

## **Analysis of a European sodium fast reactor scenario with EVOLCODE/TR\_EVOL CODE**

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### **Abstract**

*A specific scenario of the European sodium fast reactor technology (ESFR) penetration in a European fleet has been analysed by the Innovation Group at CIEMAT by means of two kinds of computational tools, a parametric fast running computer code named ECC, under development to explore cost-benefit strategies for advanced nuclear fuel cycles, and a more accurate tool named TR\_EVOL (module of the EVOLCODE 2.0 simulation system), in which reactor physics is considered in detail.*

*The proposed scenario assumes that there will be a European low energy-demand scenario of electricity. The same main assumptions as in the EU FP6 PATEROS Project were taken into account in the initial condition: an association of seven European countries, together with their nuclear material stocks, is considered in 2010. Also, electricity production is assumed to be constant during the period of reference, being 800 TWhe per year.*

*The main objective of this work was to explore plutonium availability along the whole cycle, an important issue considering the big amount of plutonium required by the ESFR reactors. Three scenarios were analysed. The first one, called LOFI 1.06, was calculated with a breeding ratio (BR) of  $\sim 1.06$  for ESFR reactor and a chronologically inverse reprocessing strategy for LWR fuel and a chronologically direct one for ESFR fuel. The second one, called LOFI 1.03, differs from the previous one only in the BR of the ESFR core,  $\sim 1.03$  in this case. In the third scenario, called homogeneous, the reprocessing process was made with no information of the year of irradiation or introduction in the storage of the irradiated fuel.*

*The results showed that the first and the third scenarios could be carried out, but the second scenario with a BR=1.03 does not generate enough Pu to develop all the ESFR in time while maintaining the electrical power requirements.*

## Introduction

The efficient design of strategies for the long-term sustainability of nuclear energy of this technology requires the study of transition scenarios from the current fuel cycle to a future one with advanced technology and concepts. This kind of study provides answers to different aspects of transition scenarios, such as the period of time needed to reach equilibrium, the number and date of the introduction of facilities in the fuel cycle, the amount of stored material, the nuclear waste, etc.

The transition from the existing LWR to the advanced FR is being implemented including Generation-III+ reactors, ready for commercialisation by NPP vendors. Additionally, the operation of the GEN-II-III reactors seems not to be constrained by a uranium shortage. Thus there is a need for the study of these alternative fuel cycle scenarios where existing LWR are progressively substituted by the GEN-III+ reactors and then by fast neutron reactors.

According to this rationale, inside the Collaborative Project for a European Sodium Fast Reactor (CP-ESFR) [1], the analysis of this fuel cycle scenario was performed following the recommendations specified in the reference document provided by ENEA [2]. This scenario was studied in a European context; they involve a limited number of European Union countries according to the choice performed in PATEROS [3]. The data necessary for this study are already available; in particular the legacy inventories with isotopic break-down in mass units of the LWR spent fuel.

In this work, this fuel cycle scenario was analysed using the TR\_EVOL code [4], a new module developed by CIEMAT in order to improve the capabilities of its burn-up simulation system, EVOLCODE 2.0 [5]. TR\_EVOL was designed to study different short-, medium- and long-term options for the introduction of various types of nuclear reactors and for the usage of associated nuclear material, giving due consideration to the isotopic composition of the material in any stage of the fuel cycle: essentially uranium, plutonium, minor actinides and fission products.

## Objectives

The deployment of the ESFR fleet in this work requires a considerable amount of plutonium. Hence the main goal of this work is to determine if there is enough material to implement this fleet while maintaining the electrical power requirements. This means obtaining plutonium availability over time in the whole cycle. Additionally, there are other interesting magnitudes to calculate in order to improve the understanding of the fuel cycle. Therefore other objectives to meet in this work are:

- calculation of the fuel mass by reactor type needed for fabrication;
- calculation of the mass of irradiated fuel and its plutonium production;
- effect of the breeding ratio due to the ESFR core design;
- comparison of different reprocessing strategies;
- assessment of the mass of the streams of separated material (U, Pu and minor actinides) after reprocessing;
- estimation of nuclear waste.

## Main hypotheses and input data

This scenario is formed by four reactor types that are named depending on the technology and the fuel type used:

- PWR UOX: For LWR (PWR or BWR) with UO<sub>2</sub> fuel;
- PWR MOX: For LWR (PWR or BWR) with MOX fuel;
- EPR: For the EPR reactor with 100% of UO<sub>2</sub>;
- ESFR: For European Sodium Fast Reactor with MOX fuel.

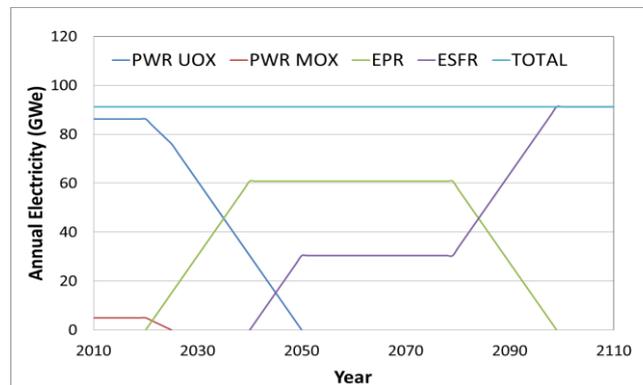
The characteristics of the simulated reactors are summarised in Table 1 and have been obtained from the CP-ESFR SP2-WP1 [2].

**Table 1: Reactors' characteristics**

	PWR UOX	PWR MOX	EPR	ESFR
Thermal power (MW)	2965	2965	4590	3600
Electrical power (MWe)	1008.1	1008.1	1652.4	1440
Energy yearly produced (TWhe)	7.143	7.143	13.036	10.204
<sup>235</sup> U enrichment (wt%)	4.2	0.25	4.5	0.25
Fuel type	UO <sub>2</sub>	MOX	UO <sub>2</sub>	MOX
Pu content (wt%)	--	8.65	--	~15.5 <sup>(1)</sup>
Burn-up (GWd/tHM)	50	45	55	99
Fuel Residence Time (EFPD)	1340	1200	1480	2050
Cycle Length (EFPD)	335	300	370	410
Average Plant Lifetime (yr)	48	40	60	60
Load factor (%)	80.84	80.84	90	80.84
Net thermodynamic yield (%)	34	34	36	42

The scenario starts with 91.2 GWe generated (112.9 GWe installed) by LWR UO<sub>2</sub> and MOX and finishes in year 2100 with the same value of generated power. Figure 1 shows the contribution per reactor type in GWe to the nuclear power fleet. Beyond year 2100, installed capacity of the scenario remains unchanged until 2200.

<sup>1</sup>This value is approximated. It changes every reload because it depends exclusively on the Pu equivalent amount and the Pu isotopic composition used for fabrication.

**Figure 1: Power generated by reactor type**

The composition of the initial legacy of spent fuel in the fleet comes from EU nuclear countries accumulated until year 2010 and it has been provided for the CP-ESFR through Pateros reference [3]. This document estimates that the total amount of plutonium in year 2010 is 386.6 tonnes with an additional amount of 126.7 tonnes in year 2022.

According to the reprocessing process hypothesis, the minimum cooling time for the fuels before this process is 5 years. The reprocessing period is 1 year. A reprocessing loss rate for Pu and U of 0.1 (wt%) has been considered. According to the specifications of this fuel cycle no other elements need to be recovered. However, Np, Am and Cm are also separated in the simulation with the same reprocessing loss rate, just for informational purposes of this waste stream.

Three reprocessing plants are considered in this scenario. The characteristics of fuel reprocessing and the year of their commission are shown in Table 2.

**Table 2: Reprocessing characteristics**

	First LWR reprocessing plant	Second LWR reprocessing plant	GEN-IV reprocessing plant
Operation date	2010	2040	2040
Heavy metal capacity	850 t	2000 t	850 t
Reprocessing order	chronologically inverse	chronologically inverse	chronological
Reprocessing Conditions	From 2006 to 2035: 100% UO <sub>2</sub> spent fuel  From 2036 to 2040: 25% PWR_MOX and 75% UO <sub>2</sub> spent fuel	From 2040 until the exhaustion of spent PWR_MOX fuel stock: 25% PWR_MOX and 75% UO <sub>2</sub>  After the exhaustion of spent PWR_MOX fuel stock: 100% UO <sub>2</sub>	First SFR MOX reprocessing: after the reprocessing of PWR_MOX spent fuel.

Regarding the UOX fuel enrichment, no maximum limit in the SWUs plants capacity has been considered here. The tails assay for <sup>235</sup>U enrichment is 0.25 until 2020 and 0.20 after this year.

The time required for fuel fabrication is 1 year for any type of fuel. No restriction in fabrication capacity has been considered in this work.

## Simulation tool

### TR\_EVOL Module description

The TR\_EVOL module [4] simulates diverse nuclear power plants (PWR, SFR, ADS, etc.), possibly having different types of fuels (UO<sub>2</sub>, MOX, etc.), and the associated fuel cycle facilities (enrichment, fuel fabrication, processing, interim storage, waste storage, geological disposal). The module is intended to simulate each reactor fleet as a single macro-reactor, although it can also simulate individually each reactor of the fleet if required (requiring, however, large computer resources). Due to this purpose and assuming that the nuclear fleet is large enough (usually tens of reactors), every magnitude is provided per year. Hence, large fluctuations of operational parameters on individual cycle facilities are averaged over the year.

The evolution of fuel composition and nuclear materials during the lifetime of the nuclear fleet is performed in TR\_EVOL by means of ORIGEN 2.2 (Isotope Generation and Depletion Code) [6] specifically in the decay and irradiation processes. In case of irradiation, ORIGEN 2.2 could use its own reference cross-section libraries or others specifically calculated with EVOLCODE 2.0 [5].

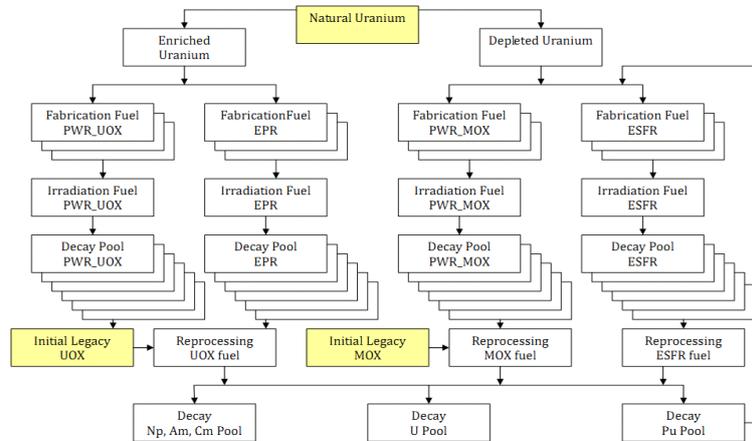
Each fuel cycle storage facility is represented by one or several different buffers. For instance, a nuclear fleet might consist of a series of PWR with N different <sup>235</sup>U enrichments fuels. Hence, data concerning fresh fuels with different enrichments would be stored in N different buffers.

Each buffer contains the isotopic vector and the total amount of material present in that storage. Storage facilities taken into account in a general fuel cycle (others could be included when necessary for particular cycles) are enriched uranium, fresh fuel for nuclear reactors, spent fuel in cooling storage, separated material from reprocessing and nuclear waste.

Connections between buffers represent mass flows. They can link one buffer to another, but can also join more than two buffers or divide different buffers. The parameters of the cycle facilities and the time-dependent interconnections are described in TR\_EVOL, using a series of basic operational instructions or rules. Each rule specifies a particular action that is applicable to a particular buffer (decay of stored material) or to a particular interconnection (fuel irradiation, fuel fabrication, reprocessing, etc.). The period of time for which that particular action is active is also specified (for instance, advanced reprocessing may be only applicable from a certain year on).

### Simulation model

A scheme of the model simulated by TR\_EVOL can be seen in Figure 2, where buffers and rules are specified. Each box represents a buffer or material stream. Each overlapped box represents a rule of one year decay over the selected buffer. It can be seen that the fabrication rule includes two years of interim decay (accounting for one year of reprocessing plus one year of fabrication) and there are five years of cooling decay after irradiation.

**Figure 2: CP-ESFR cycle simulation model**

## Results

This chapter includes the results for the relevant parameters for the CP-ESFR SP2-WP1 scenario. In particular, fuel requirements, irradiated fuel, plutonium availability, reprocessing strategies and nuclear waste, among others, have been assessed and shown here.

Since some results depend on the reprocessing strategy and the ESFR breeding ratio, two values of the BR (1.06 and 1.03 asymptotic values at the equilibrium) and two reprocessing strategies have been assessed and compared.

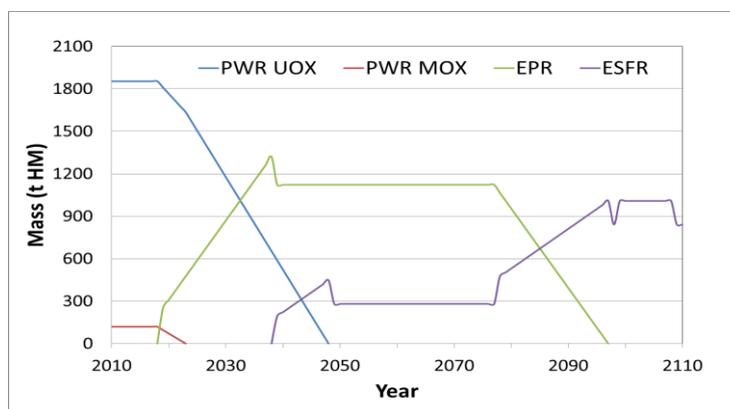
### Fuel mass fabrication

Considering the deployment strategy and the number of the reactors it is possible to obtain the mass of fuel required to satisfy the power demand during the whole fuel cycle. The fuel mass needed for fabrication is shown in Figure 3, where each curve represents a reactor type.

In order to fabricate the fuel, two contributions have to be taken into account: On the one hand, the fuel mass required to do the successive reloads; and on the other hand, the fuel mass required to fabricate the entire core for new reactors.

As given in the specifications of the cycle, there is no introduction of new PWR\_UOX and PWR\_MOX reactors. Because of this, no new cores have to be fabricated for them. The fuel mass for these reactors is required only for refueling, considered until the decommission dates.

In contrast, the introduction of the EPR and ESFR reactors in the cycle shows some peak zones at the beginning of their curves and at the second period of increase of the ESFR fleet due to the fabrication of the new cores combined with its reloads. The introduction of the EPR fleet produces the peak zone beginning around year 2019, corresponding to the beginning of the fabrication of the new cores of this reactor type, to be irradiated in year 2021 and on. A similar behaviour can be found for the ESFR fleet at years 2038 and 2078. Thus, the 78.4 ESFR cores are completed in the year 2097, explaining the drop of fuel in the year 2098. Immediately, after this year, the first third of the ESFR fleet has to be replaced and new cores have to be fabricated.

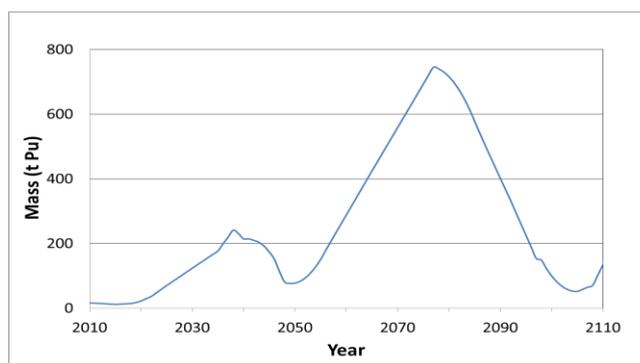
**Figure 3: Necessity of fuel for fabrication per reactor type during the whole cycle**

Due to the necessity of the fuel fabrication for the new EPR cores, the maximum fuel fabrication demand is reached at year 2019 with a value of 2 158 tonnes (1 810 tonnes for PWR-UOX, 95 tonnes for PWR-MOX and 253 tonnes for EPR), ~9% larger than the initial demand of 1 973 tonnes (1 854 tonnes for PWR-UOX plus 119 tonnes for PWR-MOX).

Natural uranium is essential to fabricate PWR UOX and EPR fuels. Through this process depleted uranium is also produced. In total around 990.000 tonnes of natural uranium is needed for the whole cycle and a maximum accumulation close to 820.000 tonnes of depleted uranium is reached.

### Reprocessing strategy

According to the reprocessing process of these plants, Figure 4 illustrates the separated plutonium mass (using a BR of 1.06) along the cycle obtained.

**Figure 4: Separated Pu**

For the reprocessing process the scenario was carried out considering two possible strategies of fuel extractions from the irradiated fuel storage.

These strategies are:

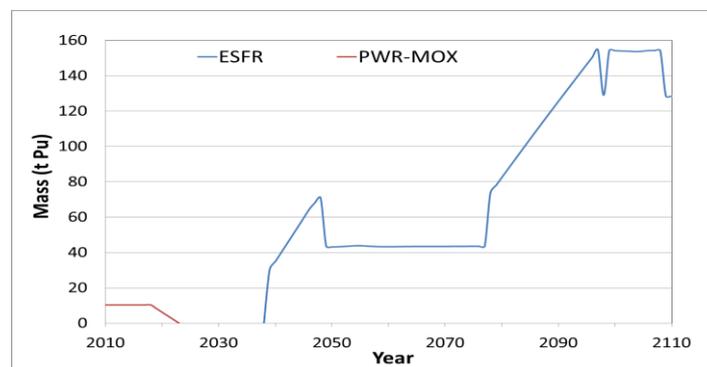
- Homogeneous extraction: The irradiated fuel storage for each reactor fleet has no information of the year of irradiation or introduction in the irradiated fuel storage. Thus this strategy is called homogeneous reprocessing.
- Heterogeneous extraction: ESFR fuels are reprocessed in chronological order, meaning that the irradiated fuels with the longest cooling time are reprocessed first. For LWR fuels, a type of reprocessing called Last Out First In (LOFI) has been considered, implying that the LWR irradiated fuel (initial legacy and the one created along the cycle) with the shortest cooling times are reprocessed first, in order to get the highest amount of plutonium by avoiding the reduction of the amount of  $^{241}\text{Pu}$  in the decay to  $^{241}\text{Am}$ .

### Plutonium requirements for the cycle

The PWR MOX fleet must use about 134 tonnes of Pu (until the last reactor ends its operation), at a rate shown in Figure 5. This amount has to come from the initial legacy, particularly from UOX spent fuel, and the irradiated fuel from the PWR UOX reactors.

With respect to the fuel for the ESFR reactor, each new core requires around 74.5 tonnes of MOX fuel with approximately 15.4% of plutonium enrichment to satisfy the equivalent  $^{239}\text{Pu}$  amount (about 11.5 tonnes of plutonium by core and 900 tonnes for the total of 78.4 ESFR reactors). For refuelling, the ESFR-MOX reload consists of 10.8 tonnes/yr/reactor of HM and ~1.7 tonnes/yr/reactor of Pu.

Figure 5: Plutonium requirements



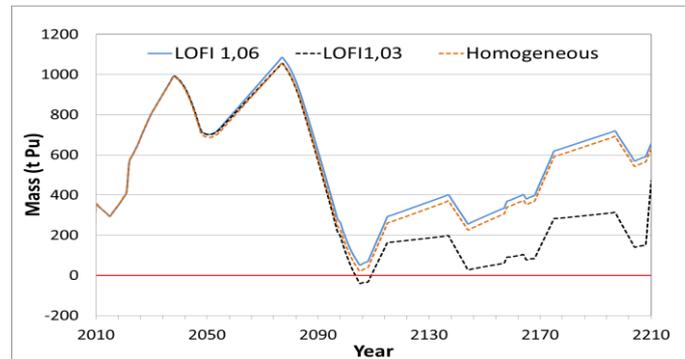
In addition to this large amount of Pu that should be available at the proper moment, an additional constraint must be considered. Up to now, we have considered that the Pu from previous irradiations is immediately available. However, there is a period for which plutonium reprocessed from ESFR spent new cores is not available, since it is obtainable after 13.94 years (irradiation: 6.94 years, cooling decay: 5 years, reprocessing + fabrication: 2 years). Therefore the total amount of fuel to fabricate through this period must be doubled ( $13.94/6.94 = \sim 2$ ), meaning that the minimum amount of plutonium to deploy the new cores of the ESFR fleet has to be around 1 800 tonnes ( $2 \times 11.5 \times 78.4$ ) in the two introduction periods (600 in the first one and 1200 in the second one).

### Plutonium availability over the cycle

Due to the significant plutonium consumption during the ESFR fleet deployments, the goal is to avoid running out of Pu. Figure 6 shows the amount of available plutonium in the whole cycle considering the two ESFR designs (B.R 1.06 and 1.03) with LOFI strategy and homogeneous strategies with B.R. 1.06. This amount includes the initial spent fuel

inventories and the irradiated fuel from the power plants available after the cooling time of 5 years. The plutonium mass in the fabrication stage is not included. The figure shows that for BR=1.06 there is enough Pu mass to cover the deployment of the ESFR fleet in the whole cycle, in view of the specifications given for the reference scenario CP-ESFR. However, when BR=1.03, there is a break-down of Pu mass (~40 tonnes) between years 2103 to 2109.

**Figure 6: Plutonium availability over the cycle**



Regarding this, the minimum values of the available Pu (mass of Pu which can be separated after the period of irradiation and the cooling time of 5 years) in the cycle is in year 2105 with amounts of 42 tonnes, -40 tonnes and 10 tonnes for the LOFI 1.06, LOFI 1.03 and homogenous BR 1.06, respectively.

### Waste generation

According to waste generation, at year 2100 around 9 000 tonnes (and 18 000 tonnes around year 2200) of nuclear waste will be generated, including fission products and actinide reprocessing losses. As reference for further studies, the amounts of separated minor actinides are ~460 tonnes until year 2100 and ~870 tonnes until year 2200.

### Conclusions

The ESFR transition fuel cycle scenario consisting in the replacement of reactors of current technology (LWR) with an advanced reactor (ESFR) fleet, through an intermediate technology (EPR), was simulated following the specifications proposed in the frame of the European Project CP-ESFR. The TR\_EVOL code was applied for this simulation, which is a new module of EVOLCODE 2.0 intended for transition scenario studies.

The viability of the reference fuel cycle scenario (LOFI 1.06) was checked by means of assessing the available amount of Pu over time. It can be concluded that the ESFR fleet is deployable since there is enough Pu mass to fabricate their required fuel. The minimum value of the available Pu is 42 tonnes in year 2105. In the case of homogeneous strategy the scenario is also viable with a minimum value of 10 tonnes. However, LOFI 1.03 strategy has a drawback at the start of the next century; this scenario needs around 40 tonnes of Pu more than the one produced by the cycle.

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