Project Final Report

Description of main S&T results/foregrounds

1. WP 1: reference scenario definition

The reference scenario considered in the frame of the ARCAS project refers to PATEROS project [1] where a regional scenario, at a European level, was analysed in detail. Scenario 1 was taken into consideration, in which spent UOX and MOX fuel discharged from LWR is reprocessed (mono-recycled) in order to separate TRU from fission products (which, together with reprocessing losses, are sent to a geological repository). Reprocessed Pu and MA are recycled in the regional transmuter facility, which in this case is the ADS-EFIT (*Accelerator Driven System – European Facility for Industrial Transmutation*) [2] and blended with TRU separated from spent fuel of subcritical transmuter fuel cycle (as soon as available) in subsequent cycle passes (Figure 1). The final goals of the scenario are:

a) to fully reprocess spent fuel legacy of some European countries (*Group A*), which are supposed to be in a stagnant or phasing-out scenario: *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 for the deployment of fast reactors, which were not simulated in this case) and to stabilize the MA inventory in European countries (*Group B*) pursuing nuclear energy generation: *France* was considered in this case.

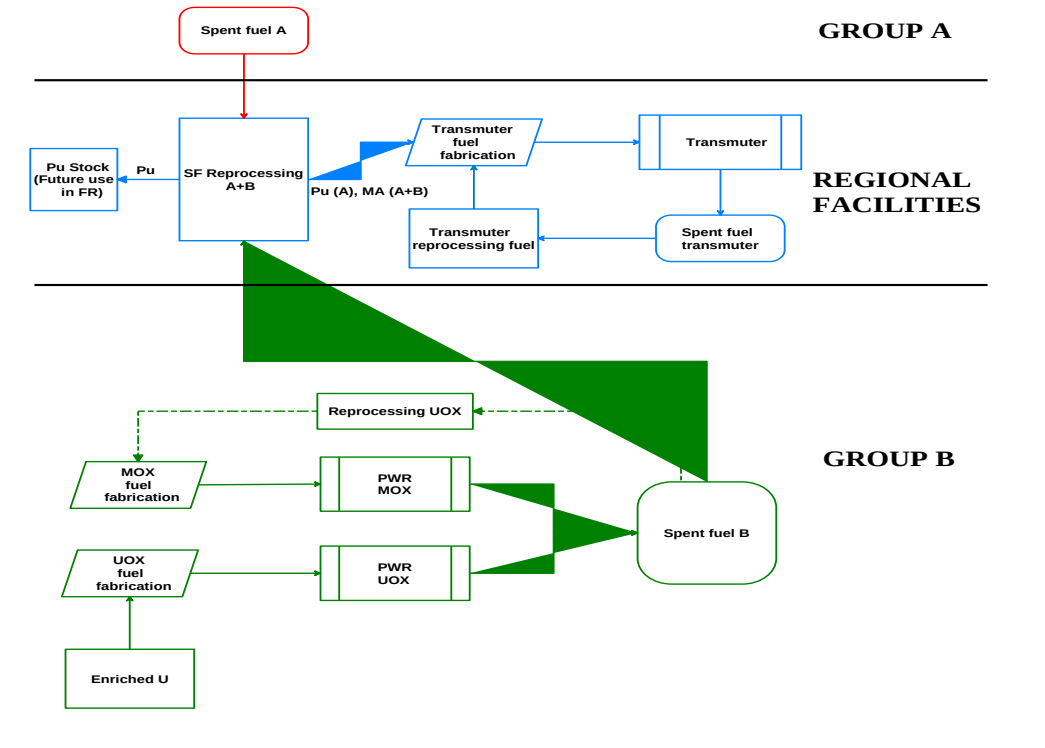

FIG. 1. PATEROS simplified flow scheme

According to scenario assumptions ADS-EFIT will be deployed in a regional centre starting from 2045 (this hypothesis should appear rather unrealistic) up to 2090 – then 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. In particular a reprocessing capacity of 850 tonnes/year was

assumed for Group A reprocessing plant, while 1700 tonnes/year were necessary in order to stabilize the inventory of Group B.

Calculations were performed with COSI6 – ver. 6.0.1, a code developed by CEA (Cadarache)[3]. In particular simulations addressed the MA streams (and their isotopic composition) evaluation from Group A (i.e. coming from a spent fuel storage after some decay time) and Group B (i.e. coming from a continuous feed from a PWR fleet with a 50,000 MWd/t burn up, fuelled by 90% UOX and 10% MOX, a 5 years cooling time and a total yearly energy production of 430 TWh_e). The outcome of the simulations is shown in Table 1: MA composition and a range of minimum and maximum annual values are indicated. It should be noted that the hypothesis that all European nations except France will phase-out during the present century may appear too optimistic from the MA waste stream amount point of view. If we consider that the nuclear power installed in France is today 63,130 MW_e, while the total for Europe is 169,932 MW_e [4], a factor of ca. 2.7 should be considered (as it appears that a phase-out of nuclear energy in the near future in OECD countries is unlikely, due also to environmental concerns about global warming, as stated by IPCC or IIASA scenarios [5][6]).

Table 1. Proposed reference MA composition

Nuclide	Content (%)
Am^{241}	39.55
Am^{242m}	0.22
Am^{243}	22.34
Np^{237}	32.91
Cm^{243}	0.059
Cm^{244}	3.97
Cm^{245}	0.95

Min. MA annual stream[1]: 2.3 tonnes/year
Max. MA annual stream[2]: 6.5 tonnes/year

It is important to stress however that the composition indicated above is just indicative: in order to adopt an efficient transmutation strategy in fact it is mandatory that fast systems (both critical and subcritical) run a closed cycle, by reprocessing their own fuel and recycling it in their fuel fabrication plants as first choice. This strategy will present some relevant consequences, which should in principle affect fuel cycle costs heavily:

Recycling of transmuters fuel, and then blending it with fresh fissile material in order to balance the fissioned mass, will obviously modify fuel isotopic vector at every new reactor load: this fact will require probably to modify fuel shares (e.g. inert matrix/heavy metal, amount of uranium, etc.), which, in their turn should affect safety coefficients, performance, burning capacity, etc.;

Recycling fuel in a closed cycle fashion will cause probably an accumulation of heavy elements, thus increasing fuel gamma and neutronic emission, such as also decay heat power: as new technologies, making use probably of remote handling and improved shielding issues, should be required this parameters should be taken into consideration accurately in costs evaluation.

Finally it should be taken into consideration in transmuters evaluation that if nations with a phasing-out policy are considered, as in case of PATEROS scenario, plutonium management should be an issue, especially if adopted transmuters are not specifically designed for this goal. Simulations show that if maximum MA stream cited

[1] PATEROS scenario
[2] PATEROS extended to all European countries with present energy production

above is adopted (i.e. present European nuclear fleet) a plutonium annual stream of ca. 24 tonnes/year results, which means an accumulation of more than 2100 tonnes of fissile material by the end of the present century. It should be pointed out also that small nations that decide to continue to produce nuclear energy without planning to use produced plutonium in fast reactors (such as France) will have to adopt a proper strategy for its final disposal (regional transmuter design should take this issue properly into account).

2. WP2: Definition of the Fast Reactor System

In the frame of the EU CP-ESFR project [7], 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. A short description of the optimized reactor concept is provided in this section, which will be used for analytical estimations in ARCAS. The cross section of the core is depicted in Figure 2.

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.

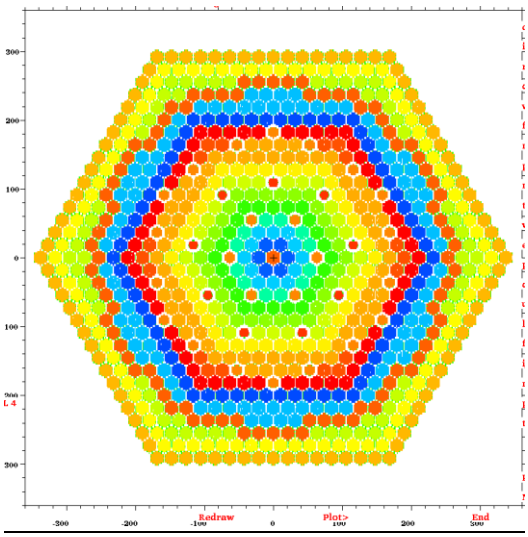

FIG. 2. Cross section view of CP-ESFR core

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.

Before the optimization process, the basic 'Working Horse' design consisted only in the active length, 1 m high, with no lower axial blanket, sodium plenum and upper absorbing layer. The WH design was intended to be a break-even core.

It is found that MA homogeneous loadings in the reference reactor lead to moderate transmutation values, up to 6.9 kg/TWhth for 4%w loading, and noticeably deteriorates reactivity coefficients (Doppler constant and core void worth). However, the deterioration depends very much on the exact core configuration. Hence, dedicated core design strategies for lowering the MA impact have an important effect for the Doppler constant, whose deterioration may decrease from 40 to 15%. The reduced void worth deterioration is found similar before and after application the optimization guidelines (some 25% in both cases). On the other hand, the extended void worth significantly decreases compared to the reduced void worth, which means that optimization guidelines are promising and should be further pursued, even targeting negative core void worth. In the meanwhile, a combination of lower MA loading, 2.5%, and optimization guidelines seem to be a promising concept, as deterioration will be lower.

Heterogeneous blanket configurations lead in general to low deterioration of safety parameters or even to little improvement when core optimization guidelines are considered. However, concerning transmutation values, virtually no net transmutation is found or just a small net value after optimization guidelines. An interesting case between homogeneous and heterogeneous has been also presented with MA loading in the outer core (together with Pu) leading to medium transmutation values (3.6 kg/TWhth) and no deterioration of reactivity coefficients.

In any case, the impact of MA loading on reactivity coefficients expand over a range of results, which illustrates the necessity for rigorous safety analysis in order to advance the issue of the core feasibility from the point of view of licensing. This is indeed an open field for research, as no fully dynamic safety analysis is yet available. Concerning first European scenario analysis, it is obtained that medium transmutation values (as of 2.8 kg/TWhth) in all reactors could lead to elimination of the neptunium and americium stock, out of the reactor site, in the frame of a century, and that the result is compatible with Pu breeding in all reactors. The curium mass stock, however, is not eliminated but just somewhat decreased. Such an objective would imply the fabrication of a very large number of MA bearing fuel assemblies at low contents, 2.5%w. Also, the Pu amount involved in fuel fabrication would be very large.

3. WP3: Definition of the Accelerator Driven System

The aim of Work Package was to select and characterize the reference Accelerator Driven System to be used in the ARCAS project. As, in Europe, there is only one design for an industrial transmutation facility available, the choice of the reference system was rather easy: the EFIT, European Facility for Industrial Transmutation, as designed in the 6th European Framework programme IP-EUROTRANS [8].

The accelerator foreseen in the EFIT design is an 800 MeV proton 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 (as opposed to lead-bismuth eutectic as foreseen in the experimental facility XT-ADS). This allows a high inlet and outlet temperature (400°C and 480°C respectively) and as a consequence a rather high thermodynamic efficiency of 40% .

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$_{th}$ [9]. The design goal of EFIT was hence to have a loss of minor actinides as close to 42 kg/TWh$_{th}$ as possible and a loss of plutonium close to 0 kg/TWh$_{th}$ [10][11]. The second goal for the design of the core was to have a reactivity swing as close to zero as possible, reducing the power fluctuations during the cycle without the need to compensate for this using the proton accelerator.

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 ADS EFIT core used for this study is based on the one defined in the deliverables D3.2 and D3.3 from the AFTRA (**A**dvanced **F**uels for **TRA**nsmutation systems) domain (DM3) within the EURATOM FP6 integrated project (IP) EUROTRANS [12][13]. For this comparative study, we used EFIT-400 (AFTRA) core with one zone configuration, a thermal power of 400 MW and with the two selected fuels for EFIT core: CERCER with MgO matrix and CERMET with Mo matrix enriched in ^{92}Mo. As shown in Figure 3, the core contains 6 rings of fuel assemblies (FAs), surrounded by 2 rings of reflector ones and a cylindrical core barrel with 30 mm as thickness. The spallation target and the surrounding region (containing mainly lead) occupy the space created by the withdrawal of 19 fuel assemblies from the central region proposed in the EFIT reference design [14].

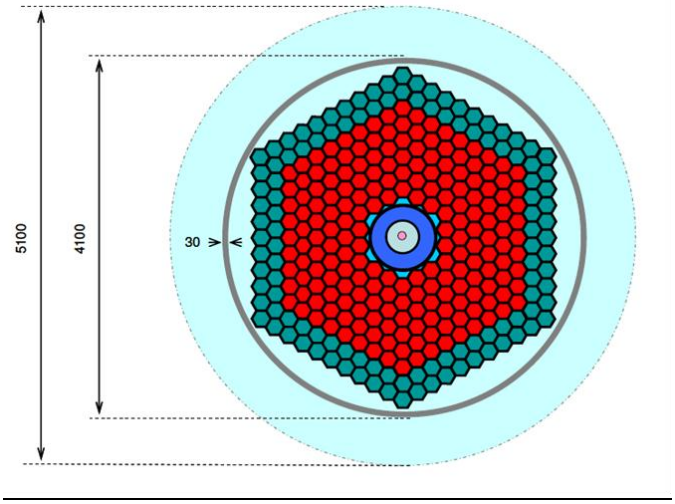

FIG. 3. Single-zone reference core model of the EFIT-400: radial layout

The results of MA transmutation rate are calculated using the ALEPH code (SCK•CEN home-made code) [15]. The ALEPH code is designed to combine a Monte Carlo codes (MCNP or MCNPX) for spectral calculations with a modified version of ORIGEN-2.2 code [16] for evolution calculation. The nuclear data used are based on the JEFF-3.1 library [17].

As shown in Table 2 and Table 3, 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 2. 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 3. 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

4. WP4: Definition of the fuel reprocessing and fuel fabrication facilities

The objective of ARCAS WP4 is to define a fuel fabrication plant and a reprocessing plant for fast reactor (FR) and ADS fuels in order to compare costs. Clearly, these plants may be different for each neutron system, but that difference will only depend on the fuel types and their irradiation conditions.

The output from WP4 comprises baseline information which identifies process differences upon which an economic assessment of heterogeneous fuel fabrication plant and spent nuclear fuel reprocessing plant for FR and ADS can be made in WP5. Inert matrices of Mo or MgO (Yttria Stabilised Zirconia) and pure MgO have been selected as model fuels for ADS and FR systems respectively. The case for reprocessing of ADS fuel using pyrochemical technology and the fabrication of ADS fuel using Sol Gel is made and appropriate high level case studies completed. Similarly, the case for reprocessing FR fuel using aqueous technology and the use of powder metallurgy as the preferred fuel fabrication route for UO_2 blanket and U/Pu oxide core fuel is made. Sol Gel is the preferred route for minor actinide (MA) fuel fabrication.

Reprocessing options are expected to fall into two “camps”. These are:

- Materials well suited to existing fuel fabrication processes and compatible with nitric acid/organic phase, PUREX or GANEX type, separation processes and;
- Those that are not where non-aqueous process routes (i.e. pyrochemical) are most likely to be deployed.

The following assumptions are made for the fast reactor fuel

- Heterogeneous actinide and MA fuel pins are U/Pu and inert matrix (MgO)/MA;
- Based on an oxide system;
- High Pu content in FR core;
- MgO is soluble and easily diverted within an aqueous reprocessing option, therefore only aqueous reprocessing options are required for this scenario;
- Oxidation and dissolution of high Pu content fuel and MA is possible;
- Aqueous reprocessing solvents are sufficiently stable to very high burn-up fuel, however, in extreme cases, the effect of radioactive content in aqueous reprocessing can reduce the effect of solvent extraction dramatically. This is especially true in the first stages of these processes where the organic solvent is in contact with fission product activity in the aqueous solution;
- An organic phase clean-up and recovery step will be included in any reprocessing scheme to maintain process efficiency, and;
- Aqueous processes will be assessed in conjunction with an appropriate scenario (e.g. sufficient cool-down time).

and for the Accelerator Driven System fuel

- Fuels are based on an actinide oxide dispersed in an, inert matrix;
- Heterogeneous actinide and MA fuel pins – Mo or MgO/PuO_2 and Mo or MgO/MAO_2;
- Provided Mo is recovered and recycled at an early stage of reprocessing, then aqueous processes should be considered viable, if not;
- Pyro processing due to the potential issues of CaesiumPhosphoMolybdate (CPM) and insoluble product formation in aqueous processes is proposed;
- Pyro-processing is used for spent fuel when fabrication techniques have required a ZrO_2 or Yttria Stabilised Zirconia (YSZ) in the MgO matrix;
- Where aqueous reprocessing is selected, the assumptions shown under FRs above also apply here ;
- All fuels will be subject to very high burn-up.

Carbide and nitride systems have been discounted from this work due to their very low technological readiness levels in comparison to oxide and metal fuels.

Both aqueous and non-aqueous process steps have been investigated and various conclusions drawn. Two baseline processes for fuel fabrication have been considered Powder Metallurgy and Sol Gel. MOX fuel production is, of course, based on powder metallurgy and is well established at industrial scale however, the production of separate MA oxide fuels is not.

Preparation and production of heterogeneous oxide fuels for the double strata advanced fuel cycle using either FR or ADS is extremely challenging due to high alpha, high decay heat, high neutron emission and high gamma activity. Any fuel processing facility will therefore necessarily need to have very high integrity containment to prevent the spread of highly mobile alpha activity, include heavy shielding for the penetrating radiation and almost certainly require the deployment of remote engineering technology for some plant operations / plant maintenance purposes. No preferred technology for fuel fabrication was identified due to the low Technology Readiness Levels, however, with dedicated production lines for each fuel type, the technology of choice can be selected when suitable technological maturity is obtained. Costs were expected to be closely related to the number of unit operations rather than technology selection.

It should be noted, the ARCAS study has been bounded to include Cm heterogeneous targets, and therefore fuel fabrication plants are required to include heavy neutron shielding. Should the decision be taken to sentence Cm to a dedicated decay store, then shielding requirements become less demanding for fuel fabrication. This scenario however, is outside the scope of ARCAS.

For reprocessing plants, 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 very low TRLs of 2-3.

All fuel fabrication processes, with the exception of U and MOX fuel are technically immature and assigned low Technology Readiness Levels of 2-3. Costs were expected to be related to the number of unit operations, shielding requirements and remote technology deployment rather than the technology selection, per se.

5. WP5: Economical comparison

The last work package of the ARCAS project is to gather all information from the other work packages in order to able to present a comparison between the two options of fast reactors or accelerator driven systems. An economic analysis and a business case description are being prepared for the EFR and EFIT nuclear plant designs with transmutation capabilities.

Two methods are used to determine the cost structures for the two options. One is to calculate the cost per kilowatt-

hour electric and per metric ton actinide waste destroyed for each design separately. The GIF tool G4Econs is being used for this. The other method is to calculate these costs for certain defined scenarios of reactor parks. Three scenarios are being considered: only Fast Reactors with heterogeneous targets, double strata with Fast Reactor burners, and double strata with ADS transmuters. (The double-strata nuclear fuel cycle consists of the commercial reactor fuel cycle (the 1st stratum cycle) and nuclear transmutation fuel cycle (the 2nd stratum cycle) based on FR or ADS that transmute the minor actinides generated in the 1st stratum.)

With the number of units needed per GWe of LWR installed and the investment cost of a transmutation unit, the investment cost per GWe is determined. For selected nuclear evolution scenarios, the total investment cost needed for transmutation can be determined. Also, the total generating costs are compared, giving an answer to the question on how much the MA transmutation would add to the cost of kWh. These costs would include both the investment, operational and fuel cycle costs. The fuel cycle costs consist of all the parts of the closed cycle, including reprocessing and fuel/target fabrication.

Both FR and ADS have transmutation capabilities. As expected from their fuel loadings and spectra, the project work packages 2 and 3 have demonstrated that ADS have very superior capability for transmutation compared to FR. Also the required transportation of nuclear spent fuel and dedicated burner fuel can be limited because of the high concentration of minor actinides in ADS fuel. The challenging question is whether these advantages could compensate for the extra difficulties and then costs of building these facilities. Table 4 shows the cost advantages and disadvantages for the three reactor systems considered. Given the extra complexity of its design (need for a reliable powerful accelerator), ADS most probably have a higher LCOE (€/MWhe) than FR, who in turn have a higher LCOE than LWR. If transmutation is not needed, if Pu is not managed separately, then utilities using LWR have no incentive to pay the extra costs of MA transmutation and LWR are by far the best and probably only choice. If however utilities would be obliged legally to manage their heavy nuclides and in particular the remaining MA after Pu removal, then a market could emerge for transmutation. Calculating the electricity costs for a nuclear park consisting of LWR and transmutation facilities, the higher costs of electricity produced by ADS may then be balanced by its limited share in the energy mix and the bigger share of lower cost kWh produced by LWR.

Table 4. 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 over-cost 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 5, the reactor system costs from Table 4 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 5: 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.

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 temporarily 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.

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