DETAILED PHASE-OUT TRU TRANSMUTATION SCENARIOS STUDIES BASED ON FAST NEUTRON ADS SYSTEMS

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Abstract

This paper presents a study of a phase-out direct TRU transmutation strategy consisting on several phases with an evolving deployment of reprocessing and transmutation plants. Detailed EVOLCODE reactor calculations (Monte Carlo transport + fuel depletion) combined with a scheme for the transmutation plant and reprocessing facilities deployment is presented for a case with a total amount of TRUs of 100 t of heavy metal coming from a standard LWR with an average burn-up of 40 GWd/T_{HM}. The presented results include the required reprocessing capacity, the profile of the installed power for the proposed ADS deployment, the evolution of the fuel composition and the evaluation of the wastes going to the final repository. Several aspect discussed in this paper for the phase-out scenario also apply for other time dependent P&T scenarios like the approach to the equilibrium and the scenarios of transitions between different fuel cycles (LWR to IFR).

Introduction

Many devices and strategies had been recently studied for the elimination of the TRU contained in spent fuel from the present U-Pu cycle nuclear reactors. Most of these studies are performed in the equilibrium scenario, in which the power generated by nuclear devices is kept constant and its main components are the present or similar critical reactors (thermal and/or fast). In the equilibrium scenarios the global transmutation efficiency is mainly defined by the reprocessing efficiencies and the reachable fuel burn-ups in the different elements of the fuel cycle. However several countries are considering the possibility to phase out the electricity production from nuclear reactors. In this, phase-out scenarios, several new considerations are most relevant. In particular the residual inventory of TRUs on the transmutation devices at the end of their operation and the fact that a limited stock of TRUs from the present reactors could prevent from reaching the equilibrium behaviour of the equilibrium scenarios. Several elements and questions of these phase-out scenarios also apply for other time dependent P&T scenarios like the approach to the equilibrium and the scenarios of transitions between different fuel cycles (LWR to IFR).

The FACET group, at CIEMAT, has concentrated its transmutation strategies research during the last months on the detailed evaluation of these phase-out scenarios with limited stock of TRUs, based on fast neutron lead alloys cooled ADS systems with fertile free fuels. Both, a direct TRU elimination scheme and several variants of the double strata fuel cycle are considered. However, in this paper we discuss a study of a phase-out direct TRU transmutation strategy consisting on several phases with an evolving deployment of the reprocessing and transmutation plants. Detailed EVOLCODE [2] reactor calculations (Monte Carlo transport + fuel depletion) combined with a scheme for the transmutation plant and reprocessing facilities deployment is presented for a case with a hypothetical total amount of TRUs of 100 t of heavy metal coming from a standard LWR with an average burn-up of 40 GWd/T_{HM}. The presented results include the required reprocessing capacity, the profile of the installed power for the proposed ADS deployment, the evolution of the fuel composition and the evaluation of the wastes going to the final repository.

Scheme of the phase-out scenario

Several stages or phases must be performed in the phase-out of nuclear energy if an important reduction on the accumulated radiotoxicity has to be achieved by transmutation. The basic stages are: a start-up; followed by a first phase of elimination of the LWR wastes until they are exhausted; then the TRU remaining on the transmutation cores must be reduced using progressively less and less transmutation plants; and finally the (single or few) last cores may be further reduced using a externally generated neutron flux. In the exercise described in this paper the scenario elements are:

a) **Start-up** loading the transmutation plant, TP, cores with a pseudo-equilibrium mixture of Pu and MA from a separated reprocessing of the LWR spent fuel.

b) **Phase 1:** Recycling the TP fuel with addition of TRU from the LWR, until these are exhausted. To accommodate for the cooling time between discharge, reprocessing, fabrication and reloading, two independent cores (set of fuel elements) are used in each TP.

c) **Phase 2:** Progressive reduction of the number of TP using the fuels of the stopped TP to top-up the active TP. Two sub-phases are considered: the first still with two cores per TP and the second with a single core per TP.

d) **Phase 3:** Use of the residual TRU fuel in the last TP, followed by its eventual reduction using an external source to sustain the irradiation neutron flux and the TARC principle to improve transmutation efficiency.

This paper presents a specific scenario to transmute 100 TRU tons from the LWR with a fuel burn-up of 40 GWd/T_{HM} with fast neutron inert matrix (TRU MOX on ZrO_2) Pb/Bi cooled ADS. [1] The main characteristics of the Transmutation Plant (TP) used in the calculations of this report are shown in Table 1. These characteristics are chosen as an illustrative simple example with maximum transmutation efficiency. Operability and safety considerations might however require slightly different design and fuel composition (including either U or Th fractions in the fuel matrix).

Table 1. **Main characteristics of transmutation plant**

Transmutation Plant, TP, power	850 MWth
Initial HM =TRU fuel mass per TP	~3 tons
TP Burn-up/Cycle	140 GWd/T_{HM}
TP Load factor	80%

Start-up of the transmutation plants

When starting the transmutation plants the only available fuel is the spent fuel of the LWR (TRU-LWR). This fuel has an isotopic composition very different from the fuels that will result after applying multiple recycling strategies when reaching the equilibrium. This might force to have very different transmutation plants and reprocessing conditions at the beginning and end of the transmutation phase-out.

One possibility to minimise these effects in the approach to the equilibrium operating conditions is to build a pseudo-equilibrium fuel (TRU-SUP) by separating the TRU streams from the LWR reprocessing in a) Pu, b) Np, c) Am+Cm. Then these streams are recombined but with a fraction of MA respect to Pu, larger than found in the spent fuel. This will improve the breading ratio and after optimisation can improve the neutron multiplication drop during is large burn-up cycle and will also keep nearly constant critical masses and cycles (from reload to reload) allowing to use the same TP design along the full phase-out process. A mixture of 60% Pu and 40% MA has been studied. This composition for the TRU-SUP fuel allows to maintain a neutronic multiplication sufficiently stable during 500 days of burn-up, using fuel reshuffling, according to previous studies. [1] In the Monte Carlo simulation, the start-up fuel discharge after a full burn-up (TRU-BUP) is approximately similar to the initial pseudo-equilibrium composition. In this Start-up-Phase stage, each TP (five in total, in the case studied) is loaded with two remittances of 3.0 tons of TRU-SUP. After the TRU-SUP is burn-up to 140 GWd/T_{HM}, 2.5 tons of TRU-BUP are left. Table 2 shows the isotopic composition of the TRU-LWR, TRU-SUP and TRU-BUP. In order to reduce the variation on the required reprocessing capacity (mass/year) and to limit the stock of the fresh TRU, a progressive starting of the TPs, with a delay between TP's starts of two fuel cycle lengths is proposed. Figure 1 shows a scheme of this process.

Figure 1. **Deployment scheme for the transmutation plants**

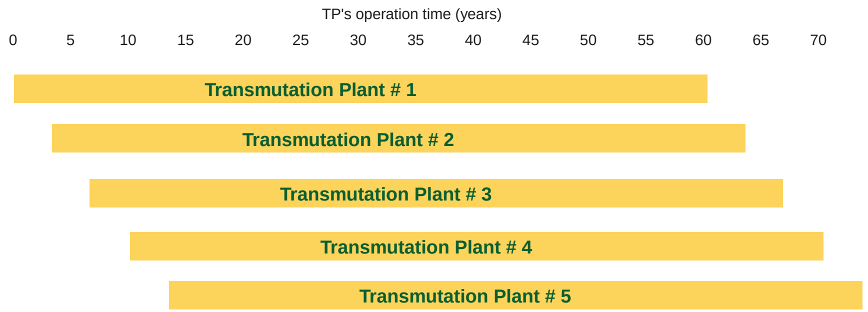


Table 2. **Isotopic composition of the LWR TRUs and the initial and discharge start-up fuels**

Isotopes	**Mass fraction** (%)	**Element fraction** (%)	**Mass fraction** (%)	**Element fraction** (%)	**Mass fraction** (%)	**Element fraction** (%)
	TRU-LWR		***TRU-SUP***		***TRU-BUP***	
^{234}U					0.044	
^{235}U					0.0035	
^{236}U					0.0027	
^{238}U					0.00001	0.05
^{237}NP	5.61	5.61	16.31	16.31	13.36	13.36
^{238}PU	1.96		1.36		7.21	
^{239}PU	50.92		35.42		28.15	
^{240}PU	22.34		15.54		18.84	
^{241}PU	5.88		4.09		4.14	
^{242}PU	5.15		3.59		4.84	
^{244}PU		86.24	0.00025	60.00	0.0007	63.18
^{241}AM	6.59		19.16		15.59	
^{242m}AM	0.021		0.061		0.739	
^{243}AM	1.25	7.86	3.62	22.84	3.46	19.79
^{242}CM	0.00005		0.00015		1.61	
^{243}CM	0.004		0.011		0.097	
^{244}CM	0.266		0.774		1.66	
^{245}CM	0.020		0.059		0.229	
^{246}CM	0.003		0.0079		0.019	
^{247}CM	0.00003		0.00009		0.0007	
^{248}CM		0.29	0.00001	0.85	0.00003	3.62

Phase 1 of the transmutation

After loading the TP with the start-up fuel, they will be operated with multiple reprocessing cycles. In these cycles the rest of the LWR TRUs is used to prepare the reload fuel, mixed with the recovered TP spent fuel. This fuel is named TRU-MIX in this study. This phase will end when the TRU from the LWR are exhausted. The main questions that arise are how long it takes to consume all the TRU from the LWR and what is the TRU inventory left afterwards. The answer depends on the characteristics of the TPs and on the total installed power from the TPs (number of TPs). Although the irradiation history is required to obtain the final solution, a reasonable approximation (not taking into account the reprocessing losses on T_{TP}) can be obtained from laws of conservation, as follows:

$$FractLeft_{TRU} = \frac{Burnup_{LWR} \cdot M_{TP}}{T_{LWR} \cdot LF_{LWR} \cdot Prod_U^{TRU}} \frac{FractPwIns_{LWR}^{TP}}{PW_{TP}} \left(1 - \frac{Burnup_{TP}}{BurnupTot}\right)$$

$$T_{TP} = \frac{T_{LWR}}{FractPwIns_{LWR}^{TP}} \frac{LF_{LWR}}{LF_{TP}} \frac{BurnupTot}{Burnup_{LWR}} Prod_U^{TRU} - \frac{(BurnupTot - Burnup_{TP}) \cdot M_{TP}}{PW_{TP} \cdot LF_{TP}}$$

$FractLeft_{TRU}$ = Fraction of TRUs left after phase 1 respect to the total TRU from LWR.

$Burnup_{LWR}$, $Burnup_{TP}$, $BurnupTot$ = Burnup at the discharge of the LWR, at the end of a TP cycle and after total consumption of all its actinides by fission (aprox. 950 GWd/T_{HM}).

T_{LWR} , T_{TP} , LF_{LWR} , LF_{TP} = Time of exploitation and load factors of the LWR and the Transmutation Plants.

PW_{TP} , M_{TP} = The power and heavy metal mass of the TP core.

$Prod_U^{TRU}$ = The mass of TRU produced in the LWR per unit of mass of the (U) fuel loaded in the LWR after its specified burnup.

$FractPwIns^{TP}_{LWR}$ = Ratio of the TP installed power over the LWR installed power.

Note that the main parameters to choose are the Power Installed fraction of TP, respect to the installed power of the LWR, and the specific power in the TP. These parameters define the number of TPs together with the power defined in the TP design. If instead of selecting a TP based on TRU in an inert Matrix, the fuel included some fertile isotopes in addition to the TRU, the main change will be that the times are increased in a factor close to the ratio of the total energy produced in the TP and the energy generated from the TRU. Note also that the burn-up of the Phase 1 remaining TP fuel is very high and that a possible consequence, is the need of a progressive licensing of the fuels for the TP.

The hypothetical 100 tons of TRU could be generated by a total thermal power in LWR of 23.5 GWth operating during 50 years with a load factor of 80% and the assumed 40 GWd/T_{HM} average burn-up. The critical parameter is the fraction of installed power in the TP respect to LWR, $FractPwIns^{TP}_{LWR}$, that is the ratio between the average nuclear energy production by LWR and the average production during the transmutation stages (the phase 1 of transmutation). We have assumed a value of 20%. If this value is increased the duration of the first phase is correspondingly reduced, but the amount of TRU left in the corresponding TPs increases and the following phases of the transmutation become longer, the net result is a small reduction on the total phase-out duration, even at values of $FractPwIns^{TP}_{LWR}$ as large as 50%, on the probable limit of public and practical acceptability for a phase-out or transitory phase. With this parameters the resulting number of TP is slightly higher than 5 and we have selected 5 as the number of TPs for phase 1. Note that this number of TPs increases linearly with the total mass of TRUs from LWR or with the LWR installed power, if the other parameters are kept constant.

Each of these TP requires 2.95 tons of TRU-SUP to reach the design k_{eff} between 0.96 and 0.97. After the burn-up of 140 GWd/T_{HM} obtained in 608 days (1.7 years) the remaining fuel (TRU-BUP) has 2.54 tons of mass. To obtain the same neutronic multiplication constant in the new cycles, the amount of TRU-LWR added to TRU-BUP to build to following cycle TRU-MIX is 0.42 tons. This amount changes slightly from reload to reload. A detailed simulation has been made of the different reloads of each core of the TP using EVOLCODE. This simulation includes the evaluation of the initial fuel to obtain the required k_{eff}, its burn-up, the final fuel composition, the reprocessing losses and the top-up fuel required to initiate the new cycle. The result is that a total of 35 reloads are needed on each TP, during a total of 60 years, taking into account the two cores. At the end phase 1, after consuming all the TRUs, 25.2 tons of TRU (25% of the total from the LWR) are left in the final cores of the TPs. It is also worth mention that the equivalent average burn-up of this final fuel is expected to be about 500 GWd/T_{HM}.

As already mention before, the deployment of TPs is distributed over several years, and in addition two independent cores are used on each TP. Figure 2 illustrate the first cycles of the phase-out phase 1. The main features of this procedure are:

- It allows limiting the required processing capacity of the LWR reprocessing plant, as shown in Figure 3. The maximum reprocessed TRU-LWR mass, approx. 8.9 tons/cycle, is required in the firsts tenth cycles (17 years). At this time two stages, Start-up of the TPs and Phase 1, coexist. The rest of the cycles are working with TRU-MIX (Phase 1), requiring less than 0.34 tons/cycle of TRU from LWR reprocessing. The difference on initial and average reprocessing capacity can be further reduced if the reprocessing is started much earlier than the phase-out P&T operation starts.
- It allows limiting the stock of the reprocessed fuel of TRU-LWR waiting to be used. This stock appears as a consequence of the preparation of the TRU_SUP fuel with an optimised pseudo-equilibrium isotopic composition, very different from the LWR discharge isotopic composition.

Figure 2. **Details of the transmutation start-up and the first fifth transmutation cycles**

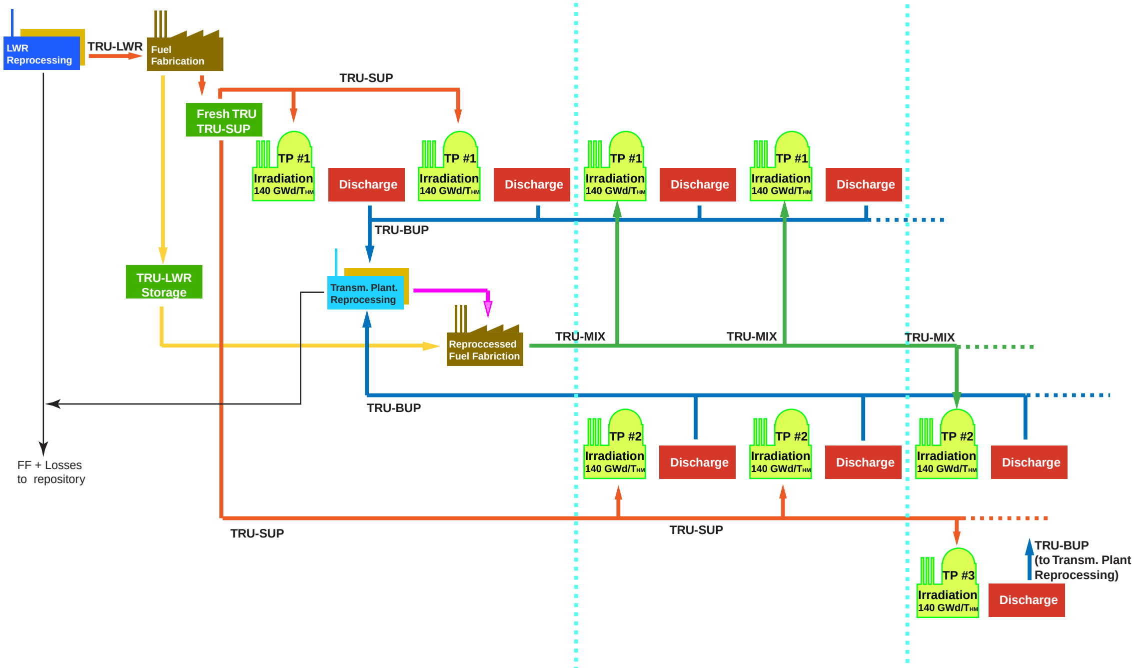
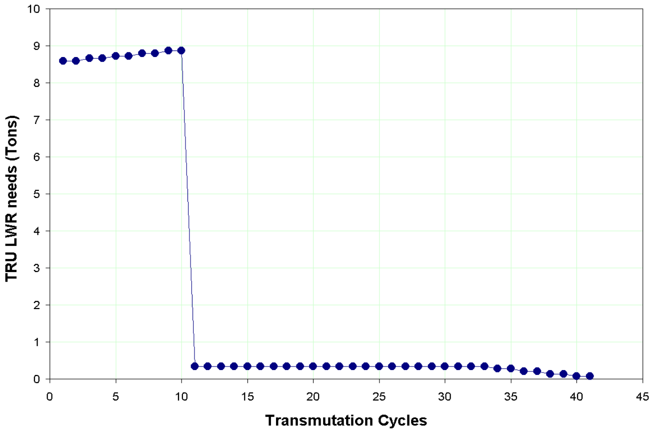


Figure 3. **Mass of TRU (TRU-LWR) that must be produced from the LWR spent fuel reprocessing for each transmutation Cycle, to fabricate TRU-SUP and TRU-MIX fuels**



The main results of the simulation of this phase are, the operativity of the same TP design with small adjustments on the fuel mass for all the cycles of the phase 1; the total amount of TRU sent to the final storage within the reprocessing losses of 0.7 tons (~0.24 from the LWR reprocessing and 0.46 from the TP reprocessing); and the total amount of TRUs left on the TP final cores after reprocessing of 25.2 tons. The isotopic composition of the reprocessing losses and of the residual cores are shown in Table 3.

It should be noted that this first phase requiring approximately the same time than the LWR exploitation producing the wastes to be eliminated, and limited to 20% of the deployed nuclear power, is able to reduce the total TRU inventory only by a factor 4. An additional phase is required to reduce further the radiotoxicity inventory. It should also be noted that the time required do not depend on the characteristics or neutron spectrum of the TP, but the viability of the multirecycling and the content on high mass actinides will be worse for thermal spectrum TPs. However the TRU mass in the residual cores after this phase 1 would be smaller for thermal TPs, following their smaller *critical mass* (M_{TP}).

Phase 2 – First part

A large fraction of the TRU are still contained in the cores of the TP at the end of the first phase. A possible solution to reduce this amount of TRU, is to progressively reduce the number of TP (and the installed power) reusing the fuels from the stopped cores in the continued TP. The isotopic composition of the fuel to be used in this second phase is just the one of the fuel at the end of the phase 1, shown in Table 3. The proposal studied is to use the same core design and reduce from 5 to 3 TPs continuing with the use of 2 independent core loadings per TP. The simulations show that using a 4 batch reloading scheme it should be still possible to reach the same burnup of 140 GWd/T_{HM}. If the TP of phase 1 were more than 5, the reduction factor could be different but should still be significant, and the details are not expected to change the general conclusions of this study.

Table 3. **Isotopic composition in per cent of the residual cores and reprocessing losses after the different stages of the phase-out (residual cores at 608 days after discharge, reprocessing losses at the time of the last discharge of each phase)**

Isotopes	**Residual cores** (%)	**Reproc. losses** (%)	**Residual cores** (%)	**Reproc. losses** (%)	**Residual cores** (%)	**Reproc. losses** (%)	**Residual cores** (%)	**Reproc. losses** (%)
	Phase 1+LWR R.L.		***Phase 2 – part 1***		***Phase 2 – part 2***		***Phase 3***	
^{234}U	0.83	1.58	0.86	0.82	0.76	0.76	0.23	0.61
^{235}U	0.25	0.15	0.31	0.29	0.30	0.31	0.68	0.72
^{236}U	0.32	0.14	0.44	0.39	0.67	0.57	0.50	0.61
^{238}U	0.97E-3	0.48E-3	0.15E-2	0.13E-2	0.32E-2	0.24E-2	0.35E-2	0.45E-2
^{237}NP	0.54	10.23	0.37	0.42	0.29	0.29	0.59	0.89
^{238}PU	4.22	4.59	4.46	4.13	3.63	3.76	1.94	1.77
^{239}PU	20.44	23.92	10.43	13.83	4.11	5.86	1.03	1.20
^{240}PU	41.50	27.77	44.01	43.07	40.06	41.79	21.40	28.82
^{241}PU	7.23	3.85	8.68	8.72	8.30	9.38	7.53	2.73
^{242}PU	12.43	7.41	14.97	14.03	19.18	17.61	25.57	25.35
^{244}PU	0.42E-2	0.18E-2	0.21E-2	0.24E-2	0.69E-2	0.47E-2	0.017	0.015
^{241}AM	4.08	14.27	3.62	3.28	2.90	2.42	4.42	9.90
^{242m}AM	0.28	0.29	0.27	0.29	0.19	0.22	1.23	1.03
^{243}AM	3.63	3.86	4.71	4.31	6.45	5.77	10.67	10.22
^{242}CM	0.027	0.089	0.029	0.39	0.022	0.32	0.016	0.010
^{243}CM	0.031	0.025	0.069	0.055	0.060	0.069	0.042	0.21
^{244}CM	2.83	1.27	4.60	4.13	8.22	7.23	12.78	6.12
^{245}CM	0.91	0.49	1.43	1.22	2.94	2.31	5.19	4.83
^{246}CM	0.39	0.14	0.62	0.53	1.58	1.11	4.87	3.95
^{247}CM	0.046	0.014	0.087	0.071	0.24	0.16	0.86	0.69
^{248}CM	0.013	0.29E-2	0.024	0.020	0.084	0.053	0.42	0.31

This first part of the phase 2 ends when the residual fuel from phase 1 is exhausted. This happens after 10 reloads on each TP, during a total of ~18 years. During this transmutation 79 kg of TRU are sent to the repository in the reprocessing losses and the residual mass contained on the TP cores has been reduced to 17.5 tons. The isotopic compositions of both TRUs are shown in Table 3.

Phase 2 – Second part

To continue reducing the amount of TRU after phase 2 part 1, we could keep running the 3 TPs but now with only one single core load per TP. In this scheme, 12 reloads are needed on each TP producing 109 kg of TRU in the reprocessing losses and leaving 9.1 tons in the residual cores. The corresponding isotopic compositions are shown in Tables 3. Depending on how much staggered can be the start-up of this stage and up to which level the fuel from one TP can be used to fabricate the fuel for another TP, the duration of these 12 reloads might vary from 22 years to 42 years.

Other solutions might be found for this second part of phase 2, that optimise further the procedure, but the details depend on deployment strategies in the very long future outside the scope of this study. The general rule is that probably the time averaged power should be reduced. However it should be noted that if the total mass of the LWR TRU to be treated is large and the number of deployed TP is increased, the second part of phase 2 could mainly consist on the progressive shut-down of TP re-utilising their fuel to top-up the remaining TP. Finally some improvements can be obtained by re-optimisation the core design for this phase.

Phase 3

Whatever solution is used for the second phase part 2, at some point there will be only fuel for a very reduced number of cores. In this study, the simplification of jumping from the end of phase 2 part 2 to 1 single TP is made. The simulation shows that in principle it might still be feasible to use the same reactor concept as in phase 1, but with slightly different fuel mass. Phase 3 requires 22 reloads, producing 54 kg of TRU in the reprocessing losses and leaving 2.75 tons in the remaining core. Table 3 shows the corresponding isotopic compositions. The total time required can never be less than 40 years and might extend well beyond 60 years.

Discussion

This study addresses the problem of LWR TRU waste transmutation with detailed simulations in a time dependent scenario, in particular for the case of the phase-out of the energy production from nuclear fission in LWR. The simulations show that it is possible to perform the TRU transmutation in a number of phases, but using the same ADS design for the transmutation plant, based on fast neutron energy spectrum concept, Pb-Bi cooled and using an inert matrix fuel, for all the different phases. The Transmuter design being the same, the fuel mass changes slightly in the different transmutation stages. In addition even when the design could be the same, the plants live will probably not be sufficiently long to handle all the phases with the same TP used from the beginning. In this case, the new TPs used for the later stages of the transmutation strategy could be better optimised for their fuel.

According to the strategy outlined in this study, it would be possible to reduce the final TRU mass being disposed to the repository, to the sum of the reprocessing losses with a total TRU mass of 0.95 tons and the last spent fuel of the final TP with a total TRU mass of 2.75 tons. The total is 3.7 tons so 3.7% of the initial TRU mass in the LWR spent fuel, equivalent to a reduction factor of 27. The isotopic contents are shown in Table 4.[1] The TRUs of the last core could be even further reduced, using an external energy source to generate the neutron flux and the TARC principle [3] to optimise the transmutation efficiency. This operation could probably reduce finally the TRU mass to nearly 1-2% of the initial LWR spent fuel TRUs. For larger initial TRU masses this level of reduction might be reachable without need of the external energy supply, but with even longer transmutation periods.

It is important to note that to reach these large reduction factors the phase-out requires a very long operation, ranging from 140 to 180 years, so nearly 3 times as long as the period of production of the TRU in the LWR. This fact do not depends much on the total TRU mass and on the installed power fraction, but it strongly depend on the desired level of TRU reduction. Reducing the TRU mass to 25% (reduction factor 4) takes 60 years in the present scheme, whereas 78 years are required to reach the

1. Note that because of the uncertainties on the decay times for the last phases, we have decided to show a simple sum of reprocessing losses at different phases without adjusting decay calculations, and so the isotopic content displayed on the table do not correspond to any particular time.

18% and if 9% is the objective, a period between 100 and 120 years will be required. In general a trade-off between the final transmutation efficiency and the transmutation rate, as a function of the installed power in TP, is observed.

Table 4. **Isotopic composition of the last residual cores and total reprocessing losses**

Isotopes	**Last core** (g)	**Isotope fraction** (%)	**Element fraction** (%)	**Total reproc. losses** (g)	**Isotope fraction** (%)	**Element fraction** (%)
^{234}U	6.31E+03	0.23		1.29E+04	1.37	
^{235}U	1.86E+04	0.68		2.01E+03	0.21	
^{236}U	1.38E+04	0.50		2.24E+03	0.24	
^{238}U	9.48E+01	0.35E-2	1.38	9.45E+00	0.10E-2	1.82
^{237}NP	1.62E+04	0.59	0.58	7.32E+04	7.73	7.73
^{238}PU	5.33E+04	1.94		4.07E+04	4.29	
^{239}PU	2.83E+04	1.03		1.87E+05	19.69	
^{240}PU	5.88E+05	21.40		2.91E+05	30.69	
^{241}PU	2.07E+05	7.53		4.57E+04	4.82	
^{242}PU	7.02E+05	25.57		9.62E+04	10.15	
^{244}PU	4.60E+02	0.017	57.15	2.78E+01	0.30E-2	69.65
^{241}AM	1.21E+05	4.42		1.11E+05	11.74	
^{242m}AM	3.38E+04	1.23		3.07E+03	0.32	
^{243}AM	2.93E+05	10.67	15.72	4.24E+04	4.48	16.54
^{242}CM	4.42E+02	0.016		1.29E+03	0.14	
^{243}CM	1.16E+03	0.042		4.08E+02	0.043	
^{244}CM	3.51E+05	12.78		2.34E+04	2.47	
^{245}CM	1.42E+05	5.19		9.54E+03	1.01	
^{246}CM	1.34E+05	4.87		4.75E+03	0.50	
^{247}CM	2.37E+04	0.86		7.02E+02	0.074	
^{248}CM	1.15E+04	0.42	25.17	2.62E+02	0.028	4.26
Total	2.75E+06			9.47E+05		

In the case of time dependent scenarios ending on a different fuel cycle (not the phase-out), a large fraction of the transmutation operations could be done in the new fuel cycle, as soon as the total TRU mass left from transmutation is acceptable by the new reactors in their cycle. This could reduce the problem to the phase 1 outlined in this study, with the corresponding reduction on the total time for the transmutation operations.

The fuel characteristics evolve from core to core increasing the demands for the fuel reprocessing, storage and fabrication systems as the transmutation stages increase the Cm content. For example, at 608 days after discharge the neutron production from spontaneous fissions becomes 3.7×10^5 n/s/g_{TRU}, 5.9×10^5 n/s/g_{TRU}, 1.1×10^6 n/s/g_{TRU} and 2.1×10^6 n/s/g_{TRU} respectively for the residual cores fuels from phase 1, phase 2 part 1, phase 2 part 2 and phase 3. At the same time the TRUs contribution to the specific decay heat becomes 0.15 W/g_{TRU}, 0.20 W/g_{TRU}, 0.29 W/g_{TRU} and 0.40 W/g_{TRU} respectively for the residual cores fuels from phase 1, phase 2 part 1, phase 2 part 2 and phase 3, with this decay heat decreasing very slowly in the following decades.

A key element for any time dependent scenario is the severe evolution of the fuel composition as the scenario progresses. In this paper we have introduced the concept of using a pseudo-equilibrium fuel, that allows to reduce the effects of the fuel evolution on the different elements of the fuel cycle (rectors, reprocessing and fabrication plants). In the present exercise it is concluded that this might allow to use a single transmutation plant (fast ADS) concept during the full strategy. This kind of fuel, in addition have the advantage of a largely smaller reactivity swing during long burn-ups than the LWR TRUs. However to use pseudo-equilibrium fuel requires an adequate planning of the LWR spent fuel reprocessing and of the deployment of the transmutation plants. On the other hand, the need of transmutation fuel reprocessing follows always directly the number of operating transmutation plants.

Acknowledgement

This work has been supported by ENRESA within the CIEMAT-ENRESA collaboration agreement for the study of long-lived isotope transmutation.

REFERENCES

[1] Miguel Embid *et al.*, *Performance of Different Solid Nuclear Fuels Options for TRU Transmutation in Accelerator-driven Systems*, CIEMAT Report DFN/TR-02/II-00. Also M. Embid-Segura *et al*. (2000), *Comparative Study of Accelerator-driven System (ADS) of Different Transmutation Scenarios for Actinides in Advanced Nuclear Fuel Cycles*. ICONE 9.

[2] E. González *et al.* (1999), *EVOLCODE: ADS Combined Neutronics and Isotopic Evolution Simulation System*. Presented in MC'99 International Conference, Madrid.

[3] A. Abánades *et al.* (2002), *Results from the TARC Experiment: Spallation Neutron Phenomenology in Lead and Neutron-driven Nuclear Transmutation by Actinide Resonance Crossing*, Nucl. Instrum. and Meth. A478 (2002) 577.