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Table of Contents

Introduction

This deliverable provides a summary of all the deliverables issued within the work packages. It first discusses the analysis of previous studies and selection of the reference scenario. Then it presents both the reference Fast Reactor System and the reference Accelerator Driven System. Next, the fuel reprocessing and fuel fabrication is discussed. It concludes with the technical/economic comparison of FR and ADS.

WP1 – Definition of the reference scenario

A review of the available literature was assessed, and in particular the outcome of the INPRO-GAINS study concerning fast systems capabilities to transmute relevant amounts of MA was presented. It was shown that fast systems, i.e. critical fast reactors and ADS, can manage efficiently the MA legacy if proper fabrication and handling technologies will be developed; moreover, by the last quarter of the century, ADS technology would give an opportunity not to overload fast reactors with the function of MA burning at the first stage of their commercial introduction.

Concerning scenarios literature, the low energy demand case of WP1 of the CP-ESFR EU project concerning analysis of a scenario for Sodium Fast Reactor deployment in Europe shows that a full replacement of LWR with ESFR technology is possible within a timeframe of 90 years, and that moderate requirements of Pu should avoid adoption of blankets; in any case an adequate plutonium management policy should be adopted, according to which a proper amount of it should be produced in order to feed the domestic fleet but without exceeding needs, in order to avoid waste storage and proliferation issues. Loading fast reactors with a 2.5% share of MA would allow reducing MA (however less efficiently for Cm).

An assessment of the legal framework, according to EURATOM regulation, lead to the observation that there are two fields of concern, radiological protection and non-proliferation, with two international tools for dealing with the risks stemming from those fields, both "strengthened" by two specific prescriptions from EURATOM, namely:

- "The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management", which is complemented and somehow amplified within EURATOM by the "Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste";
- The "Non Proliferation Treaty", which is the origin of the complete set of safeguards of IAEA, which is somehow complemented, or substituted, within EURATOM by the "Commission Regulation (Euratom) No 302/2005 of 8 February 2005 on the application of Euratom safeguards".

Both prescriptions do not convey an impediment for transmutation but transmutation will have to comply with all standards applicable, as there are safeguards, nuclear material accountancy (taking into account the change in isotopic contents of materials due to transmutation), safety and radiation protection (ALARA).

These regulations are also of very high importance during the transportation of nuclear materials from one country to another country. Almost all innovative fuel cycle approaches use a regional approach where nuclear material is transported from one country in the region to another because these countries have different policies (phase-out versus start-up of Generation IV reactors).

An insight in current options for the processing of fuels for their use in fast reactors and ADS has been written. The discussion has focussed on oxide fuels, due to their near term deployment feasibility. Currently, U-Pu oxide fuels have reached a high level of maturity, but they rely on industrial processes based on powder metallurgy, which presents a drawback because of dust production. In order to implement production technologies for MA bearing fuels, a full hot cell environment would be required; moreover, further innovation is required for implementation of dust free routes. At present, no process has reached the technological readiness level sufficient to license MA based fuels, although they have been fabricated at laboratory level all around the world.

In this context, a review of available reprocessing technologies has been presented, and in particular, the pyrochemical solution was discussed. It probably represents the best solution for special fuels such as those adopted for FRs and ADS containing a large amount of Pu and MA. However, it was noted that they did not reach the industrial level deployment yet.

A MA annual fuel stream and its isotopic vector were proposed based on the PATEROS reference scenario 1. In this scenario spent UOX and MOX fuel discharged from LWR is reprocessed (mono-recycled) in order to separate TRU from fission products (whereby these last ones, together with reprocessing losses, are sent to a geological repository). Reprocessed Pu and MA are recycled in a regional transmuter facility, which in this case is the ADS-EFIT (*Accelerator Driven System – European Facility for Industrial Transmutation*), and blended with TRU separated from spent fuel of EFIT fuel cycle (as soon as available) in subsequent cycle passes. The final goals of the scenario are:

a) to fully reprocess the spent fuel legacy of some European countries, which are supposed to be in a stagnant or phasing-out scenario (**Group A**): *Belgium*, *Czech Republic*, *Germany*, *Spain*, *Sweden* and *Switzerland*, in order to eliminate all the TRU stocks, *before* the end of the present century;

b) to store Pu (for a possible future use in the deployment of fast reactors, which were not simulated in this case) and to *stabilise* the MA inventory in European countries pursuing nuclear energy generation (**Group B**): *France* was considered in this case.

According to scenario assumptions, ADS-EFIT will be deployed in a regional centre starting from 2045 up to 2090 in a linear-growth fashion, after which a constant energy production level – i.e. number of transmuters – is assumed. Regional fuel cycle facilities such as reprocessing and fuel fabrication plants for innovative fast reactor fuel, and a spent fuel (SF) interim storage are considered to be available. In particular, a reprocessing capacity of 850 tonnes/year was assumed for the Group A reprocessing plant, while a double capacity of 1700 tonnes/year was necessary for stabilising the inventory of Group B

A range with a reasonable minimum and maximum value (respectively, from 2.3 to 6.5 tonnes/year) was discussed. Taking into account also projections of specialised institutes such as IIASA, up- or down-scalings are, however, possible. Also, the plutonium composition and its annual stream, which should be relevant from a transmuter fuel cycle point of view, were addressed. A rough estimate of the total dose rate and the heat load for the proposed fuel composition was provided, as this information should be relevant for fuel cycle issues, and in particular for its cost estimate. It should be kept in mind, however, that in order to get completely rid of the MA legacy, transmuters' fuels will have to be multi-recycled, and this will certainly modify their isotopic vector with time. The analysis showed that the Minor Actinide stream to be transmuted will be between 2.3 tonnes/year and 6.5 tonnes/year with an isotopic share as given in Table 1.

Table 1: Representative isotopic vector for ARCAS.

Nuclide	Content (%)
Am^{241}	39.55872
Am^{242m}	0.223152
Am^{243}	22.33965
Np^{237}	32.90188
Np^{239}	0.0000195
Cm^{242}	0.000572
Cm^{243}	0.059427
Cm^{244}	3.96696
Cm^{245}	0.949617

WP2 – Definition of the Fast Reactor System

In compliance with Europe's reference choice for a fast reactor system, the Sodium Fast Reactor design currently being developed in the CP-ESFR project has been chosen as the reference fast reactor system. The SFR has a long history of development and deployment of test reactors and even prototypes for electricity production.

However, two major safety risks are still unsolved for: the violent exothermic reaction of sodium with air/water and the positive coolant temperature coefficient (and voiding coefficient). Especially the latter one, in conditions where the delayed neutron fraction is small as in fuel loaded with a high quantity of minor actinides, requires detailed safety analysis.

In the context of the EU CP-ESFR project, a basic SFR concept was proposed as a 'Working Horse' (WH) design, which was further optimized in an effort to improve the original reactivity coefficients. The 3600 MWth core is composed of 225 sub-assemblies (S/A) in the inner core and 228 S/A in the outer core; 453 S/A in the whole reactor. The core S/A are MOX type, where the composition is as follows (in weight percentage of the total Heavy Metal):

- Inner core, 8 S/A active rows: 85.12% Depleted Uranium, 14.76% Pu, and 0.13% Am (as a result of Pu decay during fabricated fuel storage).
- Outer core, 4 S/A active rows: 82.72% Depleted Uranium, 17.15% Pu, and 0.12% Am.

The assumed initial Pu vector is the following:

Pu-238, 3.6%w/ Pu-239, 47.76%/ Pu-240, 29.89%/ Pu-241, 8.29%/ Pu-242, 10.46%

The core optimization is called CONF2 case and the features are:

- A lower axial blanket made of depleted Uranium dioxide.
- An upper Sodium plenum to enhance neutron leakage in the region in case of plenum voiding.
- An upper neutron absorber layer, above the Sodium plenum.

For the Fast Reactor, two different concepts of inserting the Minor Actinides in the core can be envisaged: a) homogeneous: mixing the minor actinides in the fuel elements and b) heterogeneous: dedicated assemblies containing minor actinides placed at a limited number of positions in the core.

In the homogeneous approach minor actinides subjected to irradiation are uniformly distributed throughout the whole core; hence the impact on neutronic parameters is larger than in the heterogeneous approach. In heterogeneous approach, regions with low neutronic importance are selected to load minor actinides fuels (at higher concentrations) as the reactor radial pe-

riphery in the case explained in this report. The other possibility in heterogeneous approach is loading targets with high concentration of minor actinides in a number of core positions subjected to high fluxes. In this case, the number of targets must be limited.

In the homogeneous approach, care must be taken regarding safety:

- Sodium void reactivity coefficient becomes more positive as MA contents increases. This effect is notably negative, because any perturbation producing a void in the sodium (a bubble, or a decrease in density in a certain volume) will induce a reactivity injection, which will cause a sudden power rise, immediately followed by an increase of the temperature, first in the fuel, then in the sodium, which will undergo an additional dilatation and eventually local boiling, what will cause in turn a new reactivity insertion, in a positive feedback that could be deleterious for the reactor. It is not easy to state a generalized statement about sodium void coefficient, because it depends a lot on the configuration of the fuel element and the core, as well as on the fuel composition. This means that this effect on the sodium void coefficient must be carefully calculated and validated from experimental measurements in reactors or experimental mock-ups of the same type as the reactor under study. In any case, this effect must be carefully characterized not only in an isolated way, as it is shown in Figure 1; but in the full picture of the reactor stability, what is not an easy task, but can be approached by numerical simulation. In any case, the issue of the positive void worth in large sodium fast reactor is well known since the very beginning of the technology and the traditional approach was to compensate the individual effect with the rest of reactivity coefficients, then leading to a global favourable balance of reactivity in case of assumed transients. Being conscious of the problem, researchers dedicate nowadays efforts to provide core configurations directly leading to very low and even negative void worth, generally obtained by means of a higher degree of core heterogenisation: for instance, the presence of inner absorbing axial blanket, annular cores with no active material in the reactor centre, non-uniform axial content of the fissile material, or a limited number of moderator rods.
- The Doppler effect coefficient suffers still higher degradation (the figure gives the reduction in absolute value) what makes things worse, because the reaction for reducing the reactivity as a consequence of an increase in fuel temperature, is less intense when the MA fraction in the fuel grows.
- The Delayed Neutron Fraction also suffers degradation. This entails a reduction in the margin to control the reactor. Moreover, all reactivity effects are really measured in terms of this fraction; which means that the positive feedback by sodium void is enhanced.

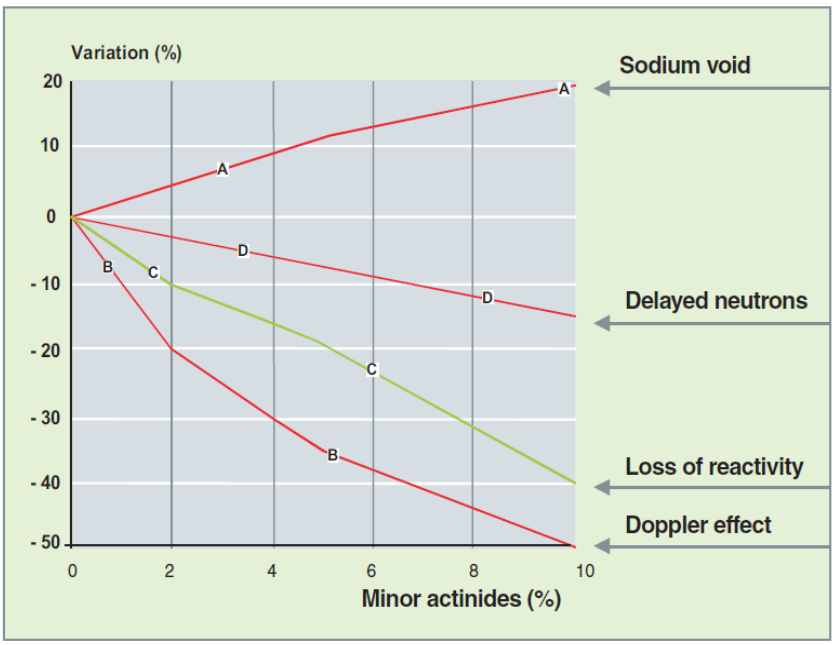

Fig. 182. Relative variations of core parameters, as a function of the minor actinide fraction held in fuel.

Figure 1: Summary of effects produced by including MA in the fuel of a Sodium Fast Reactor (taken from CEA 2008)

A summary of the calculation results for both a homogeneous and heterogeneous loading can be found in Table 2. The homogeneous loading was limited to 2.5 w% to respect a moderate deterioration of some 10-12% in the above mentioned safety parameters. Clearly, when such a reactor reaches the licensing phase, these limits must be established based on detailed safety studies for the system to be built.

In the heterogeneous approach shown in Table 2, no deterioration of the void worth reactivity was found when compared to the reactor with no minor actinide loading. It can be seen in the table that a lower transmutation rate (when normalized per produced energy) is predicted. On the other hand, an additional important feature to consider is the plutonium behavior along irradiation. Both selected designs provide breeding ratios around 1.14 because of the important contribution of the lower axial blanket (the breeding ratio is around 1.03 when no axial and radial blankets are considered).

Table 2: Performance of selected SFR designs working as MA transmuters.

System	**FR-HOM2.5**	**FR-CONF2 HET2** **Radial blanket** [1]
		Heterogeneous MA burning in radial blanket
Total power (MWth)	3600	3600
Power in driver (MWth)	3600	3543 [2]
Power in blanket (MWth)	-	57 [2]
Power (MWe)	1440	1440
Thermal efficiency	0.40	0.40
Load factor	0.80	0.80
Fuel/ target type	MA-MOX	Driver: MOX Blanket: (DU-MA) MOX
# S/A	453	453 / 84
BOI Pu content (wt% HM)	15.60% [3]	12.28% [4] / 0%
BOI MA content (wt% HM)	2.50%	0.12% [5] / 20%
Burnup (GWd/tHM)	100	100 / 6.5 [6] 15.3 [7]
MA destructed (kg/TWhe)	6.9	1.5
MA destructed (kg/TWhth)	2.8	0.6

Since SFRs will not be built solely for the destruction of Minor Actinides (they will be built for electricity production and the MA transmutation will be a "side-effect"), the deployment of SFRs must be seen in the context of a transition of the current fleet of nuclear power plants to a Generation-IV fleet.

The scenario analysed is based on the PATEROS scenarios where nuclear electricity production is assumed constant at 800 TWhe. In the scenario there is a progressive substitution of current and new generation LWR by SFR in two main steps. There is a first phase of Gen.II LWR replacement by EPR (2020-2040). Then, the ESFR technology is available for deployment in the year 2040 and it is introduced in that year for remaining LWR replacement. Afterwards, SFR coexists with the EPR type for a number of years. In the coexistence period, the electricity contributions coming from both technologies are kept constant after the ESFR introduction phase, i.e., as of 2050: 1/3 comes from ESFR, 2/3 from EPR. After that, in 2080, the EPR technology starts to be replaced by additional ESFR. Figure 2 depicts the assumptions concerning technology deployment.

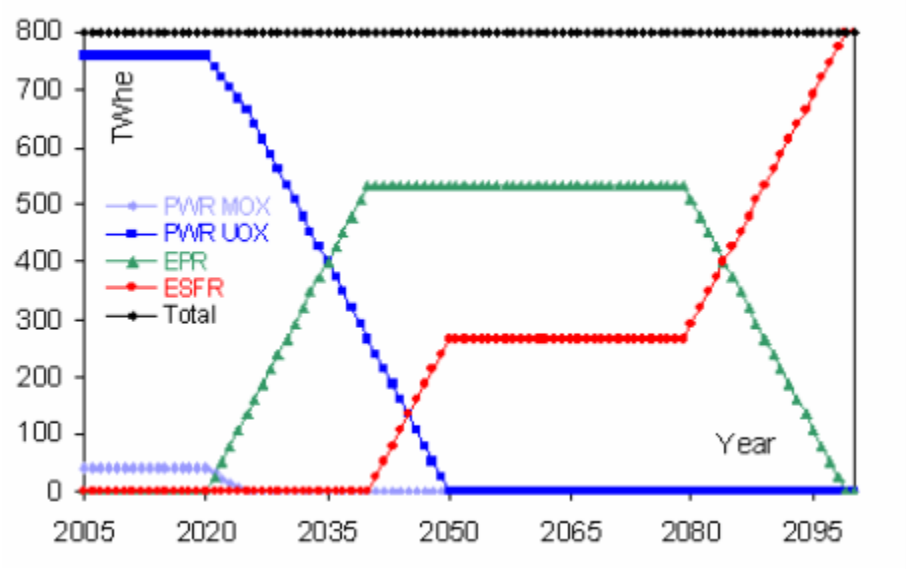

Figure 2: Assumed evolution of the electricity production, per reactor technology, for the Low Energy-Demand scenario of the CP-ESFR project. The above time schedule is an imposed input to the scenario.

The SFR reference design is a 3600 MWth core, slightly Pu breeder reactor and the emphasis of the study is put on the Pu availability along the scenario. The main result is that the scenario is feasible if the Pu BR is 1.03, and the total reactor fleet is therefore composed of 78 SFR reactors by year 2100.

A sensitivity case was run where all 78 reactors are assumed loaded with 2.5%w of MA for all 453 core S/A's and to work in transmutation mode with performances similar to case HOM2 (no CONF2 optimization). This means that 2.8 kg-MA/TWhth are destructed, or, in other words, 88 kg/reactor/EFPY.

Figure 3 shows the evolution of the actinides in the scenario. The Np and Am mass is somewhat stabilized by 2040 as the material is loaded in the first SFR deployment phase and started to be burnt. These materials are close to elimination from interim storage by 2110 as a re-

sult of the second phase deployment. In case of no MA strategy, the total mass accumulates to 650 tonnes (metric tonnes) by 2130.

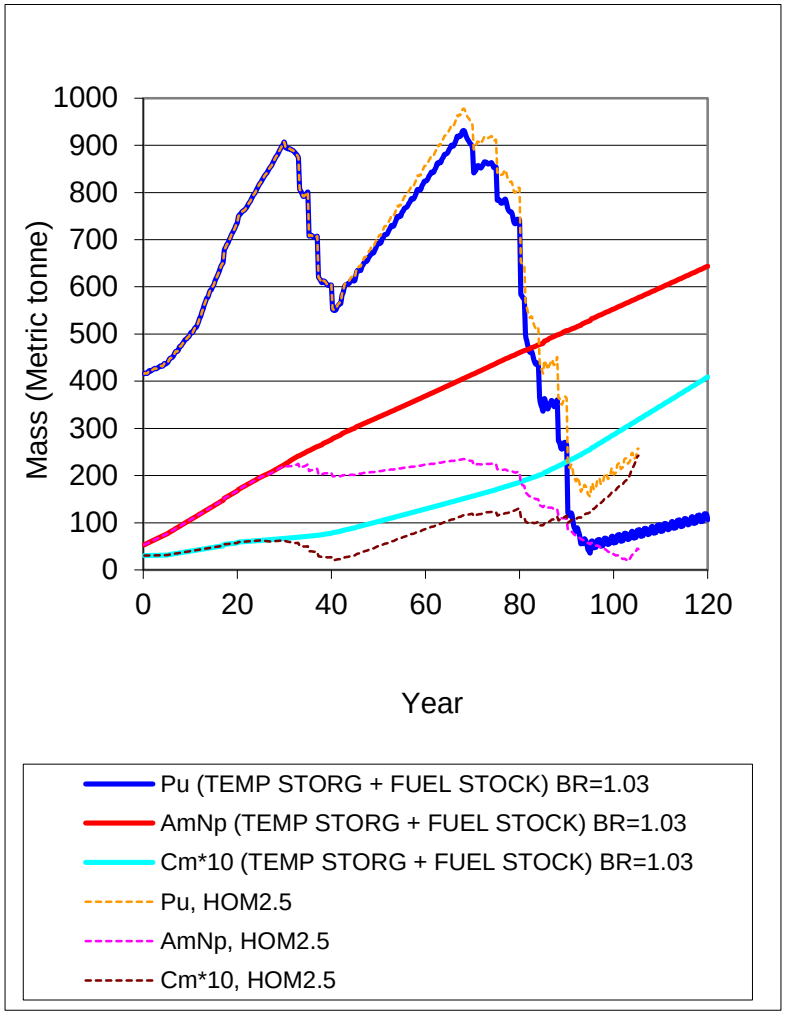

Figure 3: Material in Temporary Storage and Fuel Stock, both added. Cases: Reference (solid lines, BR=1.03) and 2.5%w MA homogeneous transmutation (dotted lines, BR=1.07).

WP3 – Definition of the Accelerator Driven System

The reference Accelerator Driven System studied in the ARCAS project is the EFIT reference design developed within the European sixth framework program IP-EUROTRANS. The European Facility for Industrial Transmutation is an ADS driven by an 800 MeV proton linear accelerator delivering 20 mA of current. This beam impinges on a windowless spallation target, where the induced spallation reactions produced the required source neutrons. The 19 central positions of the hexagonal core lattice house the spallation target which is surrounded by fuel assemblies. The number of fuel assemblies is such that the core, by design, will not become critical (even in accidental conditions). The reactor core is cooled by pure lead.

For the fuel one opts for uranium-free fuel since this avoids extra build-up of plutonium (by capture in U-238). Because there is a relationship between the energy produced and the material destroyed by fission (one fission produces about 200 MeV of energy), the final balance is always a loss of 42 kg/TWh_{th}.

Two types of advanced fuels have been analysed in the EUROTRANS project: the CERCER option and the CERMET option. The former uses a MgO matrix, the latter a Mo matrix. For the CERMET, two sub-options have been analysed: a matrix with natural Mo and a matrix enriched in the lighter isotopes of Mo, avoiding excessive neutron capture.

The reference core consists of three different fuel zones, however for the application to ARCAS, a simplified one zone model was used to reduce calculational complexity. As ARCAS uses a slightly different Minor Actinide isotopic vector (as defined in Work Package 1), a comparison is made between this vector and the original EFIT vector .

As shown in Table 3 and Table 4, in terms of total MA transmutation rate, for both ARCAS and EFIT vectors, the transmutation performances are the same: reaching values of 39kg/TWh and 36kg/TWh for EFIT-400 CERCER fuel and EFIT-400 CERMET fuel respectively.

Table 3: MA Transmutation rates (kg/TWh) for EFIT-400 with CERCER fuel

	MA ARCAS vector	MA EFIT vector
Np	-17.379	-1.331
Am	-29.589	-44.734
Cm	8.206	7.349
Total MA	-38.76	-38.71

Table 4: MA Transmutation rates (kg/TWh) for EFIT-400 with CERMET fuel

	MA ARCAS vector	MA EFIT vector
Np	-15.583	-1.215
Am	-27.096	-43.692
Cm	7.010	6.771
Total MA	-35.67	-35.5

In accordance with the statements made in Work Package 1 on reactivity safety, key parameters have been calculated for the EFIT machine using these CERCER and CERMET fuels with the ARCAS vectors. These parameters are summarized in Table 5 and Table 6.

Due to the large amounts of minor actinides present in the fuel, the delayed neutron fraction is small. The Doppler coefficient is practically zero due to the absence of fertile U-238 in the system. One can see that a partial voiding of the central assemblies has a small positive effect. However, this is captured in the subcriticality limit. And since the time-dependent behaviour of an ADS is driven by the source characteristics, the small delayed neutron fraction has no influence on the kinetics of the system. The most stringent safety requirement is that one can never reach criticality and this requirement must be enforced by design.

Table 5: Safety parameters for EFIT core with CERCER fuel

Safety parameters	***BOC***	***EOC***
K_s	**0.9578±0.016**	**0.93756±0.02**
K_{eff}	**0.97548±0.00007**	**0.96093±0.00007**
B_{eff}	**153**	**160**
K_D	**0**	**+19**
Partial void worth (pcm)	**724**	**563**
Total void worth (pcm)	**-5750**	**-9349**

Table 6: Safety parameters for EFIT core with CERMET fuel

Safety parameters	*BOC*	*EOC*
K_s	0.97335±0.016	0.90777±0.00076
K_{eff}	0.98504±0.00007	0.94217±0.00007
B_{eff}	177	190
K_D	-77	-117
Partial void worth (pcm)	684	559
Total void worth (pcm)	-7094	-10011

Using this design and the results obtained in Work Package 3, a scenario from the PATEROS project was recalculated with the aim to estimate the required installed capacity of EFITs. Two groups of nations are defined (Figure 4):

- ***Group A*** is in a stagnant or phase-out scenario for nuclear energy and has to manage his spent fuel (*Belgium, Czech Republic, Germany, Spain, Sweden and Switzerland*) – i.e. it is simulated as a decaying stock;
- ***Group B*** is in a continuation scenario for the nuclear energy and has to optimize the use of his resources of plutonium for the future deployment of fast reactors (*France*).

A common regional facility is used in order to transmute the minor actinides stock – in the present case we consider ADS-EFIT as the transmuter, which will be deployed starting from 2045 up to 2090 (and then a constant number of transmuters is assumed).

The main goals of PATEROS are:

i) to decrease the stock of spent fuel of countries A down to 0 before the end of the century;
ii) to stabilize the MA inventory of Group B within the end of the century.

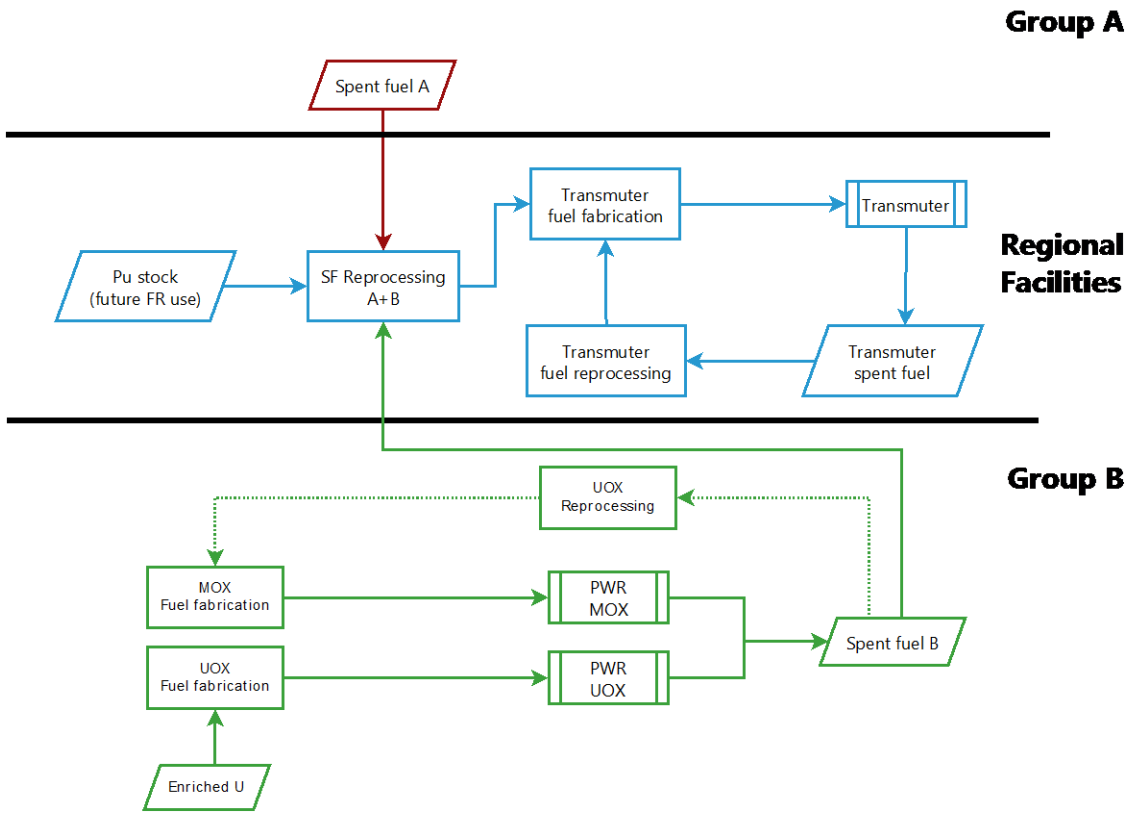

Figure 4: PATEROS simplified flow scheme.

As can be seen from Figure 5, the PATEROS goals are satisfied only when at least 15 units are deployed between 2045 and 2090 (with 20 ADS-EFIT units MA of Group B are roughly reduced to 0 up to the end of the next century). It should be noted in fact that the most demanding request (in terms of units to be deployed) between i) and ii) is the last one.

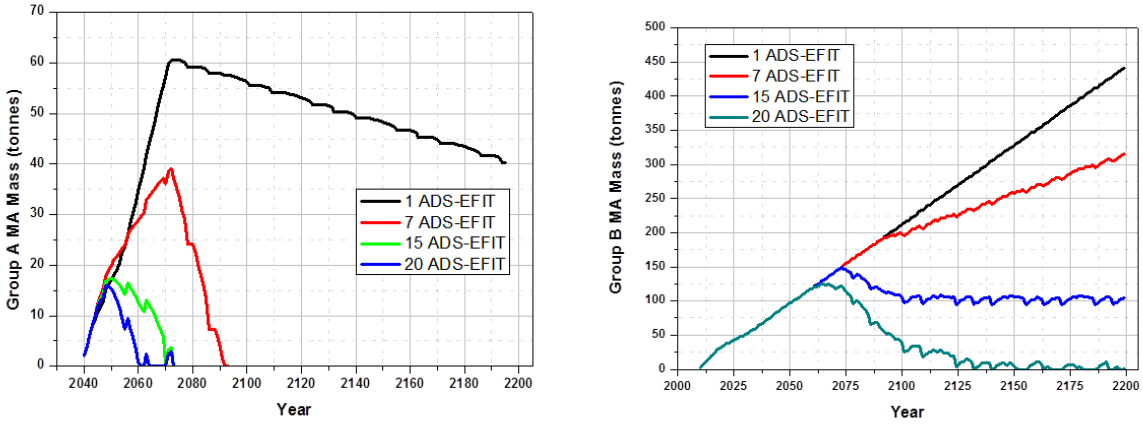

Figure 5: Group A (left) and Group B (right) Minor Actinide inventory as a function of EFIT deployment.

WP4 – Definition of the fuel fabrication and reprocessing facilities

This work package established baseline information which identifies process differences upon which an economic assessment of heterogeneous and homogeneous fuel fabrication plant and spent nuclear fuel reprocessing plant for Fast Reactor and Accelerator Driven Systems can be made in WP5.

Reprocessing

Reprocessing techniques fall broadly in two categories: aqueous and pyrochemical. The choice between either one depends on the fuel type and associated chemistry rather than whether the fuel would be used in Fast Reactors or Accelerator Driven Systems. Also the envisaged fuel cycle of the minor actinide transmutation systems will govern the choice of reprocessing.

In particular, one needs to select pyrochemical processes when a) short cool down times are required; b) the aqueous chemistry is challenged (fuel containing Mo); or c) the fuel is insoluble in nitric acid/organic media systems.

In order to ensure the main reprocessing and fuel fabrication options were considered for economic analysis to determine cost difference, it was assumed that ADS will comprise a Mo matrix fuel and/or MA/MgO(ZrO_2), and therefore, will be treated using a pyrochemical process. FR fuel was assumed to have a composition that is wholly compatible with nitric acid/organic systems and therefore did not contain Mo, ZrO_2 or YSZ. Plant definitions were therefore developed for both aqueous and pyrochemical options.

Within these aqueous or pyrochemical process technologies, a number of technically diverse sub-options were also available which, potentially, presented a considerable challenge from an analysis viewpoint. A detailed analysis of each process was recognised as not viable, as it would be beyond the scope of this study, however, it was possible to generically group and rationalise the approach into unit operations within either an aqueous or pyrochemical flow diagram. In many respects, this was easier to define for the aqueous options since actinide separation for heterogeneous fuel manufacture required readily defined separation stages for advanced PUREX or GANEX processes.

However, within the pyrochemical selection, the technologies were totally different and highly diverse such that there were few similarities between stages and unit operations and necessarily the number of attendant process steps. As a consequence, one of the technologies that had been developed, in part, to pilot plant scale was arbitrarily chosen as a test case for this study. This was the chloride salt based process currently under development in ROK, the US, Japan, India and some communities within Europe. Nevertheless, this could equally have

been the RIAR process being developed in Russia, which has reached a similar TRL and represents similar overall challenges.

An analysis of the different unit operations for both aqueous and pyrochemical options was completed. A basic gap analysis highlighted the technical immaturity of both technology options, and as expected, they were found to have a very low TRL of 2-3.

In order to compare costs (as input to Work Package 5), Table 7 gives an overview of the differences between the aqueous and pyrochemical reprocessing. It should be noted that this approach assumes the main cost elements of the options, pyrochemical or aqueous, are not dominated specifically by the technology of choice, but dominated by the number of process elements and the processing environment for given process elements for example shielding, process simplicity and therefore minimal access for process maintenance and deployment requirements for remote technology.

Table 7: Comparison of aqueous and pyrochemical reprocessing options.

	Aqueous	Pyro	Consequence
Cool-down	5 yrs min	2 yrs	Larger interim spent fuel store required for aqueous
ecladding	Benefits from established conventional process	New cladding removal technique required or Chemical pulverisation deployed	A new process is required for Pyro processing
Pre-separation	Increased oxidising conditions required (Ag II)	Chloride based process – Oxide Reduction required	Aqueous – new dissolution process Pyro - Oxide reduction requires development
Separation **Homogenous option**	Group capture possible. Actinide separation still required to balance fuel composition.	Process designed for group MA separation. Actinide separation still required to balance fuel composition Additional processing required	Recovery of individual MA species will require additional process lines for both pyro and aqueous processing
Heterogeneous option	Three distinct process steps (Separate Plant) Cannot treat some inert matrix fuels	Can treat all fuels	Pyro option only for some fuels
Conditioning	Oxide preparation might take a direct nitrate solution or use oxalate precipitation	Salt removal processes have been developed	Same process step requires development in both aqueous & pyro

	Aqueous	Pyro	Consequence
Waste	Conventional routes available (Glass & aqueous)	Glass / glass-ceramic	No aqueous waste for pyro
Solvent / Extractant	Centrifugal contactors likely to maximise throughput rate	Solvent extremely tolerant to radiation damage	Less added solvent required for Pyro Solvent treatment required for both
Inventory	Moderator can limit fissile material in plant	Greater inventory possible	Pyro is potentially more compact
Throughput High Centralised facility Low Reactor island concept	Currently designed for large scale	Parallel processing lines likely, thus nullifying compact process Benefits from compact process	High throughput suits aqueous Low throughput suit pyro

Fuel fabrication

The production routes for ceramic nuclear fuel considered in this study are predominantly Powder Metallurgy and Sol Gel Processes, and the study has focused on these two routes. Powder metallurgy is a technique that is well developed for certain fuel types, produces a fuel well suited to existing reprocessing technology and, within the scenarios developed here, has relatively few unit operations. There is also sufficient process flexibility, with development, to manufacture heterogeneous fuels, homogeneous fuels and targets for FR and ADS at an industrial scale. However, it might be argued that this process route does favour the production of a sintered pellet product restricting fuel and target pin design. The process also uses high energy milling unit operations to develop satisfactory particle properties prior to pressing and sintering. Milling is likely to lead to significant dust production at an industrial scale and while the production of dust is not desirable, particularly in the case of processing MA oxides, the development of milling processes and subsequent handling techniques are likely to reduce the production of dust which will reduce the amount of intervention necessary to maintain production at an industrial scale.

Sol gel processes are flexible and have been used to prepare complex and robust fuels, e.g. TRISO fuel used in high temperature reactors and can be readily used to prepare different fuels. The technique does, in part, require the use of a stable, inert material with respect to MA nitrate liquor and as a result fuel containing Zr or Y is highly likely, even with an inert MgO matrix. The inclusion of Zr and Y will challenge existing and developing aqueous reprocessing technology, however, the process is likely to minimise dust production at an indus-

trial scale. At a superficial level, it appears that there are more unit operations required for sol gel processing when compared to powder metallurgy and therefore the level of complexity associated with plant might be expected to be greater. However, it should be remembered that the production and management of MA oxide through powder processing routes will not be trivial and that the overall challenges to powder metallurgy or sol gel processing are likely to be similar.

Fast Reactor fuel

Since FR heterogeneous fuel is likely to comprise:

- UO_2/PuO_2 Driver fuel;
- MAO_2/Inert matrix targets, and;
- UO_2 blanket fuel (or possibly an inert reflector).

it is likely that the current process used in the preparation of MOX fuel would be used. This is a well recognised U / Pu ceramic component production technique that has been developed to high technical maturity, and is well suited industrial practice for these types of materials. Therefore this approach is probably the most appropriate choice for driver and blanket fuel. Sol gel processing might also be possible.

MAO_2/Inert matrix targets do not have well established or well defined fabrication routes and these materials can be produced by either sol gel or powder metallurgical routes. As a result, the challenge of designing a plant with either one single powder processing technology for three fuel types or a plant which encompasses two process options emerges. Ultimately, it is probable that three different dedicated process lines would be built; one for each fuel type and therefore, the technology deployed within any one process line might be chosen to suite. Potentially, the process line designed to fabricate MA fuel might also be the only line to require the heavily shielded remote access infrastructure, therefore limiting the added cost associated with MA management.

In the case of homogeneous fuels, only one single processing line would be required, although a second line would be likely to fabricate blanket fuel.

Accelerator Driven Systems fuel

In this study, heterogeneous the ADS fuel is assumed to comprise:

- PuO_2/Inert matrix neutron multiplication fuel and
- MAO_2/Inert matrix targets

Well established processing routes for these materials do not exist and there is no obvious reason why powder metallurgy should be preferred over sol gel, unless the production of dust through high energy milling unit operations is seen as a major detriment and a process consequence that future technology development will not resolve. For the purpose of this discussion, it is assumed that dust production is a major concern and that sol gel is the preferred route. It is also assumed that two separate processing lines would be used for the two types of fuel. In all probability, these processing lines will be identical, and therefore automatically provide in-built facility and process "redundancy", which is often seen as beneficial to any industrial plant lifetime operation. Interestingly, there is an argument which could be proposed which aligns to that of FR fuel production discussion above, where one process line is developed to handle MA production therefore limiting the size and attendant shielding of MA production facility.

Homogeneous fuel production would only require one heavily shielded process line.

Clearly there are technology gaps, which have been identified earlier in this report; however these are not specifically addressed here and an in-depth analysis and understanding of the gaps would be beyond the scope of this work and be the subject of a separate study.

Identification, design and an accurate estimated cost of the most appropriate fuel fabrication route would require an in-depth process engineering study, which is also beyond the scope of the work in this report. FR or ADS fuel fabrication can potentially use powder metallurgy or sol gel routes; both have their challenges, however, it is likely that the main complicating factor is the need to provide a heavily shielded facility with remote access for maintenance and process intervention, where TRUs are processed. The most favoured process will, almost certainly, be that which has minimal maintenance, a low number of simple unit operations and the least requirement for process intervention. It is assumed here that the technology selection will have minimal impact on overall cost.

It should be noted that in general, where homogeneous fuel is fabricated, there is only a single process line is required. It would be expected that this will reduce fabrication costs relative to heterogeneous options. In the case of fuel reprocessing, the distinction is less clear since MA separation is required to ensure fuel of the designed composition can be manufactured.

Cost comparisons for different fuel cycle scenarios, reprocessing and fuel fabrication technologies have been completed elsewhere however, one of the latest and probably most comprehensive studies by Shropshire et al is very briefly referred to here. Shropshire et al clearly state that the cost data was extremely difficult to establish in many cases, some for commercial reasons and others simply because the technology was immature and in some instances, the first of its kind. One of the overriding costs factors identified in the study was in the case of handling TRU elements and the need for remote handling facilities – in this case, costs were increased significantly. The authors also indicate that where pyrochemical techniques

were evaluated, this was done on the basis of a single operating plant for both reprocessing and fuel fabrication. These costs were estimated to be around $1500 kgHM for LWR oxide fuel. In comparison, fuel manufacturing costs for MOX are $4000 kgHM & $500 kgHM for core and blanket fast reactor fuel respectively, with contact handleable UOx being $240 kgHM. Discussion within the ARCAS membership queried the $4000 kgHM for MOX manufacture and it was agreed that a lower value would be more realistic for the purpose of this study. Reprocessing costs were estimated to be an additional $500 kgHM. Note the reprocessing and manufacture of inert matrix fuels was estimated to cost from several thousand $ to tens of thousands of $ per kgHM. Such a range of numbers describes the level of uncertainty which surrounds the generation of these figures. A direct comparison of technology costs was not considered possible however; cost was related to plant complexity. These figures are placed into context in WP5.

WP4 has not considered the case for recovery of the inert matrix. In cases where the only added value is would be the minimising of ILW, then the production of an appropriate waste form would be the minimum step necessary. However, for Mo, a recovery route would probably be of significant added value since the metal is required to be isotopically enriched and therefore valuable. Suitable technologies to perform this in an active environment await development.

The case for Cm separation and disposal has not been considered either. However, the case for removing Cm from the fuel fabrication process is, at face value, compelling and should be considered in a future study.

All fuel fabrication processes, with the exception of U and MOX fuel are technically immature and assigned low Technology Readiness Levels of 2-3. All spent fuel reprocessing technologies are also assigned low Technology Readiness Levels of 2-3, without exception.

WP5 – Technical and economical comparison

Using the systems described technically in the preceding Work Packages, three main different scenarios have been analysed:

- Scenario 1: A single stratum with fast reactors and recycling of Minor Actinides in a heterogeneous mode (targets). This means that total electricity demand is taken by the fast reactors.
- Scenario 2: A double stratum with LWR and recycling of Minor Actinides in a fast reactor in either homogeneous mode (Scenario 2a) or heterogeneous mode (Scenario 2b). In the former case, about 70% of electricity production will be provided by the LWR and 30% by the SFR. In the latter case, more SFR capacity is needed and the balance tuples over to about 33% LWR and 67% SFR share in electricity production.
- Scenario 3: A double stratum with LWR and recycling of Minor Actinides in an ADS. In this case, more than 97% of the electricity production is provided by the LWR while less than 3% is produced by the installed ADSs.

The electricity production shares have been established based on the hypothesis of "constant minor actinide content in the park", i.e. what is produced must be burned.

Technological Readiness Levels

It should be noted that both GenIV and ADS technologies, as well as the fuel cycle aspects of minor actinide transmutations, still require a large R&D effort. Technological readiness levels are low and many technologies have been proven on laboratory scale only. This leads to significant uncertainties in the cost estimates.

The three major building blocks of an ADS are the particle accelerator, the spallation target and the sub-critical core. Current R&D on high power proton accelerators, mainly focused on beam reliability has pushed the TRL of this component to level 3 to 4 ("component testing"). The challenge for the spallation target is the coolability and confinement. A transmuter ADS typically needs targets taking megawatt scale power. These targets have been built and operated (MEGAPIE at SINQ for example). The main challenge lies in the integration of such targets in the ADS concept. The TRL can therefore be set at level 5 (conceptual design demo). For the sub-critical, the main points of concern are the material compatibility with the coolant (lead) and the fabrication and reprocessing of the dedicated fuel. Technological Readiness Levels range from 2-3 ("lab experience") for the fuel reprocessing and fabrication whereas for the material/coolant compatibility one could estimate a TRL of 3-5.

As discussed extensively in the previous section, the Technological Readiness Levels of transmuter fuel/target reprocessing and fuel/target fabrication are quite low at levels 2-3. Only classical powder based UOX/MOX fuel fabrication can be seen as TRL 9 ("full maturity").

Including significant amounts of minor actinide fuels requires serious R&D effort and a TRL can be estimated at 3-4 ("Lab experience").

Cost estimates

Two cost models have been used to estimate the costs of electricity in all four scenarios described above. The first model, adopted by CNRS, is based on cost data per reactor system and the COSI software package. The second model, applied by NRG, uses the cost methodology as developed by the Generation IV International Forum, based on the GenIV cost estimating guidelines and software package G4-ECONS. Cost data on the different building blocks have been gathered based on previous and current EC research programmes like EUROTRANS and CP-ESFR. Also the cost of transportation of dedicated ADS and FR fuel has been analysed and compared. Table 8 below gives the cost estimates used in the CNRS model.

Table 8: Cost estimates used in the CNRS model

General parameters	LWR	FR	ADS
Load factor	0.85	0.80	0.75
Efficiency	0.34	0.40	0.32
Overnight construction costs (G€/GW$_e$)	2.94	3.82	14.5
Construction overcost, compared to LWR	-	1.3	4.94
O&M (M€/GW$_e$ per year)	75	86.25	222.75
O&M overcost, compared to LWR	-	1.15	2.97
Discount rate	8%	8%	8%
Dismantling discount rate	8%	8%	8%
Construction time (years)	6	6	6
% dismantling share of construction cost	15%	15%	15%
Reactor life time (years)	40	40	40

Based on the inputs from the different work packages and the scenario hypotheses, costs have been estimated using the CNRS model separately for the investment/operation/dismantling (Table 9) and for the fuel cycle (Table 10).

Table 9: Comparison of costs excluding fuel cycle (CNRS model)

Scenario		1	2a	2b	3
	LWR UOX	FR (heterogene-ous targets)	HOM FR burner	HET FR burner	ADS transmuter
Construction overcost vs. LWR	-	1.3	1.3	1.3	4.94
Construction costs (€/MWh$_e$)	33.1	45.8	45.8	45.8	185.5
Interest during construction (€/MWh$_e$)	12.5	18.3	18.3	18.3	79.2
O&M (€/MWh$_e$)	10.1	12.3	12.3	12.3	33.9
Dismantling costs (€/MWh$_e$)	0.2	0.3	0.3	0.3	1.3
Total reactor costs (€/MWh$_e$)	55.9	76.7	76.7	76.7	299.9
LWR share of first stratum		0	69.7%	33.3%	97.4%
Scenario electricity costs, excluding fuel cycle costs (€/MWh$_e$)		**76.7**	**62.2**	**69.8**	**62.3**

Table 10: Fuel cycle costs (CNRS model)

Scenario	1	2a	2b	3
	FR (heterogene-ous targets)	HOM FR burner (double stratum)	HET FR burner (double stratum)	ADS transmuter (double stratum)
Burn-up (GWd/t$_{HM}$)	100	100	100	
MA bearing fuel burn-up (GWd/t$_{HM}$)	15.3	100	15.3	120
LWR share of first stratum	0	69.7%	33.3%	97.4%
fuel in first stratum (t$_{HM}$/TWh$_e$)		1.71	0.82	2.39
'classical' fuel in burning stratum (t$_{HM}$/TWh$_e$)	1.03	0	0.685	
MA targets / fuel in burning stra-tum (t$_{HM}$/TWh$_e$)	0.0667	0.316	0.0635	0.0282
Fuel cost in first stratum (€/MWh$_e$)	-	4.5	2.2	6.3
Fuel cost of 'classical' fuel in burn-ing stratum (€/MWh$_e$)	2.6		1.7	
Fuel cost of MA targets / fuel in burning stratum (€/MWh$_e$)	2.7	6.3	1.3	1.1
Waste disposal costs (€/MWh$_e$)	1.0	1.0	1.0	1.0
Total scenario fuel cycle costs (€/MWh$_e$)	**6.3**	**11.8**	**6.2**	**8.5**

In Table 11 the reactor costs per MWh_e are compared from both models for each MA burner system under consideration. The main conclusions that can be drawn from this table are:

- Both models give similar cost data for all systems, where NRG's model gives somewhat higher costs. However, the differences in the total costs are smaller than 20%, which is very reasonable in view of the high uncertainties.
- O&M costs for ADS are twice as high in NRG's model, compared to CNRS.
- Fuel cycle costs are similar in both models, except for the heterogeneous SFR case. There CNRS reports 5.6 €/MWh_e, where NRG gets twice as much.
- D&D costs are three times higher in NRG's model; however, these costs form a minor fraction of the total costs and are, therefore of little influence.

Table 11: Comparison of reactor costs of both models (CNRS and NRG)

	CNRS model			NRG model		
	SFR (HOM)	SFR (HET)	ADS (EFIT)	SFR (HOM)	SFR (HET)	ADS (EFIT)
Capital costs (€/MWh_e)	64.1	64.1	264.7	73.5	70.4	289.0
O&M costs (€/MWh_e)	12.3	12.3	33.9	11.8	11.8	67.8
Fuel cycle costs (€/MWh_e)	21.7	5.6	46.1	21.4	11.4	44.0
D&D costs (€/MWh_e)	0.3	0.3	1.3	0.9	0.8	3.6
Total (€/MWh_e)	**98.4**	**82.3**	**346.0**	**107.6**	**94.3**	**404.3**

Here it should be noted, that particularly ADS is not designed for electricity production. Nevertheless electricity cost is the only parameter allowing for a clear comparison between the different scenarios. Stated differently, one can consider the extra electricity cost for MA burning as the 'price' to be paid for minor actinide recycling and transmutation. The overcost can then be viewed within the advantage of added sustainability of the closed fuel cycle, that recycles all its minor actinides, as well as from the viewpoint of reduction of long-lived nuclear waste.

In the case of ADS, although the reactor costs and, subsequently electricity production costs, are very high, the efficiency of burning minor actinides is as well. In the scenarios this leads to a small fraction of ADS needed. The high electricity costs for ADS are then compensated by a large share of LWR in the first stratum with relatively low electricity costs.

In Table 12, the reactor system costs from Table 11 are combined with the scenario results on installed capacity in order to compare the scenario electricity costs. From this table, we can

conclude that the influence of the first stratum (i.e. the use of EPR) equalises the total costs. All scenarios are comparable in terms of costs, particularly in view of the large uncertainties. Comparing with a single stratum and the use of only EPR's, so without recycling of minor actinides, the double stratum scenarios typically add 15 – 30% to the costs. One can view this as the 'price' of increased sustainability of a fully closed fuel cycle and a significant reduction of the long-lived radioactive waste. A single stratum with only fast reactors is more expensive.

Table 12: Comparison of scenario electricity costs

Scenario	1	2a	2b	3
	FR (heterogeneous targets)	HOM FR burner	HET FR burner	ADS transmuter
LWR share of first stratum	0	69.7%	33.3%	97.4%
Scenario electricity costs (€/MWh$_e$), CNRS	**82.3**	**74.0**	**76.0**	**70.8**
Scenario electricity costs (€/MWh$_e$), NRG	**94.3**	**76.8**	**84.0**	**72.3**

A more detailed follow-up study should be conducted to address in more detail the differences in the various models and scenarios. Follow-up study can also help in fine-tuning the costs, and reduce uncertainties.

As a last point for a follow-up study, plutonium management can be addressed in more detail. Within ARCAS, plutonium management is not a specific goal. Nevertheless it is important when considering a fully closed and sustainable fuel cycle with recycling of all transuranic elements.

Business models

Next, the first steps into a business plan for a transmutation facility for long-lived nuclear waste have been investigated. As no such facility is yet under construction or even planned, a detailed business plan, even preliminary, is not possible, but some conclusions could already be drawn in this stage. Most important of these is that no transmutation of long-lived nuclear waste will take place without government obligation and legislation. The existence and direction of a country nuclear program is important. If this direction is into long-term use of nuclear energy, fast reactors will probably be part of the program for reasons of fuel security of supply. The fast reactor technology developed for this program may be used than for transmutation purposes as well, causing ADS not to be used in this country. The use of ADS technology would then be limited to those countries phasing out nuclear energy or using it temporari-

ly as a ‘bridging’ technology. It remains to be seen whether these countries would make the investment for development of ADS technology to an industrial scale for the limited amount of minor actinides to be transmuted, also since the ADS facility will not eliminate the need for a final repository of highly radioactive nuclear waste.

The business strategy investigated here would be that electric utilities owning the nuclear plants will pay a fee for the transmutation of their minor actinide waste, and will add this to the electricity price. This does not exclude other strategies, e.g. sell the reprocessed plutonium and pay the minor actinide transmutation with this.

As there are no industrial transmutation facilities planned yet, three projects with some relationship with the transmutation issue have been investigated: 1) MYRRHA, an ADS research facility for actinide transmutation; 2) Pallas, a dual-purpose thermal research reactor for medical isotope production and nuclear materials research, including transmutation fuels; and 3) PRISM, a fast reactor nuclear power plant for plutonium destruction and electricity production. Still other projects could be investigated in this way, like the French Jules Horowitz research reactor and the French fast reactor research facility ASTRID. Although the three projects already exist for several years and are in various stages of development, financing is still an issue. For MYRRHA, the Belgian government has offered a partial financing, and for the other two projects all financing should come from the market.

The dependence of the economic performance of a transmutation facility from the electricity price has been investigated. If the electricity price is low, the economic performance of ADS-EFIT and EFR are comparable only for very good EFR transmutation performances, while for high electricity prices EFR is more convenient than ADS-EFIT. In case standard values are considered there is no net economical convenience in the adoption of one particular system.

When looking at the costs of electricity nuclear power plant fleets including FR and ADS respectively, the results of the comparison of these costs depend strongly on their relative costs. The increased costs of electricity produced by ADS may be balanced by its limited share in the energy mix and the bigger share of lower cost kWh produced by LWR. The discussion about the break-even price of ADS that makes the ADS scenario more competitive than the FR scenario is very difficult. Given the very low levels of readiness of most of the technologies involved in this study, whether for the reactor but also for the fuel cycle, the cost models cannot be expected to be very representative of future technology costs.