron excess. Thus, the fast systems have the potential to efficiently transmute the base ^{238}U resources, while the thermal systems will require, as indicated above, an additional source of neutrons (fissile feed) to drive the transmutation of the ^{238}U. Finally, the amount of M.A. that can be loaded in a FR is not limited from the neutron balance. However there can be limitations in a critical fast reactor, due to safety considerations.

Critical reactors vs ADS

The NEA study [12] was devoted to the comparison of critical fast reactors and subcritical ADS as transmutation devices. All transmutation strategies with closed fuel cycles could, in principle, achieve high reductions in the actinide inventory and the long-term radiotoxicity of the waste, and these are comparable with those of a pure fast reactor strategy. With respect to these reductions, the potentials of the FR and the ADS are very similar.

With regard to actinide waste production and technological aspects, the TRU burning in FR and the double strata strategies are similarly attractive. The former can gradually evolve to a pure fast reactor strategy, but requires high initial investment in fast reactor and advanced fuel cycle technology. The latter confines the minor actinides to a small part of the fuel cycle, but calls for particularly innovative technology for this part of the fuel cycle, where more R&D is needed and the cost per unit of energy produced will be probably higher.

The sub-critical operation of an actinide burner with a fast neutron spectrum offers interesting additional parameters of freedom in the core design. In particular, the possibility of operating such a burner with a uranium-free (or thorium-free) fuel supply allows the fraction of specialized transmuters in the reactor park to be minimized. A further advantage of the sub-critical operation mode is the tolerance of the system against degradations in the safety characteristics of the core. Both of these advantages are of particular relevance for systems which burn pure minor actinides, e.g. minor actinide burners in a double strata strategy.

As for the upper limit of M.A. that can be homogeneously recycled in a critical fast reactor, this varies according to the reactor size and the type of coolant. In fact, the introduction of M.A. in the core has in general a beneficial effect on the reactivity variation with burn-up (which becomes less negative), but can have the effect of worsening some reactivity coefficients. In general, the Doppler reactivity coefficient becomes less negative and, in the case of SFR, the coolant void reactivity coefficient becomes more positive. For a medium size SFR (i.e. up to ~1000 MWt), a M.A. content of approximately 10% is acceptable, but for larger size SFRs (~3000 MWt), the maximum M.A. content is of the order of 2.5-3%. In the case of a large GFR, this upper limit becomes higher (at least 5%), due to the small value of the void reactivity coefficient. In practice, the homogeneous recycling in a burner FR of a fuel composition as unloaded from a LWR at standard burn-up is feasible from a safety point of view, if the size of the FR is chosen appropriately, according to the

coolant type. At this level of M.A. content, the degradation of the effective delayed neutron fraction is not significant. A higher percentage of M.A. (e.g. in the case of U-free fuels, with a M.A. content >40%) can result in a very significant decrease of the delayed neutron fraction. Heterougenous recycling might offer complementary solutions for M.A. recycling in critical reactors but this research is still in very preliminary phases.

The neutronic properties of fertile-free TRU or M.A. fuel (and in particular the associated low delayed neutron fraction), make much more difficult to design a critical fast reactor with this type of fuel and the ADS concept has a better capability to accept U-free fuels and to reach high transmutation performances. This means that ADS-based transmutation will require a smaller number of transmuters to handle the TRU arising from the electricity producing reactor fleet, and will allow to conceive a separate stratum of the fuel cycle, leaving the fuel cycle stratum devoted to electricity production “non contaminated” by the presence of M.A..

The use of U-free fuels implies the development of the full process for such fuels, which has proven to be a major challenge. Moreover, U-free fuels can present specific characteristics at reprocessing after irradiation, which could require further innovation. These considerations could suggest exploring ADS with some Uranium in the fuel, corresponding to very low conversion ratio values (e.g. less than 0.25), for which a critical core could still present difficulties from the safety point of view. These ADS with partially fertile matrix will require slightly more time and generate more energy to consume the TRU or M.A. but the final waste characteristics and amount will not be significantly affected [19].

For a nuclear energy scenario with a finite time horizon, the full benefit from transmutation can be realized only if, in the shut-down phase, the TRU inventory is burnt and not put to waste. Due to the low power-specific heavy metal inventory of the respective burner, the TRU burning in ADS strategy features a lower steady-state TRU inventory and, in the shutdown phase, can burn this inventory more quickly than the other strategies.

Different fuel candidates and fuel fabrication options

In order to be transmuted the transuranic elements had to be loaded in the fuel of transmutation reactor or in specialized targets. The choice of fuels is a critical issue involving the selection of elements to be included (with or without fertile materials like U or Th) and the chemical form or its fabrication options. These options strongly influence the feasibility of transmutation devices and of advanced fuel cycles involving P&T. For some of the most advanced concepts like inert matrix transmutation of M.A. or TRU, no perfect solution has been found jet although several candidates are being investigated.

The choice of the fuel to be selected for one given reactor system and fuel cycle strategy depend on many elements, like design criteria, safety issues, materials properties, fabricability, reprocessability, etc. Table 1 summarizes the status, for each option considered, of the fuel types examined in Europe. The rationale behind each of these options is, of course, a mixture of the elements described above. However, in summary, one can in a very simplified way, consider the following arguments.

Fuel for ADS

The requirement given from the beginning of the development of the ADS was to maximize the transmutation rate, and thus to avoid the use of U, responsible for the Transuranic (TRU) elements production. After several trials, MgO and Mo (possibly depleted in the n-absorbing isotope) were selected as main candidates for the inert matrix of these fuels. Their capability in terms of core

design was assessed (FUTURE and EUROTRANS) and fabrication is successful. However, irradiations are only starting (2007 in PHENIX and HFR, EUROTRANS) and first results can be expected in 2009 only. Both fuels can be fabricated and reprocessed with conventional methods (aqueous). They both have some drawbacks: the Mo will be less efficient from a transmutation rate point of view, and the safety analyses confirm that the MgO might have some negative behavior from the fuel temperature point of view in accidental conditions. In all cases, the coolant of the system will determine the choice of the cladding: T91 (or equivalent) in case of Pb-Bi or ODS in case of He.

Other choices studied before and considered outside the EU include the ZrO_2 and ZrN. A newly proposed fuel is the MOX, with very high Pu and M.A. contents (up to 40% each). This composition is closer to known FR fuels, but its in-pile behavior is still unknown. The fabrication of this fuel is in principle possible, but this needs confirmation.

Reactor	Strategy	Fuel /Clad Type	M.A. concentration	Status
ADS/Pb or gas	Homogenous-Multirecycling	IMF: MgO,Mo T91? ODS (gas)?	High (40%?)	FUTURIX+HELIOS Results 2009-2010
	Homogenous-Multirecycling	MOX T91? ODS	High (40%?)	Closer to FR MOX No irradiation foreseen
SFR	Homogenous-Multirecycling	MOX SS, ODS	Low	Past experience No irradiation running
SFR	Homogenous-Multirecycling	Nitride, Carbide? SS, ODS	Low	Past experience No irradiation running
SFR	Heterogeneous-Multirecycling	UO2+M.A., IMF+M.A.	High	No experience
SFR	Heterogeneous-once-through	ZrO2+M.A.	High	No experience
LFR	Homogenous-Multirecycling	Nitride? T91?	Low	No experience Synergy with SFR
GFR	Homogenous-Multirecycling	Nitride, Carbide? ODS, SiC-SiC Plates or pins	Low	No experience FUTURIX (2009) Synergy with SFR (pin concept)
GFR and LFR	Heterogeneous	Similar SFR		No experience
VHTR	Homogenous	Coated particles	Low	Experience with Pu

Table 1: Status of the fuel types examined in Europe for the Advanced Fuel Cycles.

Fuels for Sodium cooled Fast Reactors, SFR

The SFR has been build and is still in operation in various countries and MOX is the main candidate. The fuel to be developed should have two new characteristics: higher burnup (and use of improved cladding – ODS), and incorporation of M.A. (however in small amount). An earlier experiment with M.A. (SUPERFACT) manufactured at ITU and irradiated in PHENIX has demonstrated the viability of the proposal. However, additional irradiation experiments are required. Alternative fuels (with higher actinide density and lower fuel temperatures) considered are the nitride and carbide ones. Past SFR experience exist as well and it is being reviewed.

In SFR, as well as for the other FR systems, an additional option considers the heterogeneous recycling of the M.A. (e.g. in the blankets). The matrices considered are UO2 and MgO or Mo (in

case of multi-recycling option) and ZrO_2 (for a once-through strategy). These options are considered within the EFTTRA collaboration. Experiences on the once-through option are being conducted in PHENIX and HFR. Fuel fabrication and reprocessing of these fuels are certainly possible, but further research and development is needed before going to a larger fabrication line.

Fuel of Lead cooled Fast Reactors, LFR

The situation is similar to SFR, except that the cladding is T91 or equivalent, due to the choice of the coolant. The cold nitride fuel might present some advantages that make it the preferred option. The CONFIRM project of the FP6 in the UE was dedicated to this type of fuel, but no program is running today in the EU, although a large R&D effort is devoted to nitride fuels in Japan. A synergy with the SFR is expected.

Fuel of Gas cooled Fast Reactors, GFR

The specificity of the GFR is the coolant (He) and mainly its temperature (800°C or more), and also the need of a compact core. Therefore, nitride and carbide fuels are the preferred options, each of them presenting arguments and challenges. However, the main challenge lies in the development of a new cladding, able to sustain the high irradiation conditions: SiC reinforced by SiC fibers is the preferred option, with ODS (and lower temperatures) a back-up. Moreover, two main designs are considered: the plate-type fuel and the classical fuel pin. Some irradiations are under preparation (PHENIX), but additional programs (in synergy with the other FR) are required.

Hydrometallurgical vs. Pyrometalurgical reprocessing

Actinide transmutation implies the handling of fuels with very high decay heats and neutron source strengths. A significant effort is required to investigate the manufacturability, burn-up behaviour and reprocessability of these fuels. This applies particularly to fuels with high minor actinide content, which can probably be reprocessed only with the help of pyrochemical methods. These methods have to be further developed to tolerate from ten to more than twenty times higher decay heat levels than those encountered in the pyrochemical reprocessing of fast reactor fuels.

The PUREX aqueous reprocessing is in commercial exploitation for LWR fuels and very well suited for large amounts of spent fuel to be reprocessed. Large R&D has been conducted to prepare advanced hydrometalurgic reprocessing able to separate not only the Pu and U but also the M.A.. These extensions can be done to obtain streams of individual actinides or of grouped actinides, more resistant to proliferation. This technology will most probably be selected for the reprocessing of all the LWR spent fuels, UOX or MOX.

Indeed, the PUREX aqueous reprocessing can be considered as valid for the FR-MOX fuel in the plutonium-burning and double strata schemes. Reprocessing of this fuel within short cooling times and with the required high recovery yields, however, will require the plutonium dissolution yield to be improved and the PUREX flowsheet to be modified. Due to the high radioactivity of FR-MOX fuel, its handling will require measures to be taken to reduce the radiation doses in the fabrication plant and during the transportation of the fuel assemblies. The increased requirements for shielding, and preference for short transportation paths, of multiple recycled fuels might favour the pyrochemical reprocessing method.

However the organic materials used in the liquid-liquid extraction of PUREX and other advanced hydrometallurgical reprocessing techniques will be degraded by the radiolysis and the high temperatures of the transmutation fuels with high content of M.A. and Plutonium. The Pyrometalurgical reprocessing technologies had been proposed for this type of fuels. The introduction of pyrochemical processing techniques at the industrial level will require the

development of new process flowsheets and the use of potentially very corrosive reagents in hostile environments. These processes will generate chemical and radiological hazards which will have to be mitigated. The technology has also been proposed as a complementary step after a hydrometallurgical separation of U and Pu, like in the advanced UREX process.

5. General Conclusions

Partitioning and Transmutation applies the general principle of most sustainable industries of classification (partitioning) and recycling (transmutation) of the components that are useful or dangerous for the population or the environment to the nuclear fuel cycle. With reasonable extrapolation of the performances of present technologies, P&T will allow to largely reducing the long term burden of the spent fuel and high level waste, and in this way it can contribute to significantly improve its management.

The main objective of P&T are the transuranium actinides, Neptunium, Plutonium, Americium and Curium, although the transmutation of some long lived fission fragments, particularly Iodine and Technetium, could also provide interesting benefits. P&T can provide a reduction larger than 100 on the mass of these transuranium elements sent to the final disposal, reaching the same reduction factor on the radiotoxicity for the total of all the high level wastes after few hundred years. This large reduction on the inventories provides significant reduction of the consequences of low probability accidents, like human intrusion, and drastically reduces the potential proliferation interest of the repository. The inventory reduction also implies that the radiotoxicity reaches the level corresponding to the Uranium mined for the fabrication of the fuel within 1000 years, whereas the spent fuel in the open cycle will take several times 100000 years to reach the same level.

In order to reach this reduction, very high separation efficiency (99.9% for U and Pu and 99% for M.A.) is required in the reprocessing technologies. The feasibility of this reduction also requires the use of fast neutron system for all or, at least, a part of the transmutation systems. Fast critical reactors or ADS could both be used in this sense. In addition, it is also necessary to find a final use or final disposal for unused Uranium.

This reduction of the transuranium actinides results, in addition, in a large reduction of the thermal load of the wastes send to the geological disposal. Indeed, if the recycling is applied to all the transuranium elements, the thermal load is largely dominated by the Cs and Sr fission fragments. Their short half live, 30 years, provides a fast decay of the thermal load send to the repository. If all the high level wastes are sent to the repository after 50 years cooling time, the gain on thermal loads, although depends on the details of the fuel cycle, will be modest. However delaying the disposal time for 100 or 200 years provides, in the case of fully closed cycles with P&T, large reductions, above a factor 10, on the heat load to the repository. Alternatively, the separation of these two elements from the high level waste produces immediately the same thermal load reduction factors. In this second case, a specific interim storage is required for the Cs and Sr.

The thermal load is the critical parameter determining the capacity of granite or clay deep geological repositories. The reduction of thermal loads from P&T can allow to increase the repository capacity or to reduce the disposal gallery length needed. If the HLW disposal is delayed by 100 years or Cs and Sr are separated by at least 100 years and P&T had been applied to all transuranium elements, the disposal capacity can increase by more than a factor 10, and in optimal conditions it is possible to reach a factor 50. Even if there is not such optimization, the capacity can increase by factors from 2 to 6. These gallery length reduction factors can be used to reduce the cost of the repositories or to reduce the number of sites.

Especial attention will be required to the selection of low activation structural materials and very low level impurities content, and to the optimization of the intermediate level waste management, as otherwise their increase in the advanced fuel cycles could seriously compromise the advantages of P&T for the repository in some geological formations and for large reactor parks.

The P&T technologies will not significantly alter the dose to the average public person from the normal critical groups. Without P&T this parameter is designed to be more than one order of magnitude below the regulatory limits and the natural radiation background on the surface. This dose is mainly expected from the fission fragments and activation materials and so P&T will not provide significant reduction, except if Iodine is transmuted. On the other hand, attention should be put to avoid that the new ILW do not significantly increase this dose, particularly in the case of large reactor parks.

Different options are possible to implement P&T integral Fast Reactors, Double Strata with ADS, phase-out with ADS and others. The best solution for a country or region depend on its plans for the future use of nuclear energy and the present and future fuel cycle available technologies.

For countries planning for a sustainable use of the nuclear energy from fission, P&T is an unavoidable component. It is needed to extend the potential use of nuclear fuel from less than 200 years to several thousands and simultaneously reduce the amount of high level radioactive waste per unit of energy generated, avoiding the need of large number of repositories along the time of exploitation.

P&T is also useful in case of reduction or shut down of nuclear energy, as it allows reducing the burden for final storage, both from the size and the duration points of view. The collaboration within countries in a region will reduce the R&D efforts required to implement this technology for countries reducing nuclear energy exploitation, and may lead also to reduction on the number of geological disposal sites required within the region.

P&T technologies are attractive also from the point of view of countries considering launching a new program of nuclear energy. It provides the framework for minimizing the difficulties of the back end of the fuel cycle and allows the progressive development of nuclear technologies. Indeed, P&T share several technologies with proposed future generation reactors (spectrum, coolant, fuels, materials,…).

P&T requires the development of new technologies for many components of the nuclear fuel cycle: reactor technologies, accelerator technologies for ADS, fuel fabrication, advanced reprocessing technologies, coolant and material compatibilities. No real show stopper has been found on any of these fields, but the R&D effort needed is large and a clear planning and intensive efforts are required to make these technologies industrially deployable by the 2040-2050, when present estimations indicates they will be required. The next critical step of this R&D is the design and construction of demonstration plants for an advanced fast system optimized for actinide transmutation, possibly a subcritical system, an advanced reprocessing facility and an advanced fuel fabrication facility.

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