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Impact assessment report for fuel cycle implications

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D8.5 Impact assessment for fuel cycle implications

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CONTENT

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ABBREVIATION LIST

ADS	Accelerator Driven System
CEA	Commissariat a l'energie atomique et aux énergies alternatives
EXAM	Extraction Process of Americium
FR	Fast Reactor
HLW	High Level Waste
ILW-LL	Intermediate Level Waste - Long Lived
LILW-LL	Low-Intermediate Level Waste- Long Lived
LWR	Light Water Reactor
MA	Minor actinides
MOX	Mixed Oxide
P&T	Partitioning and Transmutation
TRU	Transuranic
UOX	Uranium Oxide

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INTRODUCTION

In order to prioritize the Partitioning and Transmutation (P&T) strategies in the EU, it is necessary to assess them regarding economic factors. Cost benefit analysis is an important decision-making input for proposed fuel cycle schemes and many comparative studies can be found on this basis. However, when it comes to the management of back-end fuel cycle activities, qualitative factors can have equally significant impact on decision: such as socio-political issues, environmental aspects, technical bottlenecks, proliferation resistance and public acceptance. For instance, a political shift (e.g. postponing a R&D programme in one reactor design) in the future may create added cost for a defined scenario.

This report qualitatively compares various P&T scenarios considering both conventional[2] and advanced systems. Advanced systems include Fast Reactors (FRs) and Accelerator Driven System (ADS) which employ fast neutron spectrum while conventional systems refer to the current nuclear fleet using thermal neutron spectrum. Initially proposed in the previous report[3], these scenarios as given in Table 1 have been examined and clarified with the aim of providing as far as possible objective insights about P&T systems. For instance, this report does not only focus on the beneficial impacts of the P&T but also identifies the challenging aspects which hinder their commercialisation. The qualitative differences between these scenarios and their viability are evaluated with the help of several industrial experts who are dedicated to the development of P&T technologies.

Table 1: Proposed P&T scenarios in the previous report

#	Partitioning	Transmutation
1a	Mono-recycling of U and Pu	Thermal reactors
1b	Multi-recycling of U and Pu	Fast reactors
2	Multi-recycling of U, Pu and Am	Fast reactors
3a	Multi-recycling of U, Pu and all MA	Thermal reactors followed by ADS
3b	Multi-recycling of U, Pu and all MA	Fast reactors followed by ADS

More importantly, these elaborated scenarios were put into the context of the sustainability goals of advanced nuclear energy systems with emphasis on economic, socio-political and

[2] In this report, conventional nuclear is used for the term of Light Water Reactors (LWRs).

[3] In this report, the term of "previous report" is used for the report D8.3 delivered by LGI Consulting on 8 November 2018.

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environmental point of view, and general feasibility. These goals for such advanced systems are based on tackling one of the perils of nuclear energy i.e. the spent fuel management.

OBJECTIVE AND STRUCTURE

The major objective of this report is to assess whether the elaborated scenarios are worth a substantial effort required to deploy them as well as which extent to claimed sustainable goals in each scenario are likely to be attained. This was achieved through conducting interviews with experts on technical, environmental, economic and socio-political aspects of P&T and asking them to input to various scenarios (the scenarios and findings are detailed later in this report).

Regarding the sustainability goals of the nuclear energy in the EU, the present study complements motivations and challenges of each scenario with their variants among other possible P&T systems.

While the section “Technical background” concentrates on motivation of the P&T strategies with advanced fuel cycles, the section of “Preliminary Findings applying to advanced P&T Strategies” highlights main challenges which are likely to hinder the advancement of the innovative fuel cycle technologies.

Meanwhile, the Section of “Elaboration of proposed scenario” gives details about the scenarios proposed by the previous report by clarifying the flowsheets of each scenarios as well as their applicable variants.

All these motivation, challenges and extended scenarios are discussed with selected key industrial experts through online interviews. Main results pertinent to the P&T systems and scenarios-based conclusions are given in the Section of “Summary of the interviews”.

Finally, the outcome of this report given in the “Conclusion” aims to provide the future researchers and decision makers with possible approaches for the P&T implications.

METHODOLOGY

Regarding the objective of this report, the work is divided into three steps:

- Desk research – Analysing and gathering the supportive and disincentive factors for the P&T and elaborating the scenarios proposed in the previous report,
- Undertaking interviews – Discussing the elaborated scenarios and the information obtained in the previous step in order to exploit from first-hand results from industrial experts who are developing P&T technologies,

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- Validation – After synthesising the results and establishing the impacts of each scenario, validating them through steering committee and concluding the study.

TECHNICAL BACKGROUND

Continued debates on environmental and public concerns stemming from the back end of nuclear fuel cycle activities have always been the impediment of sustainable development of nuclear energy. Maximising the use of energy resources, partitioning and transmutation of transuranic[4] (TRU) elements fulfils the sustainability goals for nuclear energy through the reduction in:

- radiotoxicity[5],
- decay heat,
- wastage of valuable sources in the spent fuel,
- safety requirements and the size of geological repository[6],
- proliferation materials' attractiveness.

While significant partitioning processes have been advanced at the laboratory scale, further R&D efforts and demonstration facilities are a glut need to attain the plausible industrial partitioning. As of today, only one partitioning process – PUREX has reached the industrial scale.

On the other hand, transmutation of major actinides would require the deployment of advanced reactor systems with reformed fuel cycle options other than those used in conventional nuclear systems. This need is due to the greater transmutation (higher fission or capture cross section) probabilities of all TRU isotopes in fast neutron spectrum of which the description is not included in the scope of this report.

RADIOTOXICITY

Dashed red lines in Figure 1 plot the impact of eliminating the major actinides on radiotoxicity evolution of spent LWR (UO_2) fuel irradiated to burnup of 50 GW·d/tHM. Without recycling

[4] TRU elements which are also called major actinides, include plutonium and minor actinides: americium, curium and neptunium. These are formed during the burn-up of the nuclear fuel.
[5] Definition of dose equivalent in terms of Sv in order to describe hazardous biological effects of radionuclides on public or environment through different pathways such as ingestion, inhalation or direct radiation.
[6] Any initiatives promoting sustainable nuclear energy oblige States with nuclear energy programme to construct a geological disposal site to permanently host the high-level wastes (HLW) either in vitrified cannisters or integral spent fuel generated from fuel cycle activities.

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these elements, it takes more than a hundred-thousand years for the radiotoxicity induced by spent fuel to reach the reference toxicity level of natural uranium.

While the radiotoxicity is initially dominated by fission products[7], the long-term radiotoxicity is induced by major actinides, especially plutonium and americium. Partitioning plutonium by itself from spent fuel leads to reduction the radiotoxicity by a factor nearly 10 [1]. Plutonium recycling is the only industrialized and technologically mature partitioning practice, which uses PUREX process (see the Scenario 1). Following the plutonium, americium is present in a large amount in the spent fuel and a major contributor to the radiotoxicity. Combined with its relatively higher transmutation probability, americium is the most notable minor actinide to be partitioned from spent fuel (see the Scenario 2).

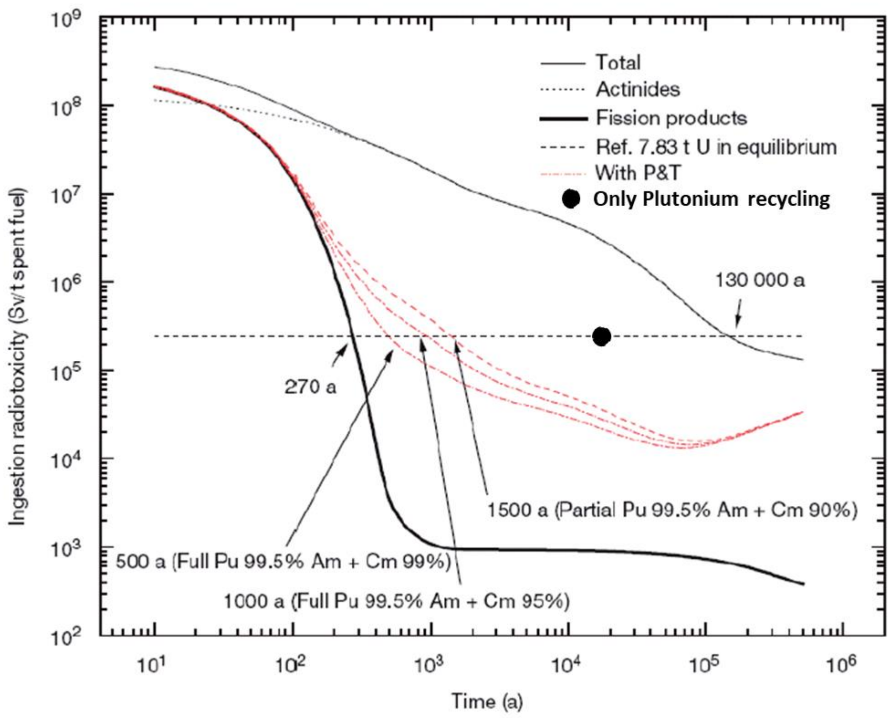

Figure 1: The radiotoxicity evolution of final waste over years with different fuel cycle options are affected by removing TRU elements. The figure is excerpted from the [2] and modified by the information obtained from [1].

Figure 1 also shows that radiotoxicity can be decreased to the reference level within 500 years by partitioning all actinides from spent fuel and eventually transmuting them into less radiotoxic radionuclides. In this regard, various partitioning processes which have been in detail explained in the previous report (variations of SANEX: i-SANEX/1c-SANEX or EURO-

[7] Significant fission products include ^{135}Cs, ^{99}Tc, ^{79}Se and ^{126}Sn. It is essential to note that some volatile fission products whose half-life is very long such as ^{129}I and ^{14}C is released to the environment in a regulated way during the reprocessing of spent fuel resulting in lower dose in HLW vitrified canisters.

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GANEX), which have not been industrialized yet, aim to selectively partition these actinides and fission products from the bulk raffinates (Scenario 3). As a fully closed scenario, this requires multi-recycling of actinides which should gradually be separated from fission products over years and continuously returned to the reactor core[8] to be burned together by topping up with new fresh fuel or new target[9].

On the other hand, complete recycle of actinides would at best be unlikely in any scenarios given technical aspects. For instance, curium and its principal isotopes in the spent fuel has a relatively lower transmutation probability that is unlikely to be destroyed in the reactor core. In spite of the difficulty for the separation of americium and curium, CEA developed an extraction process of americium (EXAM) from PUREX raffinates in order to recycle americium itself to produce $(U,Am)O_2$ pellets, however further efforts are required to demonstrate its viability at industrial scale [3]. As mentioned earlier, Scenario 2 considers the americium partitioning from the spent fuel and envisages to fabricate separate Am fuel[10].

It is disputable that elimination of actinides mass in final waste form would lead to a limited impact on performance of an inevitable geological repository. Results obtained from the RED-IMPACT project indicate that transmutation of minor actinides in either advanced fast reactors or accelerator driven systems would have a slight effect on radiotoxicity [4]. This is because:

- Maximum radiological environmental dose is controlled by fission products,
- Minor actinides have very low solubility in groundwater and have a high sorption capability by natural and engineering barriers.

The most prominent benefit of the reduction in the actinide content from the final waste is the prevention of the accidental scenarios in a case of human intrusion such as deep drilling of the ground resulting in dose intake for workers.

In this regard, thermal considerations such as decay heat on performance of the geological repository may outweigh the importance of reduction in radiotoxicity of final waste.

DECAY HEAT

In the light of the imperativeness geological disposal for any nuclear fuel cycle scenario, decay heat output of HLW plays major role as it limits the capacity of any geological disposal sites and determines the waste density. Figure 2 illustrates the change in decay heat generation

[8] Fast reactors or accelerator driven systems.
[9] In cases where energy production is not pursued, i.e. minor actinides burning in ADS, target is used instead of fuel.
[10] Transmutation of americium on heterogonous mode.

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from both actinides and fission products. While the latter dominates the decay heat process in the spent fuel nearly 80 years, actinides - notably americium and plutonium isotopes, become the major decay heat contributors to the final waste.

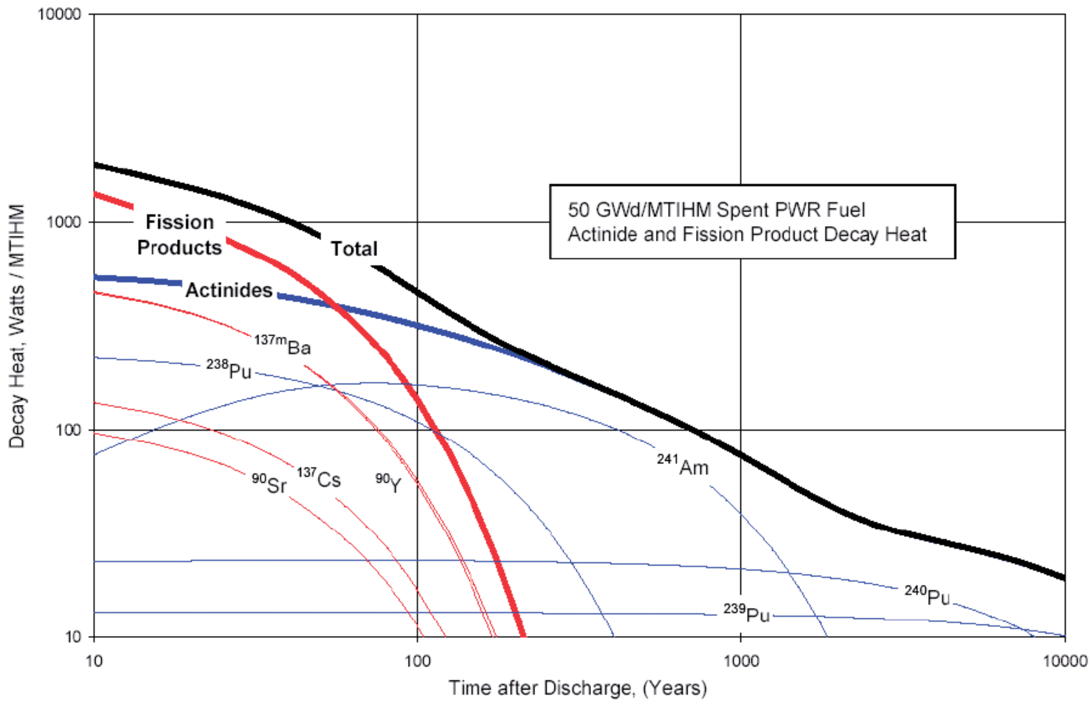

Figure 2: Heat generation rate in LWR spent fuel irradiated to 50 GW·d/t [2]

ELABORATION OF PROPOSED SCENARIOS

Table 2 described the P&T scenarios which are based on those found in the previous report and given in Table 1.

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Table 2: Elaborated P&T scenarios with their simplified fuel cycle and final waste content

Scenario	Simplified fuel cycle order	Partitioning process	Fuel	Transmutation media	Final waste
1a	1. Fabrication of enriched UOX fuel 2. Burning UOX fuel 3. Mono recycle of Pu and U from spent UOX fuel 4. MOX fuel fabrication 5. Burning MOX fuel 6. Final waste disposal	PUREX	UOX + MOX	Thermal reactor	-Spent MOX fuel and vitrified HLW including MA and fission products, - Compacted ILW-LL arising from reprocessing of spent UOX fuel
1b	1. Fabrication of MOX fuel and U blanket (breeder) 2. Burning fuel and blanket 3. Recycle of Pu and U from spent MOX fuel …. Multi-recycle as per Steps 1 to 3…. 4. Final waste disposal	Advanced PUREX	MOX + U blanket	Fast reactor	-Vitrified HLW including MA and fission products, -Compacted ILW-LL arising from reprocessing of spent MOX fuel and spent U blanket
2	1. Fabrication of MOX fuel, U blanket (breeder), and Am target 2. Burning fuel, blanket and target 3. Recycle of Pu, U and Am from spent MOX fuel …. Multi-recycle as per Steps 1 to 3…. 4. Final waste disposal	Advanced PUREX + Advanced partitioning	MOX + U blanket + Separate Am target	Fast reactor	-Spent Am target, -Vitrified HLW including MA and fission products, -Compacted ILW-LL arising from reprocessing of spent MOX fuel and spent U blanket

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3a	1. Fabrication of enriched uranium UOX fuel 2. Burning UOX fuel 3. Mono recycle of Pu and U 4. Fabrication of MOX fuel, 5. Burning MOX fuel, 6. Mono recycle of TRU from spent MOX fuel 7. Waste disposal of spent fuel (minus extracted TRU) 8. Fabrication of TRU targets 9. Burning targets in ADS 10.Advanced partitioning of spent ADS fuel, ...Multi-recycle as per Step 8 to 10... 11. Final waste disposal	Advanced PUREX + Advanced partitioning	UOX and MOX + MA targets	Thermal reactor with second strata - ADS	-Vitrified HLW including MA and fission products, -Compacted ILW-LL arising from reprocessing of spent UOX fuel, spent MOX fuel and spent ADS fuel
3a-1	1. Fabrication of enriched uranium UOX fuel 2. Burning UOX fuel 3. Mono recycle of TRU from spent UOX fuel 4. Waste disposal of spent fuel (minus extracted TRU) 5. Fabrication of TRU targets 6. Burning targets in ADS 7.Advanced partitioning of spent ADS fuel, ...Multi-recycle as per Steps 5 to 7... 8. Final waste	Advanced partitioning	UOX + MA targets	Thermal reactor with second strata - ADS	-Vitrified HLW including MA and fission products, -Compacted ILW-LL arising from reprocessing of spent UOX fuel and spent ADS fuel

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3b	1. Fabrication of MOX fuel and U blanket (breeder) 2. Burning fuel and blanket 3. Recycle of Pu and U from spent MOX fuel (Co-extraction of MA) …. Multi-recycle as per Steps 1 to 3…. 4. Waste disposal (minus extracted TRU) 5. Fabrication of TRU targets 6. Burning targets in ADS 7.Advanced partitioning of spent ADS fuel, ... Multi-recycle as per Steps 5 to 7... 8. Final waste	PUREX + Advanced partitioning	MOX + U blanket + MA targets	Fast reactor with second strata - ADS	-Vitrified HLW including MA and fission products, -Compacted ILW-LL arising from reprocessing of spent MOX fuel, spent ADS fuel and its matrix
Vitrified HLW at the least includes Pu as it is lost during separation processes.					
Advanced PUREX refers to the modifications of the PUREX flowsheet in order to improve the plutonium dissolution yield. PUREX is applied to spent UOX while advanced PUREX aims for the reprocessing of spent MOX.					

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The detailed flowsheet for each scenario is illustrated in Figure 3 – Figure 8 which are excerpted from the relevant reports [4], [5] by modifying and adapting them to the scenarios of interest in the report.

Undoubtedly, all P&T scenarios contribute to the sustainability efforts of nuclear energy. The degree of added value is so far associated to the implementation of cutting-edge systems and innovative technologies. However, these scenarios should not evoke an idea that they are the most potential and realistic spent fuel management strategies regarding economic and technical point of view in order to make nuclear energy more sustainable. Instead, these scenarios have the potential to apprise the decision makers and public of the need and consequences of the prospective P&T systems for the burning of minor actinides and alleviating the spent fuel management.

It is essential to note that these scenarios do not consider important parameters such as fissile and fertile content of fuels, burn-up rate of the initial fuel and reprocessed masses of each cycle, which are not included in the scope of this report. Amid the current socio-political and environmental landscape, the review of these scenarios aims to reassess the employability of featured P&T technologies whilst producing more qualitative outcomes as a result of the feedback from industrial partners.

Finally, it is assumed that all scenarios based on fast reactors consider the replacement of current nuclear power fleet by fast reactor technologies meaning that there is no mass flow between the conventional nuclear fleet and advanced fast reactors except for depleted uranium generated during the fuel cycle activities of conventional feet.

SCENARIO 1

Independently from the reactor system with either thermal or fast neutron spectrum, the first scenario is based on the existing PUREX process which is an industrialized and mature partitioning technique. Both reactors consist of a fissile core of MOX fuel which have a greater amount of plutonium content. As a well-known and mature technology, the reprocessing of spent fuel recovers the plutonium to be burned in the reactor core, but it raises the concern over potential proliferation risks linked to accessibility to pure plutonium. In both cases, final waste arising from fuel cycle activities includes fission products and actinides, however these amounts vary between the two-reactor design.

Scenario 1a: Mono-recycle of plutonium in LWR

Characterised by its maturity, this fuel cycle option partitions plutonium from spent fuel and transmutes (burns via fission) it in a conventional nuclear reactor core. This scenario (depicted

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in Figure 3) which is adopted in France and the UK, can be considered as the sole P&T in the present situation. In comparison to the once through cycle, the radiotoxicity of final waste is reduced tenfold (as shown in Figure 1). Spent MOX fuel is not subjected to second reprocessing meaning that it should directly be disposed in an integral form without further reprocessing.

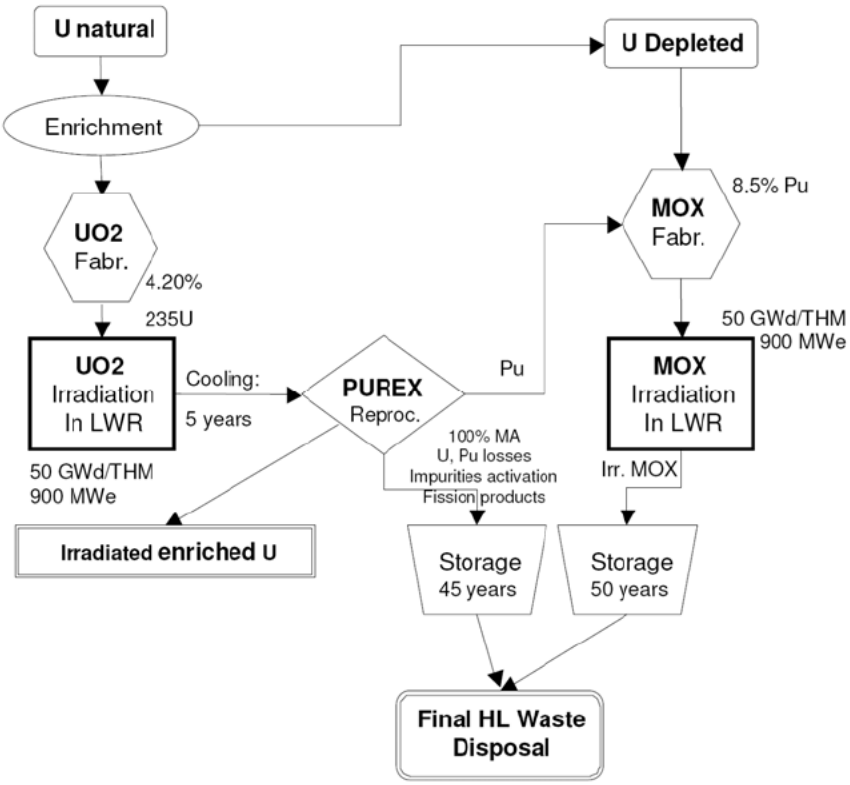

Figure 3 : Mono-recycle of plutonium in LWR [4]

Scenario 1b: Multi-recycle of plutonium in FR

The scenario given in Figure 4 envisages the substitution of the existing conventional nuclear fleet by fast reactors which could burn both fissile and fertile isotopes[11]. In addition to the MOX fuel in the core, the outermost part of fast reactors' is surrounded by fertile uranium blanket leading to the formation of ^{239}Pu, which then undergoes a fission reaction. Depending of the number of cycles, fast reactors continuously fed by reprocessed plutonium eliminate the greater extent of minor actinides. However, residual actinides and secondary waste arisings during each reprocessing cycle of spent fuel remain in the final waste to be disposed of. Therefore, final wastes include vitrified HLW covering the residual major actinides and fission products, and compacted ILW-LL arising from reprocessing of spent fuels and uranium

[11] ^{238}U, ^{238}Pu and ^{240}Pu

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blanket. The radiotoxicity would fall somewhere between the two-cases given in Figure 1 (only plutonium recycling and with a partial PT (Pu + 99.5% Am 90% Cm).

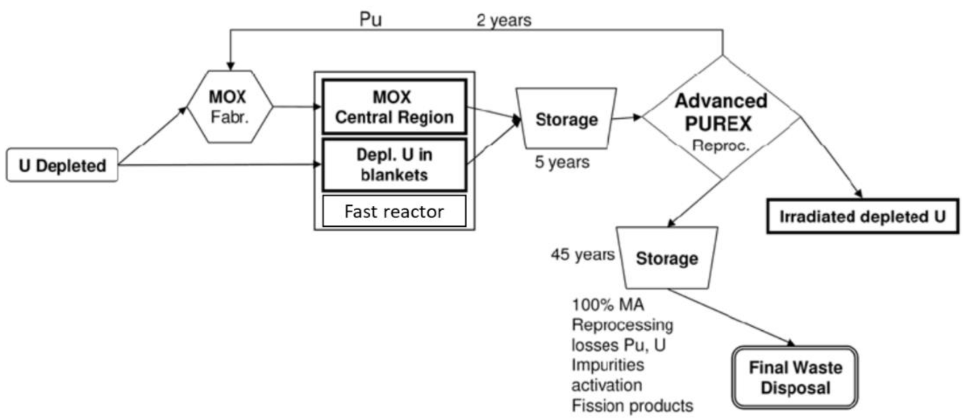

Figure 4 : Multi recycle of plutonium in FR [4]

SCENARIO 2

In light of the important advancements in selective partitioning technologies, the greater quantity of minor actinides can be eliminated from the final waste as shown in Figure 1. Heterogenous transmutation[12] of americium in fast reactor, which is illustrated in Figure 5, is an attractive strategy which is based on Scenario 1b. As discussed earlier, after eighty years americium is the highest contributor from minor actinides to the radiotoxicity and thermal loads of final waste. Thus, partitioning americium through EXAM process and fabricating it into separate targets to be destroyed in a fast reactor core could have a significant effect on the performance of geological repository.

While heterogenous mode provides flexibility in terms of radioprotection and reactor core safety characteristics, fabrication of separate americium target can also benefit from existing technologies. On the other hand, economic and environmental impact analysis should be studied in order to compare performances between the two-scenario (Scenario 1b and Scenario 2). It can be argued that the implementation of Scenario 2 accounts for a lower radiotoxicity and results in favourable drop in decay heat as shown in Figure 2.

[12] Two main options are: homogeneous mode where Am is mixed with Pu in the fuel; Heterogeneous mode where Am is mixed with depleted uranium in radial blankets disposed outside the fissile core.

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Final waste includes spent americium targets without further reprocessing; vitrified HLW covering minor actinides and fission products; compacted ILW-LL arising from reprocessing of spent MOX fuel and uranium blanket.

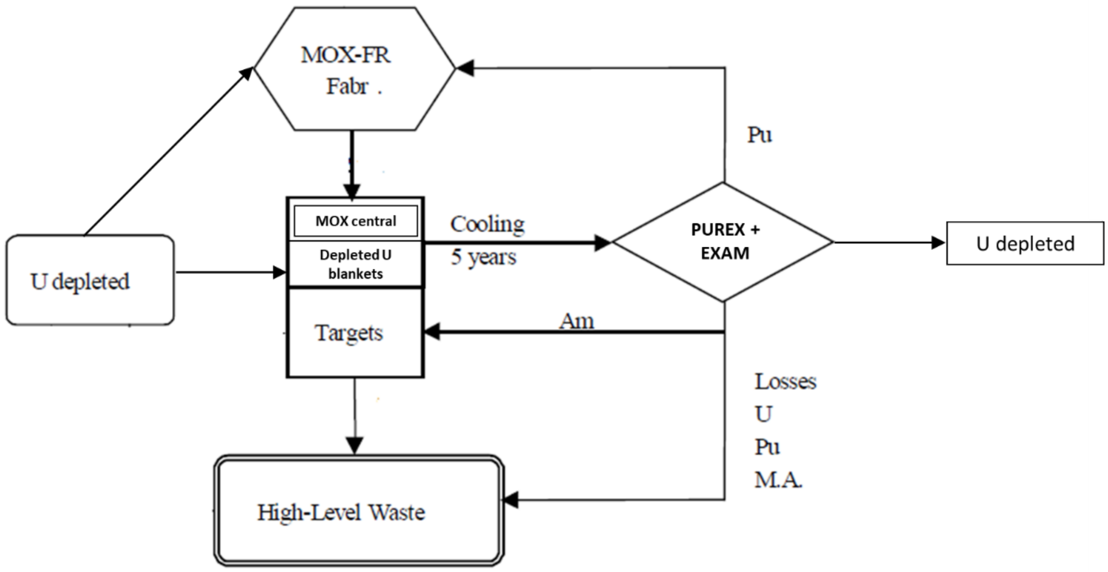

Figure 5 : Burning Americium targets on heterogenous mode in FR [5] [4]

SCENARIO 3

Being similar to Scenario 1, Scenario 3 with a second strata envisages ADS integration to the fuel cycle of nuclear power reactors with either thermal or fast neutron spectrum. Two partitioning modes bring their own benefit and disadvantages:

- (Heterogenous) A separate extraction of each major actinide would facilitate the target fabrication and operation. Eliminating fissile content such as plutonium in the target to be destroyed in the ADS is preferable in order to avoid the build-up of new minor actinides during transmutation;
- (Homogenous) Cogeneration of all major actinides together from the spent fuel (GANEX 1st and 2nd cycle, EUROGANEX) – this is a suitable process for the strategies envisaging reduction in proliferation risks while handling of the highly radioactive “hot fuels” during fabrication and operation adds a new level of complexity to the overall process.

Regarding the partitioning mode with coherent extraction process, ADS could transmute major actinides generated from first stratum given by Scenario 1 into the smaller fragments without electricity generation.

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Scenario 3a: LWR's MOX recycling coupled with ADS

The scenario given in Figure 6 aims at burning minor actinides arising from the fuel cycle option detailed in Scenario 1a. The recovery of plutonium from spent fuel generates power while transmuting major actinides in the ADS with preceding MOX recycling maximises the waste reduction at final disposal.

Operating the ADS benefits from the advantage of the absence of uranium and plutonium from the targets to be destroyed in the ADS. Decreasing the fissile content – Uranium and plutonium in the targets leads to an increase in transmutation rates by avoiding breeding new actinides.

Owing to the pure plutonium existence in the process, this strategy raises the proliferation concern as is the case in other scenarios with plutonium recycling from spent fuel.

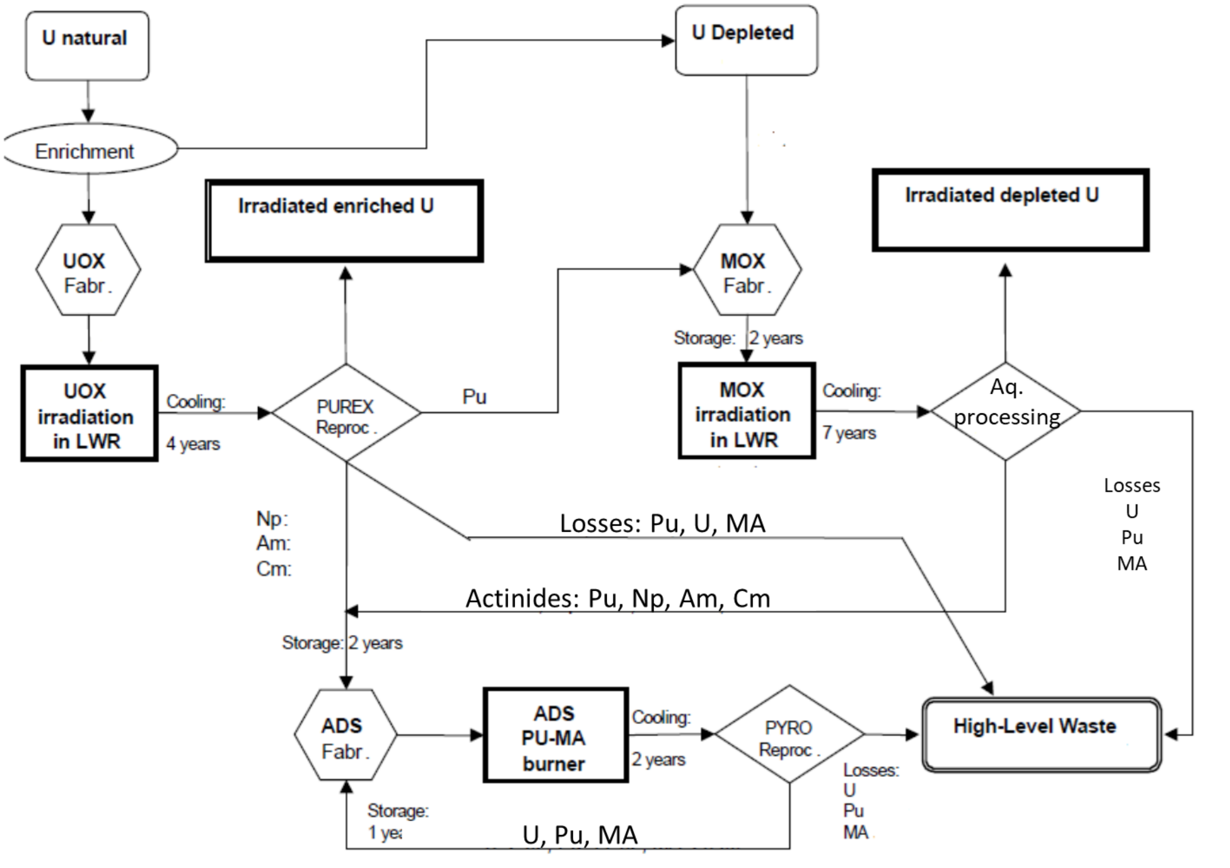

Figure 6: LWR's MOX recycling coupled with ADS [5]

Scenario 3a-1: LWR's once through cycle coupled with ADS

Figure 7, as a variant of Scenario 3a, illustrates that ADS can be integrated into the conventional fleet with once though cycle which is adopted by most of the nuclearized

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countries. Scenario 3a-1 simply promises the destruction of major actinides in the ADS whilst reducing the proliferation materials' attractiveness. As a homogenous mode, this brings along challenges related to fabrication of "hot" fuels as well as issues of radioactive heavy isotopes accumulation in the target during transmutation in the ADS due to initial plutonium (^{239}Pu) content.

The content of high-level waste at the end of cycle is similar as in the Scenario 3a, but the amount is variable.

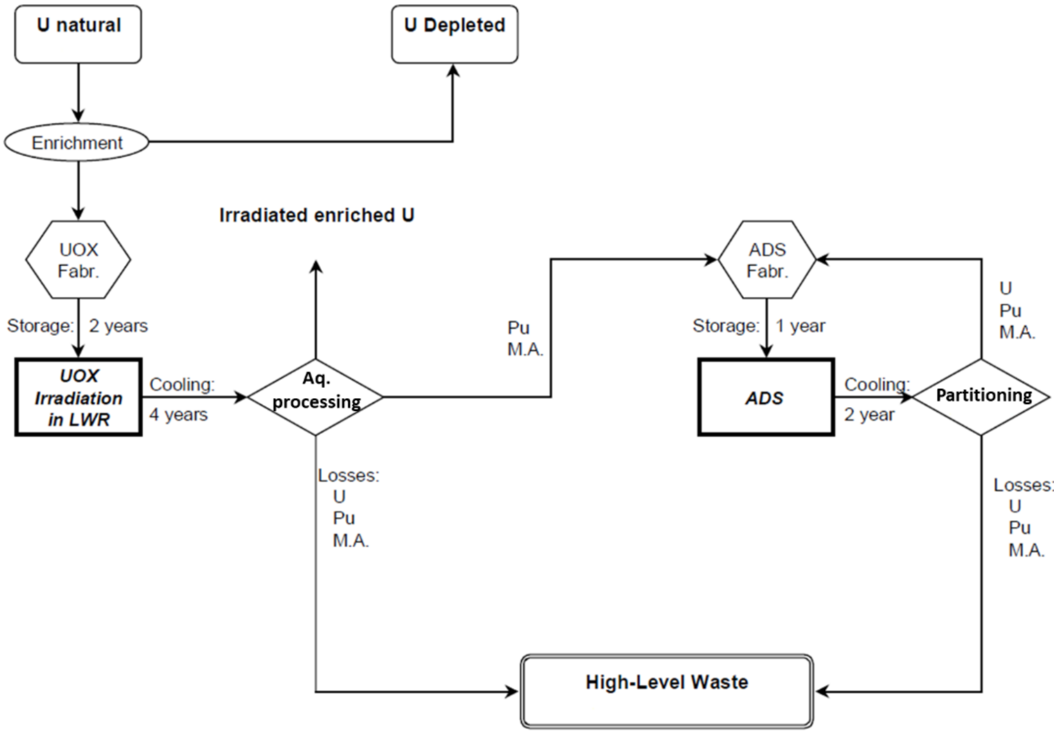

Figure 7: LWR's once through cycle coupled with ADS [5]

Scenario 3b: FR's multi recycle coupled with ADS

Figure 8 shows the second strata of Scenario 1b which aims to selectively separate major actinides from spent MOX fuel. Plutonium is used in MOX production which then generates electricity in fast reactors and minor actinides are transmuted into shorter half-life elements in the ADS.

It is likely that this scenario brings about higher actinides destruction and thus provides a major performance increase in the geological disposal site by reducing further radiotoxicity.

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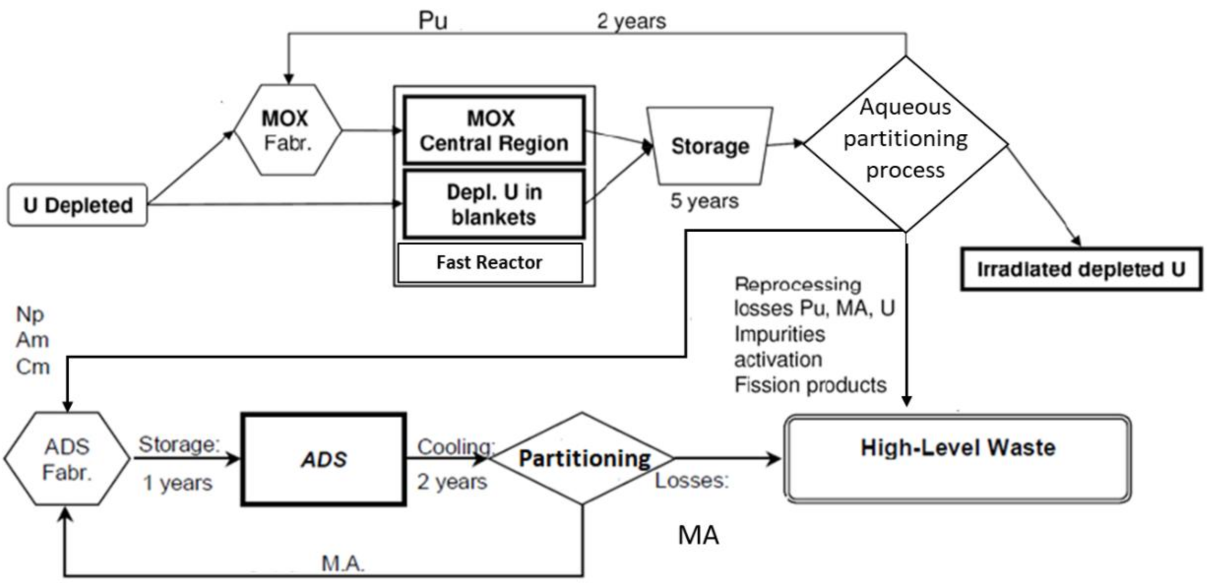

Figure 8: FR's multi recycle coupled with ADS [4] [5]

PRELIMINARY FINDINGS APPLYING TO ADVANCED P&T STRATEGIES

In this section, preliminary findings which entail risks for the implementation of the P&T systems are established in an unbiased manner through desk research. These findings have been discussed with industrialist experts who endeavour the deployment of P&T technologies. Main interview questions and their simple answers were given in the Appendix A while main results are discussed in the next section.

The thematic analysis of these findings is gathered under the broad pillars:

- Economic factors,
- Technological consideration,
- Socio-political issues,
- Environmental aspects.

FINDING 1: ECONOMIC FACTORS

1. The ambitions to vitalise the P&T technologies that are encouraged by their promises on the sustainability of nuclear energy do not adequately lead fast reactors to advance their commercial deployment. Even though it is argued that P&T of radiotoxic isotopes in fast reactors is a strategic approach to manage legacy stockpiles of high-level waste which would enable operator to generate electricity as a by-product, fast reactors do not produce electricity on a basis of cost competitiveness [6]. It is well understood that P&T strategies are costly procedures bounded by uncertainties and future risks.

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2. Compared to nuclear energy, cost competitiveness of renewable energy systems has dramatically increased. Given large costs and lack of societal preferences for nuclear energy, private investors, without State-backed interventions, are unlikely to invest in financially risky innovative nuclear technologies. On the other hand, renewable electricity production is intermittent and economically comparison with nuclear electricity production may not be convenient.
3. The cost of P&T operations will be reflected into the electricity bills. Although a positive aspect of sustainable nuclear energy is esteemed by the society as an added value, the public prefer cheaper electricity. Thus, the cost increase might have an adverse effect on the belief of public acceptance to the P&T.
4. Uranium prices have been on a downward slope for a decade[13]. Being not bounded by a uranium shortage, new nuclear build projects suffer from their increased capital cost in the wake of stringent regulatory demands. While the longevity of nuclear energy with over decades' experience acquired in the design and operation of LWRs is being discussed in the EU, a substitution of the existing nuclear fleet using the conventional nuclear reactors by advanced fast reactors, which requires remarkable technical and economic investments, is still arguable topic in the EU.

FINDING 2: SOCIO-POLITICAL ISSUES

1. Advanced reactor systems, notably fast reactors, are usually differentiated from current systems by sustainability advantages such as reduction of waste volumes, elimination of radiotoxicity, increase in proliferation resistance as well as efficient use of resources. It should be admitted that these positive aspects are in the interest of public because sustainability and "cleanliness" of nuclear energy can play a major role in tackling its public acceptance which is a significant deal for the advancement of nuclear industry.
2. Public acceptance of different scenarios for the P&T plays a major role in the implementation of the infrastructure on the one hand and the construction of these facilities on the other. Perception of new fuel cycle facilities, especially for the recycling, partitioning and fuel fabrication plants are subject to public scrutiny and heightened sensitivity.
3. Advanced P&T strategies and fast reactors are still far from its implementation. Postponing of the Astrid project, announced in late August 2019, strengthens this argument. Delays in the R&D efforts for Astrid, the most advanced European project in the prototyping of GEN IV reactors (and the only industrial-scale GEN IV reactor), may affect the driving force of P&T strategies even beyond of 2050. In this regard, it is

[13] https://www.cameco.com/invest/markets/uranium-price

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notable that the construction of most of first-of-a-kind Generation III reactors in the EU, which are based on well-known and mature reactor technologies, are already more than a decade behind schedules. It can be argued that the commercial operation of advanced reactors would put off until the next century.

FINDING 3: TECHNICAL CONSIDERATION

1. The complete destruction of actinides is not possible in practice whatever scenario is chosen. The residual waste with long half-life actinides and fission product should be disposed in final repositories. Burning the actinides in any advanced system with the aim of reduction in final HLW volume are likely to increase the secondary waste amounts of low-intermediate long-lived waste (LILW-LL). As the number of (multi)cycle increases, the quantity of LILW-LL also increases. It is important to note that waste in LILW-LL category also requires to be disposed in geological repository.
2. Some radionuclides such as curium and most of the fission products are not amenable to partitioning and transmutation because of the difficulty in their isotopic separations and their low transmutation probabilities. For instance, existence of curium in the fuel target would lead to formation of longer-lived radioisotopes as a result of neutron absorption.
3. With its reasonably large cross section, americium is the most notable minor actinide which can be transmuted by the combination of neutron captures and fissions. While separation between curium and americium is difficult, a recent devised partitioning process, which still requires practical application at industrial level, proposes the selective extraction of americium (EXAM) from the spent fuel. In addition to crucial safety parameters for the actinides burner core design which are not included in the scope of the report, americium-bearing targets would generate a large amount of alpha particles ionizing the material and resulting in gas production (i.e. helium) [14] which causes fuel swelling and pressurisation of fuel pins. Moreover, ^{241}Am and ^{242}Cm are continuously replenished as a decay product of ^{241}Pu and ^{242}Am, respectively. Contamination during fuel cycle activities is inevitable and it occurs even the greater partitioning rate is attained by EXAM because of the radioactive decay of content in fuel target over time.
4. P&T requires the construction of advanced and reformed fuel cycle facilities. The development of fuel targets containing highly radioactive and “hot” elements is a real challenge given a requisite for cost-efficient nuclear energy production or spent fuel

[14] This is also the same case for plutonium.

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management, if the aim is to only burn minor actinides and diminish its content from final waste due to increased engineering and safety systems required.

FINDING 4: ENVIRONMENTAL ASPECT

1. Recycling of minor actinides and fabricating them into the targets and fuel demand substantial multi-stage chemical processes and new assembly lines, respectively. In addition, greater radioprotection requirements will be in place in order to mitigate the dose exposure to workers. Secondary wastes will be generated through use of recycling and associated fuel manufacture, which will also increase decommissioning wastes due to the construction of new plants and processes. Costs will also increase as a consequence of new plants construction.
2. A geological repository will be inevitable whatever the scenario chosen for the spent fuel management. It is argued that reduction of actinide content in the final waste compared to that of fission products would have a slight effect on the performance of geological disposal site. This is because of the limited solubility of actinides in the repository environment. However, volatile fission products may have a greater contributor to the radioactivity doses in case of leakage to the biosphere through groundwater.
3. P&T is usually claimed as a strategy to manage legacy stockpiles of high-level waste. Given the accumulated amount of vitrified HLW in France and elsewhere in the EU, it is unlikely that a substantial amount of the HLW legacy stockpile could be reduced by the commercialisation of P&T systems in the long term. This is because vitrifying the reprocessing waste generated from spent UOX fuel is an irreversible process meaning that P&T is only effectual for non-reprocessed spent fuel and new waste streams. It is noted that R&D for the P&T studies in France is one of the leading programmes within the EU States with long term plans for further investment in current nuclear technologies and advanced systems. The latter is however interrupted at the moment.

SUMMARY OF THE INTERVIEWS

Semi structured interviews were initially planned to discuss above findings and the employability of elaborated scenarios with key experts, these interviews could not be performed amid global health crisis. Thus, an interview was virtually carried out with expert partner from EDF - Frédéric LAUGIER and Benjamin FLEURY.

A list of findings with relevant thematic questions was prepared and sent to interviewees to review and provide comment on each question. Then, Main results were gathered through a combination of the interview and in-house review undertaken of different scenarios.

Assessing both challenges and motivations for the implementation of closed fuel cycles in the near future, each scenario's impact on sustainability goals have been established.

MAIN RESULTS

Multiple fuel cycle options consolidated with enhanced partitioning processes would accomplish the desired hundred-fold radiotoxicity reduction as shown in Figure 1. The degree to achieve that goes well beyond the selection of the most appropriate P&T scenario with a higher sustainable feature. A chosen scenario is not necessarily the best approach in order to deal with the perils of nuclear energy. On the assumption of devised and industrialised P&T technologies, ensuring the greater reduction in waste volume and its radiotoxicity meanwhile decreasing the attractiveness for the proliferation materials and the secondary waste generation may not be technically and economically feasible. Furthermore, every State has a different agenda for the spent fuel management and nuclear fuel cycle issues of which their national context would demand the implementation of another strategy that could not be chosen by other. Thus, a universal "best in class" scenario is unlikely be found and each scenario is required to be investigated and evaluated on the national basis policies in addition to its economic feasibility.

The viability of the P&T is subject to the cost competitiveness of nuclear energy. Surrounded by heavy shielding applications due to its harsh radioactive environment, fuel cycle operations such as recycling actinides and manufacturing them into a suitable form for destruction should be economically optimised by simplifying the processes and equipment as much as possible instead of integrating the technically complex and expensive facilities. In this regard, reduction in waste management cost and improved performance on waste repository due to transmutation would be a supporting benefit in cases where the capital cost of the proposed P&T infrastructure competes with other clean energy technologies.

Represented by its actualisation in long-term, advanced fuel cycles overcome key challenges which impede a sustainable growth of nuclear energy. Reducing waste volume and interim storage for the spent fuel management prevent to reach its saturation. However, there is no single P&T approach to fulfil all sustainability goals of nuclear energy given in the "Technical background" section. For instance, reprocessing of spent fuel in order to merely extract plutonium aiming at its efficient burning may decrease the radiotoxicity of final waste on the one hand, but on the other this process eases the accessibility of plutonium meaning increased proliferation risks. Due to long lead times combined with the required investment in the reactor systems and new remotely operated fuel cycle facilities (fuel fabrication, reprocessing, partitioning, storage etc), P&T is not a strategy *per se* that can be applied to the fuel cycle of

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conventional nuclear fleet but the consolidated major component of the prospective nuclear renaissance for novel nuclear energy applications.

It is clear that knowledge loss and shortage of researchers pursuing the demonstration of P&T technologies might show up in the near future in spite of continued novel research in this field. Thus, it is important to maintain the current efforts for the development of sustainable nuclear energy applications.

It can be concluded that what is best from the point of efficiently using the resources and increasing the proliferation resistance is not the best in terms of the reduction in cost and final waste amount at disposal.

COMPARATIVE RESULTS APPLYING TO EACH SCENARIO

Notwithstanding the fact that significant experience is acquired in mono-recycling of uranium and plutonium from spent fuel – Scenario 1a using MOX fuel cycle, further efforts are needed in order to commercialize innovative P&T applications. Particularly, R&D efforts devoted to the P&T combined with deployment of advanced technologies require a remarkable investment, research as well as public acceptance which might outweigh any benefits from minimizing the radiological impact of disposed waste.

The maximum reduction in radiotoxicity and the volume of final waste are achieved when the number of cycles increases in the fully closed cycle option. This criteria advantages Scenarios -1b, -2 and -3b, which are based on fast neutron spectrum using multi-recycling of fuels through enhanced fuel cycle facilities. On the other hand, this also implies a greater amount of dose uptake and risk per cycle due to radioactivity and decay heat arising from actinides, also complicating the reprocessing, handling and fabrication of the fuels. Each recycle would increase the quantity of the secondary waste, which are ILW-LL to be disposed in geological repository. Thus, multi-recycling should be limited and dropped to a reference level in where the cost benefit analysis is the highest. This is also the reason to limit the recycling of americium to the single cycle in Scenario 2.

The approval of the partial financial contribution by the Belgian government to the MYRRHA accelerator-driven research reactor reinforces the concept viability for the transmutation of the actinides in the ADS. As an innovative technology with multiple scientific purposes, the MYRRHA can be used to demonstrate the destruction of heavy radioisotopes on a sub-industrial scale without safety concerns arising from a deterioration in the reactor's core. Considering the large capital investment in fast reactor deployment combined with the political counter views (i.e. ASTRID project suspension), Scenario 3 is presently the most attractive P&T scenarios among other advanced applications. A difference between Scenario

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3a and Scenario 3a-1 stem from resources-saved fuel and proliferation resistant fuel, respectively. Depending on the national policy driving the P&T strategies, both scenarios can be claimed to be the most applicable advanced technologies given present timeliness of their deployment.

In light of current nuclear energy policies and socio-political environment, the Scenario 3b is the most complex among others since it requires the deployment of both fast reactors and the ADS meaning that highest investment and enormous initiatives for R&D are needed. It can be concluded that these scenarios employing fast reactors are the furthest from commercialisation. Thus, implementation of the partitioning processes which have been designed for the transmutation of major actinides in advanced fast reactors are likely to be beyond 2070.

In cases where fast reactors are not favourable to be industrialized, a strategy how to manage depleted uranium originating from LWR's fuel cycle activities (i.e. reprocessing and enrichment) should be investigated and defined. This is also binding for the Scenario 3a which will continue to use uranium resources and produce depleted uranium.

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CONCLUSION

Having been investigated for several decades, P&T aims to reduce the hazard potential and heat load of long-lived radionuclides formed during nuclear energy generation. The key constituents for successful deployment of the P&T discussed in this report include, but are not limited to: advanced separation processes for various radionuclides, proper fuel fabrication under harsh environment conditions, and transmutation media using fast neutron spectrum designed to be operated in a multi-recycle mode.

Although P&T is scientifically plausible and innovative, the economic and technical viability of the P&T is a separate question. Rising capital cost, lengthening construction duration and increased social opposition have all merged to build barriers against new nuclear projects. In this regard, P&T assists public acceptance through tackling the spent fuel management, one of the perils of nuclear energy.

On the other hand, the idea to make nuclear energy completely renewable by means of fully closing the advanced fuel cycle using fast neutron spectrum is costly, challenging and very long-term. Innovations originated from the deployment of advanced reactors, which promote sustainable nuclear energy, do not make progress towards commercial development of fast reactors. Thus, the efforts should be devoted to bringing down the capital and construction cost of new reactors systems and their fuel cycle facilities. While lowering the cost is a good indicator to convince decision makers to invest in such infrastructures, their potential sustainability benefits such as reduction in waste amount and its radioactivity level would be an added value for both operators and public's perspective.

In other respects, incineration of major actinides by the ADS integrated to the conventional nuclear fleet could play a major role in order to show the achievability of P&T for prospective advanced nuclear systems. This MYRRHA not only benefits from the existing conventional nuclear technologies, but it could also prepare for actinide recycling in advanced fast reactors. It should however be noted that any political decisions to delay the project would again hamper the implementation of the P&T.

As a conclusion, endeavours to meet the sustainability goals in the EU will always make the P&T options central issues in the nuclear energy. However, innovative approaches should fulfil the future demand rather than dealing with the historical problems given the fact that industrial scale systems executing the P&T will be available by the end of XXI century.

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APPENDIX A: QUESTIONNAIRE FOR SEMI-STRUCTURED INTERVIEWS

ENVIRONMENTAL ASPECTS

- Which scenario is the most promising to increase the performance of repository in terms of reduction of waste volume, reduction in thermal load, reduction in radiotoxicity in disposal at 500 years, 10000 years, or more?

  Geological repository is designed to confine nuclear waste during geological eras, so the reduction of radiotoxicity is not a driver for the advanced fuel cycle options and should not be considered as an objective for investments.

  The main drivers for advanced fuel cycle options that will make investments worthwhile are related to the sustainable development of nuclear energy:

  - Reduction of waste volume, not only for geological repository but also for interim storage,
  - Reduction of natural resources consumption

  Regarding geological repository, the main driver to be considered should be the reduction of thermal load to reduce the size of the repository.

  Therefore, the best scenario is the multi-recycling of plutonium and uranium in advanced GEN IV fast reactors (scenario 1b) with a long-term option for americium transmutation (scenario 2).

- Do any cost benefits from reducing the waste volume ultimately sent to the disposal outweigh these investments and R&D on advanced fuel cycle options?

  Long-term future cost benefits do not outweigh near future or present investments. But reducing waste volume could be a good investment to reduce present interim storage and to prevent to reach saturation. And it could be achieved at relatively low cost by mono-recycling (scenario 1a).

  Another point is that advanced P&T strategies will need dedicated cycle facilities, handing highly radioactive materials and separated "hot" elements, instead of "classic" HLW-LL. Public acceptance for these new nuclear facilities will not be easy. This could lead to an increase of nuclear risk perception for the public.

ECONOMIC FACTORS

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- Do you think that the decrease in uranium prices undermines the economic rationale for the deployment of advanced reactors and for the multi recycle use of the fuel?
  Yes, because advanced fast reactor is more expensive than LWR and uranium prices are presently very low. There is no interest for an electricity utility to invest in fast reactors as long as they have not reach economic competitiveness.
- Does the reuse of the fuel (i.e. fully recycling of actinides topping up with new fresh fuels) seem effective enough to warrant the expense and additional operational risk of transmutation including modification in fuel cycle supply chain (construction of new fuel cycle facilities)?
  Only for the reuse of plutonium and reprocessed uranium. The energy content of other actinides is too low.
- What is the net economic and environmental benefit of developing the P&T technologies given the fact that huge investment needed for advanced reactors systems such as GEN IV fast reactors or ADS as well as its fuel cycle facilities?
  The environmental benefit of GEN IV fast reactors lies in the reduction of waste volume and in the reduction of natural resources consumption (uranium). Also, P&T of americium could bring a reduction in the size of the geological repository which could be by itself a critical resource.
- Is it feasible to transmute actinides in terms of economic and environmental aspects given the fact the impracticability of transmutation of fission products?
  It is difficult because you will always need geological repository.

SOCIO-POLITICAL ISSUES

- What do you think about the political decision for the Astrid project? Is the commercialisation of advanced fuel cycle options postponed to XXII century?
  ASTRID reactor is postponed but the French R&D program on GEN IV fast reactor is still going on. And France is now working on multi-recycling in LWR (a new scenario…). Other countries in the world are interested by GEN IV fast reactors: Russia, China, India. Therefore, we think that the commercialisation of advanced fuel cycle options could occur during the XXI century.
- Do you consider the option for the deployment of advanced fast reactors possible in Europe? When? Mid or long-term?
  After 2050: a small R&D device. By the end of XXI century: first GEN IV reactors

TECHNICAL CONSIDERATIONS

- How the production of secondary wastes should be minimised for the potential net gain of PT?

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The risk is likely. A global assessment of secondary wastes is needed including the dismantling of dedicated devices for transmutation and environmental footprint.

- Americium and curium are continuously replenished as a decay product of 241Pu and 242Am, respectively. Does this mean that EXAM process extracting americium will continuously yield to curium as a non-desired radioelement in the inventory?
  242 Americium produces 242 Curium with a half-life of 162.8 days. After 5 years storage, 242 Curium will have completely decreased.
- Which partitioning process can be used for the ADS spent targets?
  The one with less secondary waste and with the lower environmental footprint