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Nuclear fuel cycle synergies and regional scenarios for Europe

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Foreword

Under the auspices of the NEA Nuclear Science Committee (NSC), the Working Party on Scientific Issues of the Fuel Cycle (WPFC) was established to co-ordinate scientific activities regarding various existing and advanced nuclear fuel cycles, including advanced reactor systems, associated chemistry and flow sheets, development and performance of fuel and materials, and accelerators and spallation targets. The WPFC has established various expert groups to cover the wide range of scientific issues associated with the nuclear fuel cycle.

The Expert Group on Fuel Cycle Transition Scenarios Studies was created in 2003 to review the R&D needs and relevant technology which would enable an efficient transition from current to future advanced reactor fuel cycles. The objectives of the expert group are to: *i)* assemble and organise institutional, technical and economic information critical to the understanding of the issues involved in the transition from current fuel cycles to long-term sustainable fuel cycles or a phase-out of the nuclear enterprise; *ii)* provide a framework for assessing specific national needs related to that transition.

A regional approach is proposed in order to implement the innovative fuel cycles associated with partitioning and transmutation in Europe. The impact of different deployment strategies and policies in various countries is addressed. Regional facilities' characteristics and potential deployment schedules are also discussed.

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Summary

Regional strategies can provide a framework for the implementation of innovative fuel cycles, with an appropriate sharing of efforts and facilities among different countries, taking into account proliferation concerns and resource optimisation. Specific scenarios have been investigated within a wider effort underway in Europe to shape a roadmap for the implementation of partitioning and transmutation (P&T) technologies.

As far as the impact of the implementation of P&T at a regional level, the results of the scenario studies indicate that the expected benefits, *i.e.* reduction of radiotoxicity in a repository to the level of the radiotoxicity of the initial ore after few hundred years, and the reduction of the heat load in the repository (more than one order of magnitude), applies to whole region, providing a significant potential benefit to all the countries of that region (*e.g.* Europe), despite their different policies in terms of nuclear energy. Moreover, the present studies have shown the potential of a regional strategy with regard to a nuclear renaissance in some countries.

The indications obtained so far also allow defining specific features both of the reactor systems and of the fuel cycle facilities to be implemented at a regional level. As for the reactors, if fast reactors with homogeneous recycle of non-separated transuranics (TRU) are envisaged, the fast reactor characteristics (*e.g.* the conversion ratio) and the fuel cycle characteristics (*e.g.* the out-of-pile fuel cooling time) must be optimised in order to meet the potentially different objectives of different countries within a regional area.

Another relevant finding of the study is related to the characteristics of the accelerator-driven system (ADS), if it is chosen to transmute minor actinides (MA) in scenarios of the "double strata" type. In fact, most ADS design studies have considered a fuel loading and a transmutation potential mostly adapted to MA, as opposed to TRU, consumption. Thus, this type of ADS is more apt to be used in a "regional" scenario where different countries with different objectives share resources, facilities and spent fuel inventories in order to minimise wastes. The same type of ADS will not be useful in the case of a country committed to a stagnant or decreasing use of nuclear energy that would decide to deploy P&T in "isolation" for waste management.

Total reprocessing and fuel fabrication needs have been quantified and should now be evaluated from an economic point of view in order to assess the viability of the different scenarios or suggest possible optimised variants.

Further studies are obviously necessary, in particular for the investigation of practical issues (like fuel transport, etc.) and institutional issues which will be, without doubt, very challenging.

Chapter 1: Introduction

1.1 Purpose of the study and choice of scenarios

Implementation of P&T and advanced fuel cycles within an original regional approach (Salvatores, 2005; Boucher, 2007) has been considered. In fact, it seems essential to study the possibilities to share fuel cycle facilities and to envisage a concerted use of materials, in order to develop sustainable nuclear energy at a regional level, with optimised use of resources and investments and waste minimisation in an enhanced proliferation-resistant environment.

1.2 Regional fuel cycle scenarios definition

The scenarios consider different groups of countries:

- Group A is in a stagnant or phase-out scenario for nuclear energy and has to manage its spent fuel.
- Group B is in a continuation scenario as concerns nuclear energy and must optimise the use of its plutonium resources for future deployment of fast reactors.
- Group C is a subset of Group A which, after stagnation, envisages a nuclear "renaissance".
- Group D includes countries that initially do not possess nuclear power plants, but decide to go nuclear.

Four different scenarios have been considered. All scenarios make use of fast spectrum reactors, either ADS type (Scenarios 1 and 2) or critical (Scenario 3).

Scenarios 1 and 2 consider the deployment of a group of ADS shared by the countries in Groups A and B. The ADS use the plutonium of Group A and transmute the minor actinides of the two groups. The plutonium of Group B is either mono-recycled in a PWR and then stored for future deployment in fast reactors (Scenario 1) or is continuously recycled in PWR (Scenario 2). The deployment of critical fast reactors is not simulated in Scenarios 1 and 2. Scenario 3 considers the deployment of fast reactors in Group B. These fast reactors use the plutonium of Groups A and B and recycle all the minor actinides.

Scenario 4 corresponds to a certain "renaissance" of nuclear energy in selected countries. Starting from Scenario 3, both Group B and some Group A countries will employ fast reactors to handle their own TRU inventories. These scenarios are not intended for a strict classification of the European countries in a given category, nor are they intended to be an exhaustive list of possible scenarios, but rather as a tool employed to allow a systematic approach to the subject. The numerical examples have been based on information provided by a group of selected European countries (Belgium, Czech Republic, France, Germany, Spain, Sweden and Switzerland), that are fairly representative of the current overall European situation. In these scenarios, the regional facilities to be deployed are:

- the standard spent fuel reprocessing facility for Group A and for Group B;
- the fast reactor fuel fabrication facilities and (if ADS are to be deployed);
- the ADS spent fuel reprocessing facility;
- the ADS fuel fabrication facility;
- the ADS.

All studies have been performed with the CEA COSI code (Boucher, 2006). FZK has provided results for Scenarios 1 and 2 (based on the deployment of ADS) and the CEA has focused on Scenarios 3 and 4 (based on the use of critical fast reactors). The scenarios were previously described in Salvatores (2007), where some preliminary results for Scenarios 3 and 4 were also presented.

Chapter 2: Scenarios 1 and 2

2.1 Scenario description

These two scenarios consider the deployment of a transmuting ADS fleet shared by the countries in Group A (Belgium, Czech Republic, Germany, Spain, Sweden and Switzerland) and Group B (France). The ADS will use the plutonium of Group A and will transmute the minor actinides of the two groups; the plutonium of Group B will be mono-recycled (Scenario 1, Figure 1) or multi-recycled (Scenario 2) in PWR and then stored for future deployment in fast reactors (starting from 2040).

The main objectives of these scenarios are:

- to decrease the stock of spent fuel in Group A countries down to zero at the end of the century;
- to stabilise the MA inventory of Group B by the end of the century;
- to investigate the required number of ADS to be deployed;
- to determine the number and capacities of the fuel cycle facilities needed;
- to stabilise the Pu inventory of Group B.

The ADS facility used is the lead-cooled European Facility for Industrial Transmutation (EFIT) prototype design with top level design parameters as delivered in the framework of EUROTRANS project (Artioli, 2007).

The parameters used for this facility and its fuel cycle are summarised in Table 1.

The assumed EFIT availability was 87%. To obtain high MA transmutation rates uranium-free oxide fuel has been utilised. The Pu and MA oxide have been inserted in an MgO inert matrix. The fuel composition adopted in the present study was fixed at 55% MA/45% Pu. The reference transmutation strategy adopted in this kind of reactor allows burning 40.17 kg of MA per every TWh_{th}, versus only 1.74 kg of Pu.

Figure 1: Schematic diagram of Scenarios 1 and 2

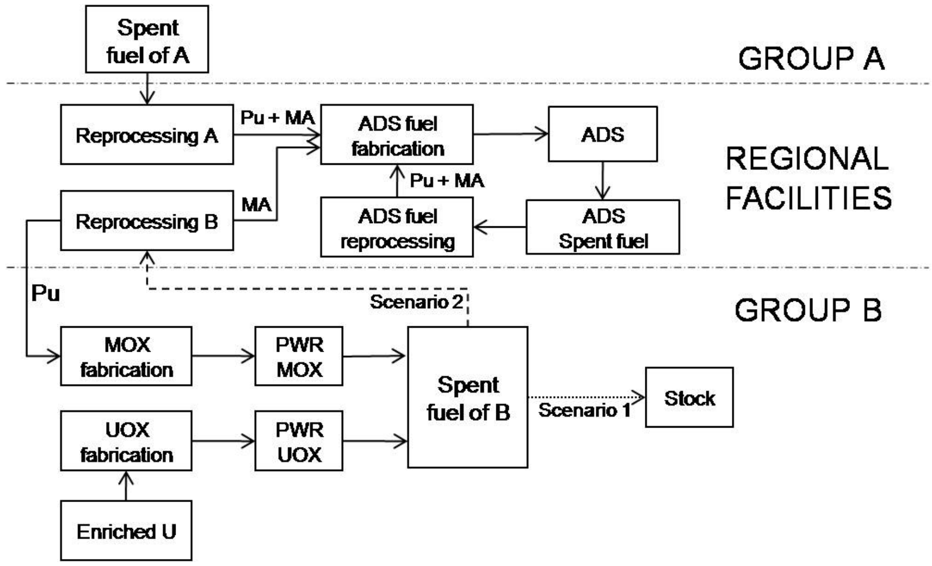


Table 1: Top-level EFIT design parameters

Target k_{eff}	0.97 (BOC)
Core inventory	5 325 kgIHM
Thermal power	384 MW_{th}
Discharge burn-up	78.28 MWd/kg
Fuel management	3 batches/core
Cycle time	368 days

2.2 Scenario 1

2.2.1 Detailed results

In order to stabilise the MA main stock inventory of Groups A and B, the optimal number of ADS to be deployed according to Scenario 1 was investigated. It was found that in total 25 ADS EFIT (384 MW_{th}) units are required to achieve this goal. The ADS deployment pace is provided below (see Figure 2).

The spent fuel inventory in interim storage in Group A countries is reduced to zero if reprocessing is undertaken before the end of the century (by 2072), see Figure 3.

The total mass of spent fuel in interim storage remains constant until 2022, when the German spent fuel legacy is added. Reprocessing plants then start operation in 2040, and reprocess all the spent fuel by 2072.

Figure 2: ADS electric power production vs. time

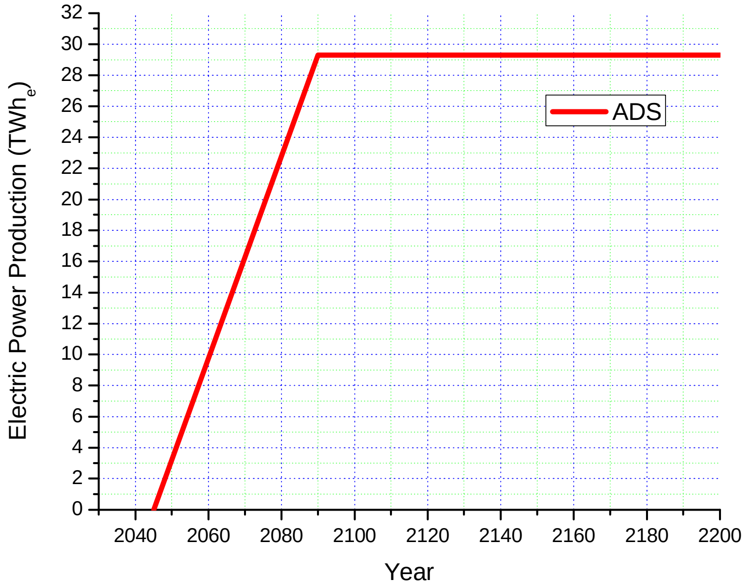
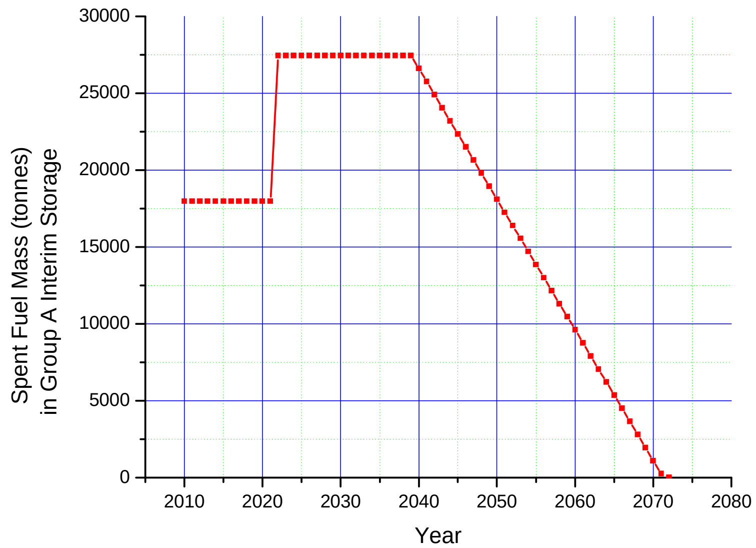


Figure 3: Spent fuel cumulative inventory (in tonnes) in Group A spent fuel interim storage



2.2.2 Minor actinide inventory

According to Scenario 1, in 2100 the minor actinide total inventory (Figure 4) will be approximately 267 tonnes, the breakdown of which is: *i)* americium: 185 tonnes; *ii)* neptunium: 63 tonnes; *iii)* curium: 19 tonnes.

In Figure 5 two MA inventories are compared: *i)* build-up in the regional approach; *ii)* accumulated stock of Groups A and B where no P&T strategy is deployed (*i.e.* no ADS units deployed).

The advantage of a regional scenario is clear: in 2100 the percentage difference of MA inventories is equal to about 40%, increasing to 104% in 2200.

2.2.3 Scenario 1: Required facilities

Fuel fabrication

It was observed that a capacity of ca. 1 000 t/y for UOX plants, 100 for MOX, and 30 for ADS would be required, in accordance with the defined annual electricity production per fuel type (387 TWhe for UOX and 43 TWhe for MOX).

Fuel reprocessing

The reprocessing capacities required in Scenario 1 for the regional approach and the scenario without transmuter (*i.e.* no P&T) are described in Table 2.

Figure 4: Minor actinide total mass (in tonnes) in all facilities

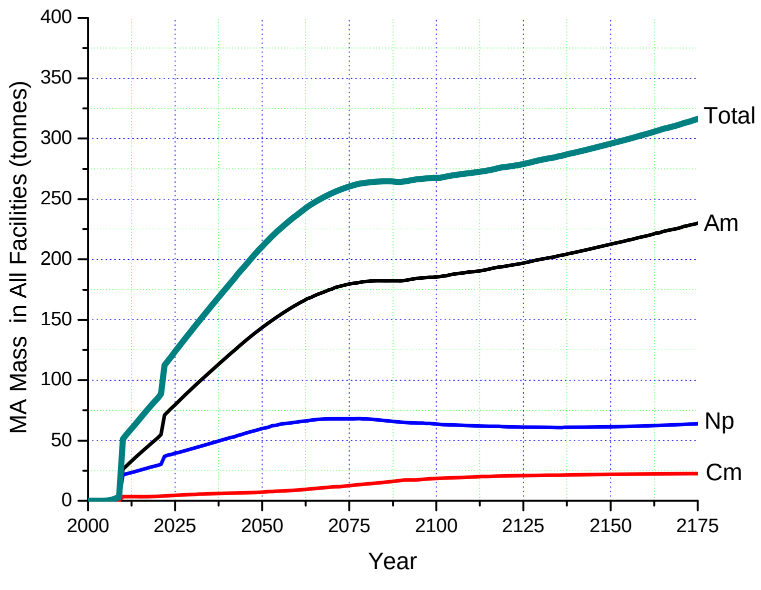


Figure 5: Total MA mass comparison between regional (Scenario 1) and "no transmuter" case

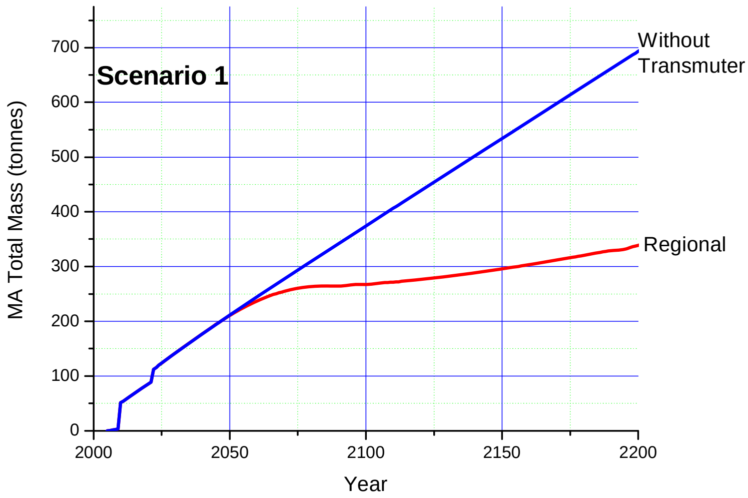


Table 2: Reprocessing capacities (in tonnes/year) for regional (Scenario 1) and "no transmuter" approach

Scenario 1			
Regional		Without transmuter (no P&T)	
UOX	2 350	UOX	1 500
MOX	500	MOX	500
ADS	850	ADS	0
Total	3 700	Total	2 000

The lesser reprocessing capacity in case of a separate (without transmuter) scenario is given by the absence of the Group A – phasing-out nations – (850 t/y) and ADS (850 t/y) reprocessing facilities: the difference between the two cases considered in the table is in fact 1 700 t/y (half of which, as stressed in the text, of "new type", *i.e.* ADS fuel).

2.3 Scenario 2

2.3.1 Detailed results

In order to assess and stabilise the stockpile of separated MA arising from the spent fuel reprocessing of Groups A and B, the optimal number of ADS to be deployed was investigated. It was found that in total 27 ADS of the EFIT type are required to achieve this goal (two more units than with respect to Scenario 1).

The ADS energy production is shown in Table 3.

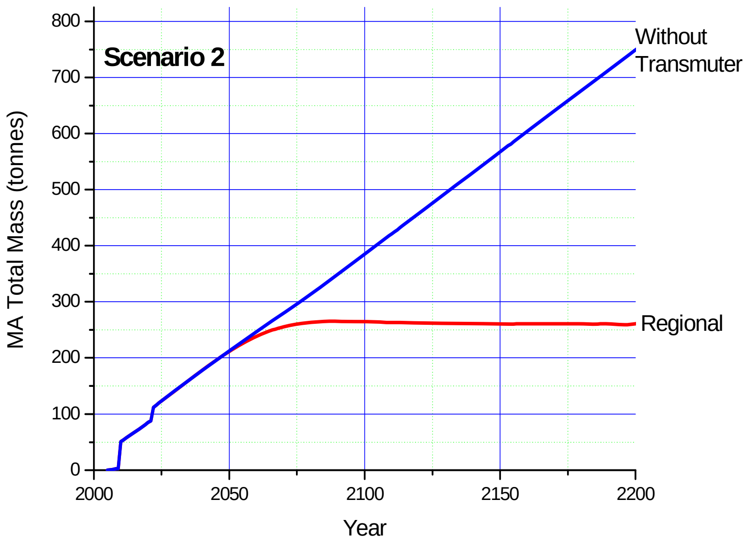
Table 3: Deployment pace of ADS fleet (energy demand)

Time period	Scenario 1 Annual energy production (TWh_e)	Scenario 1 No. of total ADS deployed	Scenario 2 Annual energy production (TWh_e)	Scenario 2 No. of total ADS deployed
2045	0	0	0	0
2090-2200	29.3	25	31.6	27

Two MA inventories are compared in Figure 6: *i)* accumulated in the regional approach; *ii)* build-up in Groups A and B together without transmuter (*i.e.* no P&T: no ADS units deployed) approach.

The advantage of a regional scenario is clear: in 2100 the percentage difference of MA inventories is equal to about 45%, in 2200 up to 187%.

Figure 6: Total MA mass comparison between regional (Scenario 2) and "no transmuter" case



2.3.2 Required facilities

Fuel fabrication

As for Group B, the annual fabrication capacity of about 690 t/y for UOX-fuelled plants, 90 for MOX and 300 for MOX RMA is required. The fabrication capacity needed for ADS is approximately 40 tonnes per year.

Fuel reprocessing

The reprocessing capacities required in Scenario 2 for the regional approach as compared to the case without transmuter (*i.e.* no P&T) are described in Table 4. Here again, the differences are caused by the absence of ADS and associated reprocessing facilities.

Table 4: Reprocessing capacities for regional (Scenario 2) and "no transmuter" approach

Scenario 2			
Regional		Without transmuter (no P&T)	
UOX/MOX	2 450	UOX/MOX	1 600
ADS	850	ADS	0
Total	3 300	Total	1 600

2.4 Comparison between regional Scenarios 1 and 2 and the case without P&T

In order to keep the out-of-pile fuel inventory in interim storage as low as possible (with a given cooling time) both in Scenarios 1 and 2, and in order to reduce the consequent middle- and long-term radiotoxic impact on repository, the number of required ADS units to be deployed is much higher than the number required simply to stabilise the MA inventory. A total of 25 units were necessary to achieve this goal (versus 16 in order to stabilise only the MA main stock inventory) for Scenario 1; whereas 27 units are needed for Scenario 2.

If MA stabilisation is the only goal pursued, the advantage of the regional approach is evident from the COSI6 simulations: a smaller number of ADS units have to be employed.

An important point is the reduced need for separate fuel cycle installations when comparing the regional deployment of P&T and the deployment of P&T by countries "in isolation". In fact, in the regional case there is no need for specific installations in Group A.

Due to the specific EFIT performance, which does not burn plutonium, this type of transmuter is suitable essentially for a regional approach, where the excedent plutonium is used to generate more energy. However this feature is a serious drawback when considering nations phasing-out nuclear "in isolation", as discussed below.

Finally, the particular composition of ADS EFIT fuel should be considered (45% Pu, 55% MA), since it would require specific technology developments (particularly complex, considering that the reprocessing and fabrication of ADS fuel is not yet a proven technology).

A point to be taken into account in the mono-recycling scenario is the ageing of the Pu in FR stock. In fact a considerable amount of ^{241}Am will be generated by radioactive decay over time, forcing to shorten the storage period as much as possible by a more aggressive fast reactor fleet start-up.

As for the Pu multi-recycling option (*i.e.* with recovering of plutonium from spent fuel), it allows extracting more energy from the mined uranium, slightly enhancing the fuel's utility, and consequently that of natural resource utilisation. The multi-recycling of Pu in the LWR induces a significant increase of MA production, compared to the monorecycling case. However, this contribution is less important than the difference in the Pu vector. The drawback is finally a lesser (perhaps insufficient) quantity of plutonium available for a future fast reactor fleet.

If Group A pursues independently the P&T transmutation strategy, the ADS units should obtain the plutonium needed for their start-up cores from its (*i.e.* Group A) spent nuclear fuel. In 2022 Group A spent fuel legacy should contain, according to a preliminary assessment, ~320 tonnes of plutonium and ~44 tonnes of MA. Since plutonium constitutes 88% of the TRU mass, the ADS used to transmute that TRU must necessarily employ relatively short cycles. Schneider (2004) demonstrated that the steep burn-up reactivity gradient resulting from use of Group A TRU inventory limits the ADS cycle burn-up to 40 MWd/kg (with a reactivity swing $\Delta k_{eff} = 0.03$) and the cycle time to slightly less than half of a year (168 days), in case of a sodium-cooled metal-fuelled ADS (840 MW_{th} and LBE target). The very low Pu transmutation rate of EFIT (less than 2 kg/TWh_{th}) would imply for phasing-out nations of Group A no significant reduction in total Pu inventory and the lack of benefit which the destruction of Pu isotopes (especially ^{238}Pu) brings for disposal options. These restrictions of ADS performance constitute a drawback for Group A acting alone and might daunt the nations phasing-out from choosing EFIT as dedicated facility to transmute their TRU.

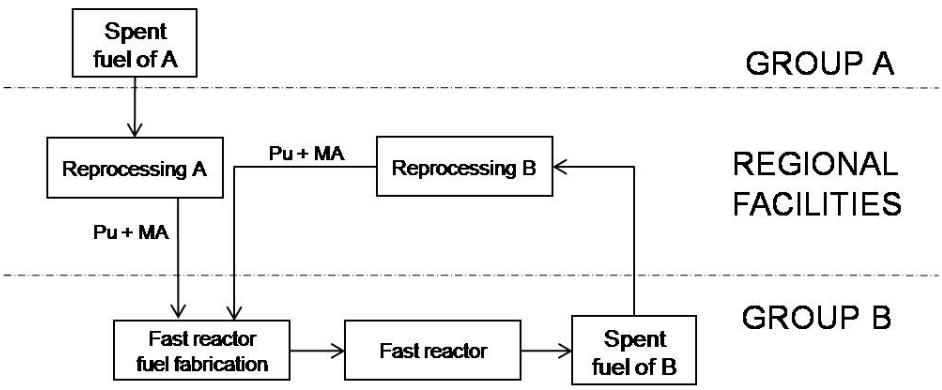
Chapter 3: Scenarios 3 and 4

3.1 Parametric studies on Scenario 3

A major objective of Scenario 3 (Figure 7) is the consumption of the TRU legacy stocks of Group A at a reasonable time horizon. It was shown in Salvatores (2007) that there exist a number of options in that respect, since the time necessary for the consumption of the TRU of Group A depends on a number of parameters, such as:

- The breeding gain of the FR in the Group B: the lower the gain, the more efficient the FR for transmutation [the time necessary for the consumption of the actinide inventory can be reduced by using the CAPRA concept (Roualt, 1995) in the transition period].
- The out-of-reactor time in Group B: the higher this time, the more TRU needed from Group A for the fuel cycle TRU inventory in Group B.

Figure 7: Schematic diagram of Scenario 3



It was shown in Salvatores (2007) that, whatever the out-of-reactor time, with a FR having a low breeding gain (-0.196), the TRU inventory of Group A is consumed within less than 100 years. With 1+2 years and an intermediate breeding gain (-0.061), there impact on the TRU inventory of Group A is minimal.

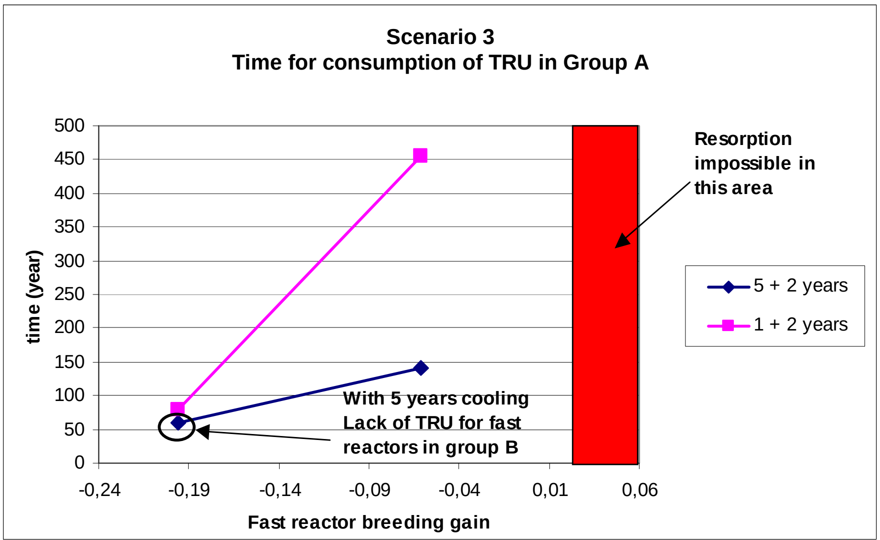
The other important parameters are:

- the number of countries involved in the regional approach (impact of the initial inventories);
- the date and pace of deployment of the fast reactors;
- the load factor in PWR and FR (more electricity can be produced with the same installed capacity);
- the production of Pu in the PWR which can be increased if necessary by reducing the burn-up of the fuel;
- the preliminary step for Pu as a MOX in PWR.

Figure 8 summarises the trends relating to the time needed to consume the TRU of Group A countries on both parameters. Later in this chapter, the results of the scenario corresponding to the low breeding gain (-0.196) and one year of cooling will be presented in detail, because these assumptions allow to:

- have the shortest time for TRU consumption in Group A;
- deploy fast reactors in Group B without lack of TRU.

Figure 8: Scenario 3 – parametric studies



3.2 Parametric studies on Scenario 4

An important outcome of Scenario 4 (Figure 9) is the potential for restarting a sizable nuclear power fleet in some countries of Group A. Here again, a parametric study was performed in order to indicate significant trends and options and the main results have been described in Salvatores (2007) and are shown in Figure 10.

Figure 9: Schematic diagram of Scenario 4

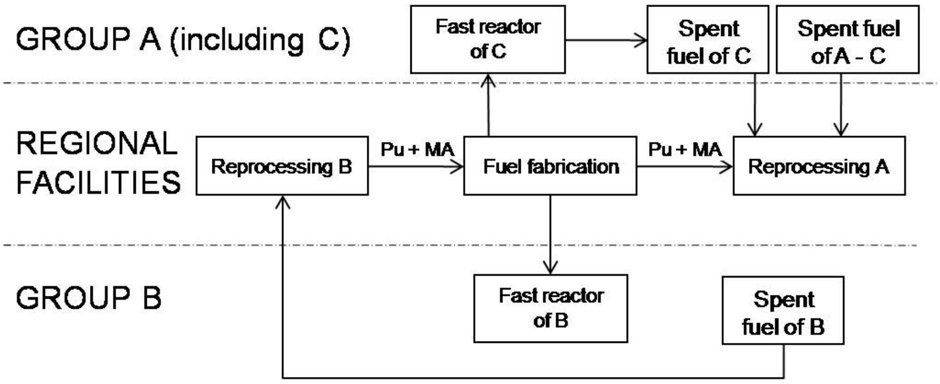
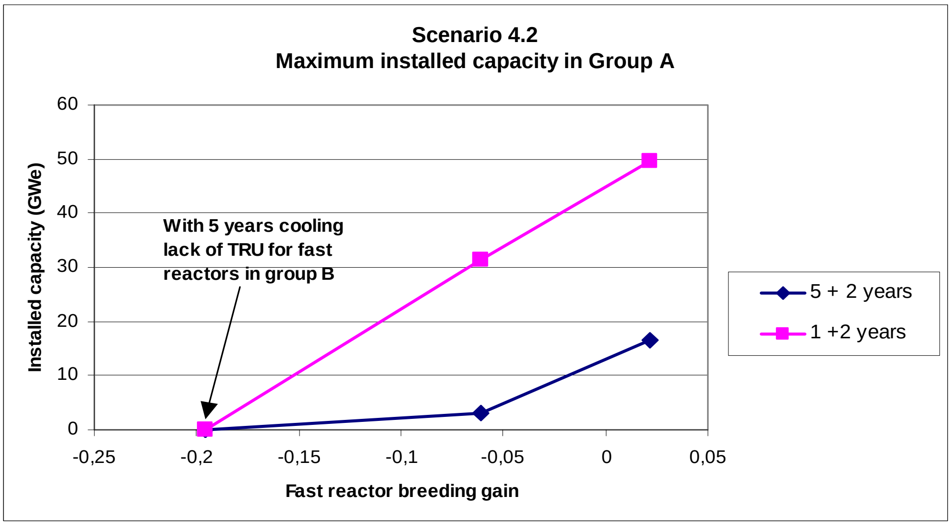


Figure 10: Scenario 4 – parametric studies



The parametric study did show that the maximum installed capacity in Group A depends on:

- breeding gain of the fast reactors (the higher the breeding gain, the higher the number of reactors that can be deployed);
- out-of-reactor time for TRU, which determines the TRU fuel cycle inventory.

With an out-of-reactor time of 1+2 years for the fast reactor fuel cycle, the deployment of new fast reactors in Group A is still possible in 2050.

The maximum achievable installed capacity corresponds to 49.5 GWe in Group A, corresponding to 330 TWhe (load factor = 76%, breeding gain = +0.022). The pace of deployment is 1.5 GWe/year.

An out-of-reactor time of 5+2 years would allow a lower achievable installed capacity.

As in the previous case, other important parameters can play a significant role in the overall scenario assessment:

- number of countries involved in the regional approach (impact of the initial inventories);
- date and pace of deployment of the fast reactors in both groups;
- date and pace of decommissioning of the PWR in Group B;
- load factor in the PWR and FR;
- breeding gain in the fast reactors which can be fitted to produce or to adjust the required Pu inventory;
- production of Pu in the PWR which can be increased if necessary by reducing the burn-up of the fuel.

Later in the chapter, the results of the scenario corresponding to the higher breeding gain (+0.022) and one year of cooling will be presented in detail, because this allows deploying the maximum installed capacity in Group C.

3.3 Detailed results of Scenarios 3 and 4

3.3.1 Plutonium inventory

Figure 11 displays the plutonium inventories in the cycle for Scenarios 3 and 4.

For these two scenarios, the evolution of the Pu inventory depends on the breeding gain of the fast reactors.

For Scenario 3, the objective was to eliminate as quickly as the possible the TRU inventory of Group A and the FR chosen have a negative breeding gain. In this case, the total Pu inventory decreases once the entire FR fleet is deployed.

Due to negative breeding gain, a permanent lack of fissile materials appears as of year 2120; lacking Pu is provided by an external Pu source (“infinite Pu”) and the inventory is artificially stabilised.

For Scenario 4, the objective was to restart as many FR as possible in Group C. That is why FR with positive breeding gain were chosen. In this case, the Pu inventory increases.

3.3.2 Minor actinide inventory

The minor actinide inventories in the cycle for Scenarios 3 and 4 are shown in Figure 12.

Figure 11: Scenarios 3 and 4 – plutonium inventory in the cycle

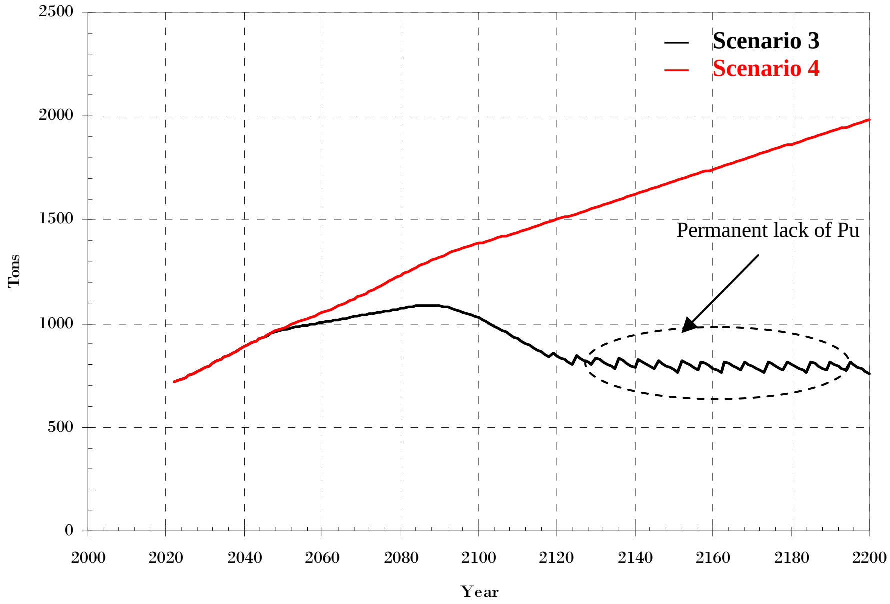
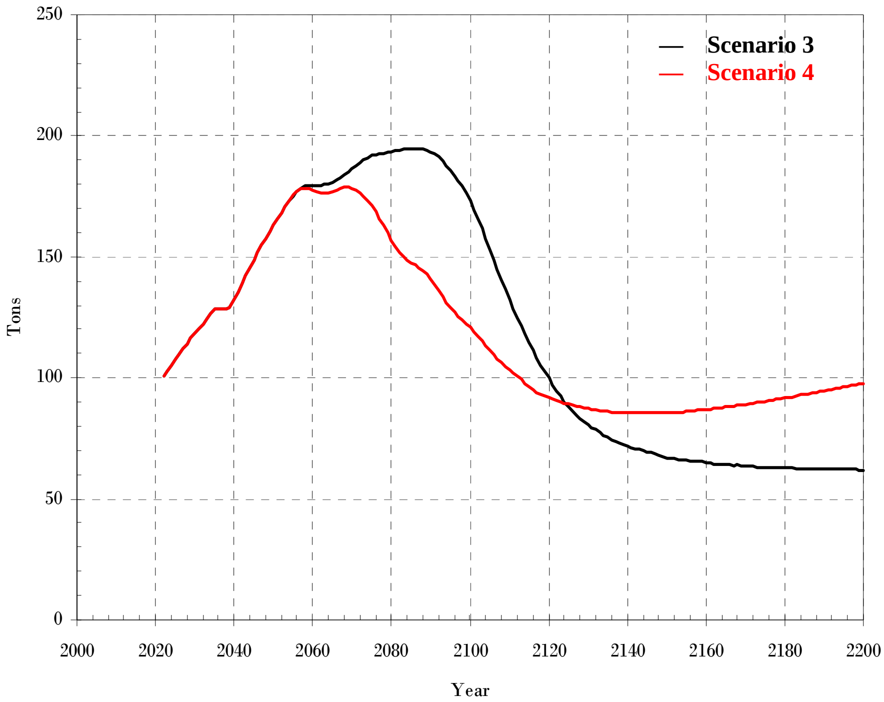


Figure 12: Scenarios 3 and 4 – minor actinide inventory in the cycle



For Scenarios 3 and 4, the evolution of the MA inventories depends on the transmutation strategy applied. In both scenarios, the MA are transmuted in the FR as soon as they are deployed. For that reason, the total MA inventory decreases when enough FR are deployed.

At the end of Scenario 4, the MA inventory increases because of the positive breeding gain.

3.3.3 Scenarios 3 and 4: Required regional facilities

For Scenario 3, the regional facility to be deployed is the reprocessing plant (or plants) to be used by both Group A and Group B countries. For Group A, the reprocessing capacity needed depends on the time of consumption of TRU. Considering the total amount of spent fuel in Group A, *i.e.* 29 000 tonnes (mainly UOX) and the minimum time for reprocessing of this fuel, *i.e.* 35 years, the maximum reprocessing capacity for the needs of Group A is 850 tonnes of initial heavy metal per year. This value can be reduced by increasing the period for reprocessing. For Group B, an additional capacity of 850 tonnes per year for PWR UOX and MOX spent fuel is sufficient for the deployment of fast reactors. An additional capacity of 300 tonnes in order to reprocess FR spent fuel is necessary at the end of the century (100% fissile fuel).

For Scenario 4, the regional facilities needed are the reprocessing plant for Groups A and B and the fuel fabrication plant for the fast reactors of Groups A and B.

Reprocessing facility

For Group A, the maximum reprocessing capacity is necessary at two different stages. At first, for the reprocessing of the initial PWR spent fuel, *i.e.* roughly 850 tonnes per year (as for Scenario 3). Subsequently, when fast reactors are deployed, the maximum installed capacity in Group A related to the newly deployed fast reactors is 49.5 GWe (GRG = 0.022 and one year of cooling). The reprocessing capacity is then approximately 400 tonnes per year (61% of fissile fuel and 39% of blankets). For Group B, the required reprocessing capacity is around 500 tonnes per year (61% of fissile fuel and 39% of blankets). This value is higher than for Scenario 3 because the fast reactors also contain axial and radial blankets which need to be reprocessed.

Fabrication facility

The full fabrication capacity for the fast reactors of Groups A and B is needed at the end of the century, when all fast reactors are deployed.

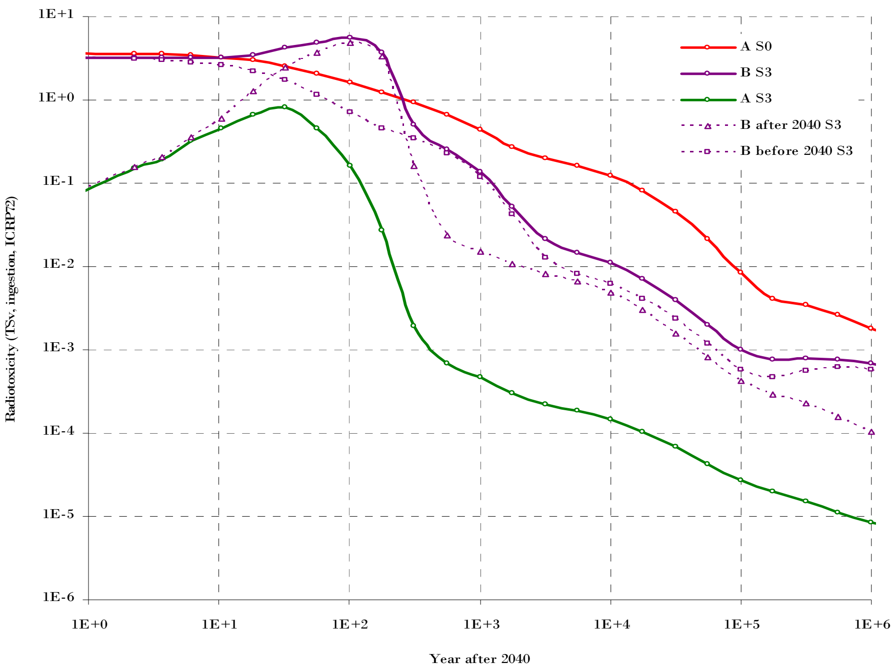
As the maximum installed capacity for Group A is 49.5 GWe (GRG = 0.022, one year of cooling), the annual fabrication capacity should be approximately 400 tonnes per year (61% of fissile fuel and 39% of blankets).

For Group B the maximum installed capacity is 64.5 GWe at the end of the century (430 TWhe per year, load factor = 0.76%), thus the fabrication capacity needed is approximately 500 tonnes per year (61% of fissile fuel and 39% of blankets).

3.4 Impact on waste disposal

Figure 13 shows the cumulated radiotoxic inventory of the HLW in Groups A and B for Scenario 3. The HLW accounted for is that produced between 2010 and 2200. The radiotoxic inventory is presented from 2040, date of the beginning of the partitioning of the MA. The increase of the "B S3" plots (total value given by the solid line; contributions before and after 2040 given by the dashed lines) during the first 100 years is due to the HLW produced by the reprocessing of fast reactor spent fuel and blankets.

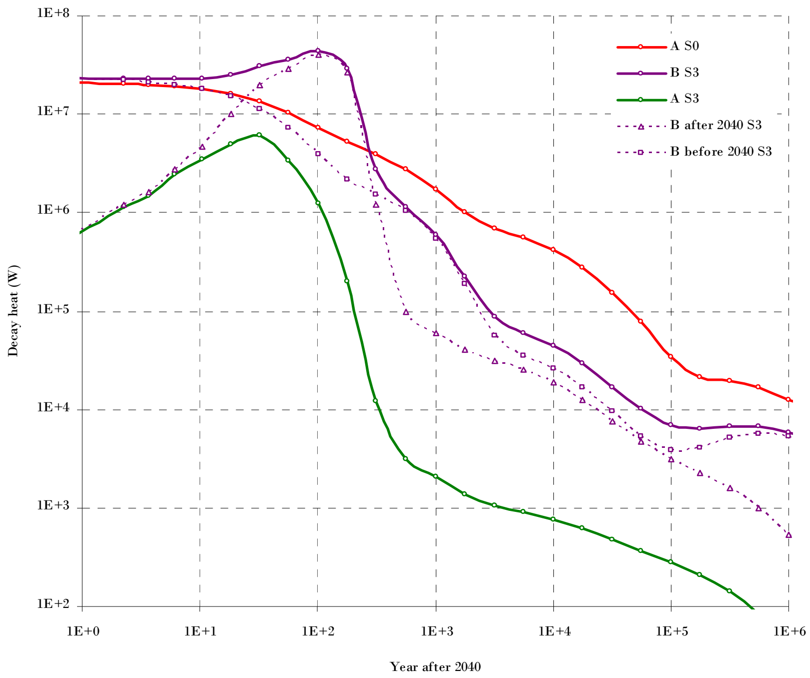
Figure 13: Scenario 3 – radiotoxic inventory of high-level waste



The red plot gives the evolution of the radiotoxic inventory of the spent fuel of Group A when no reprocessing and transmutation strategy is applied for TRU. The green plot indicates that the radiotoxic inventory of the HLW has been reduced by a factor 1 000. The reduction is due to the separation efficiency of the regional reprocessing plant (0.1% for U, Pu and MA). The plot "B before 2040" indicates that the major part of the radiotoxic inventory in Group B originates from the HLW produced before P&T implementation. It should be noted that the initial HLW in 2010 have not been accounted for in these calculations.

Figure 14 displays the decay heat of the cumulated HLW in Groups A and B for Scenario 3. The HLW accounted for are the waste produced between 2010 and 2200.

Figure 14: Scenario 3 – decay heat of high-level waste



The red plot (A S0) gives the evolution of the decay heat of the spent fuel of Group A where no reprocessing and transmutation strategy is applied for TRU. The green plot (A S3) indicates that the decay heat of the HLW after 100 years of cooling has been reduced by a factor 10. At this time, the contribution of the fission products to the decay heat of the HLW remains important.

Figure 15 gives the cumulated radiotoxic inventory of the HLW in Groups A and B for Scenario 4. The HLW accounted for is that produced between 2010 and 2200.

Result for Group B

For a cooling time higher than 500 years, the radiotoxic inventory is dominated by the waste produced before the deployment of P&T, as for Scenario 3.

Result for Group A

For a cooling time higher than 500 years, the radiotoxic inventory is decreased by a factor higher than 10, compared to the direct disposal of spent fuel. It should be noted that the annual electrical production in this group is 330 TWhe, compared to the direct disposal case where no electricity is produced.

Figure 16 gives the decay heat of the cumulated HLW in Groups A and B for Scenario 4. The HLW accounted for is that produced between 2010 and 2200. The same trends are obtained as for radiotoxic inventory.

Figure 15: Scenario 4 – radiotoxic inventory of high-level waste

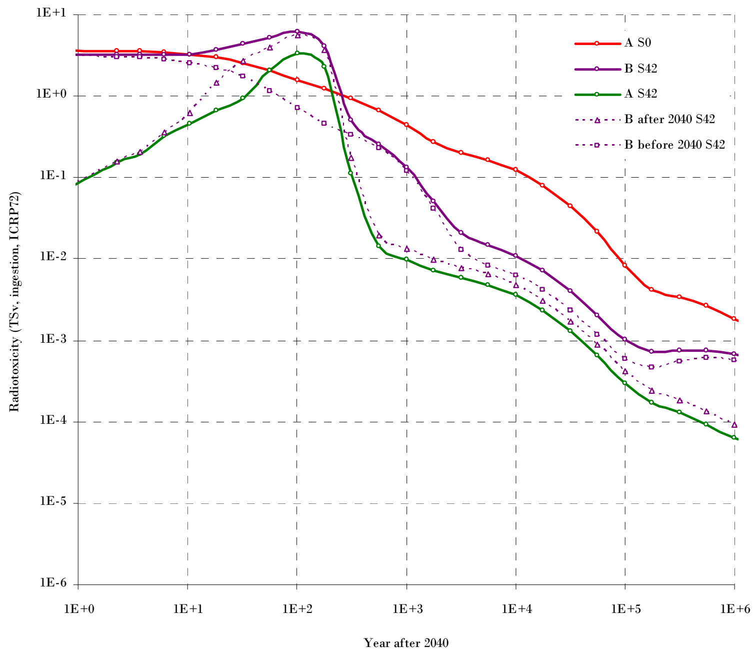
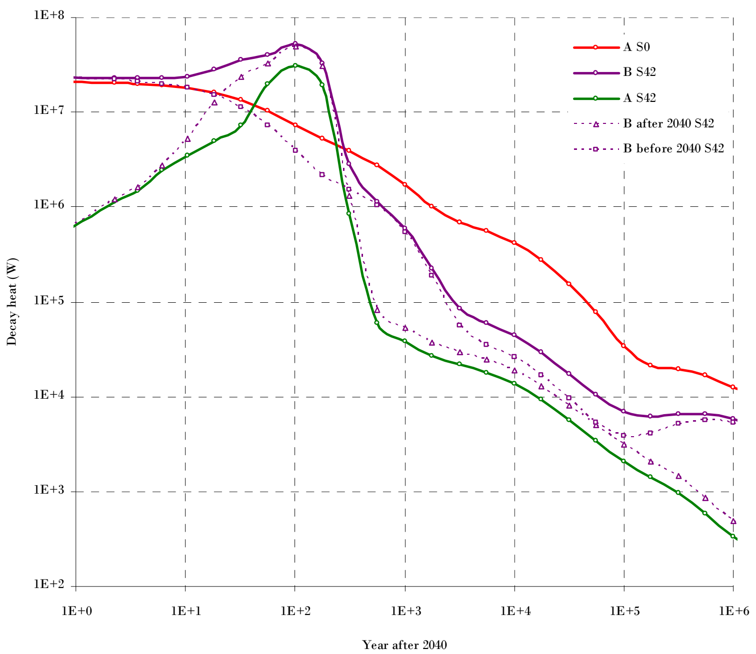


Figure 16: Scenario 4 – decay heat of high-level waste



Chapter 4: Conclusion and perspectives

4.1 Summary of Scenarios 1 and 2

The main results of the regional P&T Scenarios 1 and 2 can be summarised as follows.

The spent fuel stock of Group A can be decreased, as required, down to zero by 2100: all the fuel was reprocessed by that date. In Scenario 1 the Pu mono-recycle option implies that the reprocessed plutonium is kept in order to be successively transferred to fast reactor plutonium stock; it will be introduced in a later stage in the FR fuel cycle of Group B. In order to stabilise the MA production from Group B, the required number of ADS of EFIT type (384 MW_{th}) was determined to be 25 units for Scenario 1, and 27 for Scenario 2 (due to plutonium multi-recycling and consequently higher MA generation). The final plutonium inventory available in Scenario 1 at 2100 for the fast reactor fleet will be 840 tonnes. The results of the Scenario 2 simulation with COSI6 show that the plutonium main stock inventory of Group B is stabilised starting from 2100 at ca. 100 tonnes, while the total inventory increases slightly vs. time due to the accumulation of "bad quality" plutonium resulting from the MOX multi-recycling (which is however associated with a reduced MA production by radioactive decay with respect to plutonium mono-recycling).

For the proposed transmutation strategy, a total reprocessing capacity of 3 700 tonnes per year is needed if Scenario 1 is implemented and of 3 300 tonnes if Scenario 2 is implemented: 850 tonnes per year for ADS reprocessing plant, 850 for Group A spent fuel legacy, and 2 000 for Group B in Scenario 1, 1 600 for Group B in Scenario 2. The PWR fuel reprocessing capacity required for Scenario 1 is about 18% higher than that currently available in France, while the ADS reprocessing facilities must obviously be developed and deployed in the future.

In Scenario 1 the annual capacity of fuel fabrication plants should be 1 000 tonnes/year for UOX, 100 for MOX and 30 for ADS. The required capacity for Scenario 2 is 690 tonnes/year for UOX, 390 for MOX, and 40 for ADS. The total capacity is quite similar in the two cases considered, while only MOX/UOX fabrication capacities proportions are somewhat different (respectively, 1:10 and 1:1.77).

As a final consideration on the EFIT design, it should be mentioned that this type of transmuter offers potential benefits only in regional scenarios, but it does not seem suitable for phasing-out nations implementing a P&T strategy in isolation, because its transmutation performance is focused exclusively on MA and leaves most of the Pu stock unchanged.

4.2 Summary of Scenarios 3 and 4

The major result of Scenarios 3 and 4 is the possibility to manage the Pu and MA of several countries through a regional approach with fast reactors either burners or breeders, depending on the strategies applied in the countries.

The flexibility of a fast reactor and the reversibility from burner to breeder could be quite useful, as demonstrated in past studies (Newton, n.d.). The transition from burner to breeder configurations for the fast reactors (all or part of them) could then be made at a specific point in time. This feature can allow tuning future strategies at a regional level that account for both sustainability and waste minimisation.

A significant reduction of the radiotoxic inventory of the high-level waste is obtained for both groups of countries, even in the case of a restart of nuclear energy in Group A.

Moreover, the added value of the fast reactors compared to the ADS is the electricity produced (330 TWhe per year in Group A in Scenario 4).

It has also been pointed out that the optimisation of scenarios depends, as expected, on a number of parameters; those that characterise the fuel cycle (cooling times, etc.) are particularly significant and will have to be investigated in detail.

4.3 Overall summary and perspectives

Regional strategies can in principle provide a framework for the implementation of innovative fuel cycles, with appropriate sharing of efforts, accounting for proliferation concerns and resource optimisation. In the present paper we have presented the first results of specific scenarios, presently investigated within a wider effort underway in Europe in order to shape a roadmap to implement partitioning and transmutation technologies.

The indications obtained so far underline that if, *e.g.* fast reactors with homogeneous recycle of not-separated TRU are envisaged, there is the need to optimise the fast reactor characteristics (*e.g.* the conversion ratio), and the fuel cycle characteristics (*e.g.* the fuel out-of-pile cooling time), in order to meet the potentially different objectives of different countries within a regional area.

In the present study, we did not investigate the impact of introducing critical fast reactors using heterogeneous recycle of MA; this can perhaps be the object of future studies. However, the potential limitations in terms of maximum allowed amount of MA that can be loaded in a target and the potential absence of fertile blankets can reduce the flexibility of fast reactors, as discussed above, that would allow coping with a range of objectives within a regional area.

Another relevant finding of the study is related to the characteristics of the ADS chosen to transmute MA in scenarios of the "double strata" type. In fact, most ADS design studies, and in particular those performed in the framework of EUROTRANS, have considered a fuel loading and a transmutation potential mostly adapted to MA, as opposed to TRU, consumption. This type of ADS is thus more apt to be used in a "regional" scenario where different countries with different objectives share resources, facilities and spent fuel inventories in order to minimise wastes. The same type of ADS will not be useful in the case of a country committed to a stagnant or decreasing use of nuclear energy that would decide to deploy P&T in "isolation" for waste management.

In this respect, an interesting addition to the present study would be the introduction of a critical "burner" fast reactor (*i.e.* with a conversion ratio in the range 0.5-0.8) in Scenarios 1 and 2.

As far as the impact of the implementation of P&T at a regional level, the results of the scenario studies indicate that the expected beneficial potential of P&T, *i.e.* reduction of the radiotoxicity in a repository to the level of the radiotoxicity of the initial ore after a few hundred years, and the reduction of the heat load in the repository (more than one order of magnitude), applies to the whole region, providing a potentially significant benefit to all the countries of that region (*e.g.* Europe), despite their different policies in terms of nuclear energy. Moreover, the present studies have shown the potential of a regional strategy in order to favour a nuclear "renaissance" in some countries.

Further studies are obviously needed, in particular in order to investigate practical issues (such as fuel transport, etc.) and institutional issues which will without doubt be very challenging.

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