C. R. Mecanique 339 (2011) 209–218

Contents lists available at ScienceDirect

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Industrial research for transmutation scenarios

Recherche industrielle pour les scénarios de transmutation

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ARTICLE INFO

Article history:
Received 26 January 2011
Accepted 28 January 2011

Presented by Robert Dautray and Jacques Friedel

Keywords:
Fast neutron reactors
Transmutation
Americium
Minor actinides
Nuclear cycle

Mots-clés :
Réacteurs à neutrons rapides
Transmutation
Américium
Actinides mineurs
Cycle

ABSTRACT

This article presents the results of research scenarios for americium transmutation in a 22nd century French nuclear fleet, using sodium fast breeder reactors. We benchmark the americium transmutation benefits and drawbacks with a reference case consisting of a hypothetical 60 GWe fleet of pure plutonium breeders. The fluxes in the various parts of the cycle (reactors, fabrication plants, reprocessing plants and underground disposals) are calculated using EDF's suite of codes, comparable in capabilities to those of other research facilities. We study underground thermal heat load reduction due to americium partitioning and repository area minimization. We endeavor to estimate the increased technical complexity of surface facilities to handle the americium fluxes in special fuel fabrication plants, americium fast burners, special reprocessing shops, handling equipments and transport casks between those facilities.

RÉSUMÉ

Nous présentons dans cet article des résultats de scénarios de recherche pour la transmutation de l'américium vers la fin du XXI^ième^ siècle. Nous considérons un parc nucléaire français hpothétique constitué à cette époque de réacteurs à neutrons rapides à caloporteur sodium. Nous évaluons les avantages et les inconvénients de la transmutation de l'américium par rapport à un scénario de référence où le parc nucléaire de puissance 60 GWe est constitué de surgénérateurs dimensionnés seulement pour la production et le recyclage du plutonium. L'un des scénarios de parc projette dans la deuxième moitié du XXI^ième^ siècle (2064) la pratique industrielle du recyclage dans le parc d'EDF à eau légère. Nous rappelons à ce sujet que seules 22 tranches REP sur 58 sont chargées en combustible MOX en 2010. Nous calculons avec les codes d'EDF les flux des principaux radionucléides dans les différentes usines de tout le cycle : les réacteurs des centrales, les usines de fabrication, les usines de retraitement et le centre de stockage géologique que l'on suppose ouvert dans l'argile du callovo-oxfordien. Nous apportons une attention particulière à la réduction de la charge thermique en stockage quand l'américium est séparé et géré dans les réacteurs et dans les installations de surface. Cela permet de réduire l'emprise du stockage géologique, réduction dont des valeurs quantitatives peuvent être données avec les hypothèses de dimensionnement actuelles des ouvrages souterrains projetés. La comparaison de la complexité accrue des différentes installations

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1631-0721/$ – see front matter
doi:10.1016/j.crme.2011.01.006

de surface et de la réduction de l'emprise du stockage permet de définir les principes d'une démarche coûts/bénéfice appliquée en premier lieu aux investissements des installations de transmutation.

1. Introduction

Transmutation studies have been performed since the early 1970s with the SUPERFACT experiment in PHENIX [1]. The 1991 and 2006 French waste laws have encouraged the academic and public research center communities to pursue research in long term nuclear fuel cycle scenarios, using transmutation. Industry on its side also participates in the debate and follows the 2006 law by performing R&D with its own tools and means. Since it has industrial facilities to run on a day to day basis, it incorporates in the numerous scenario studies some of its actual industrial practices, having in mind that simplicity is often a key success factor in technology deployment. For that purpose, we present here the results of scenario studies for americium transmutation in a 22nd century French nuclear fleet, using sodium Fast Reactors (FR's).

This article is organized as follows: in Section 2, we describe briefly the current EDF fuel management system for its 58 LWR reactors fleet. In Section 3, we give the main technical parameters for the americium scenarios studied as well as comparisons to the reference case consisting of 60 GWe of plutonium fast breeders. Section 4 describes briefly the simulation tools and Section 5 describes the results in terms of actinides (major and minor) in the whole cycle, as well as the consequences for underground disposal. Particular emphasis is placed on underground thermal load, underground disposal area and volume for the inventories produced around 2150. Section 6 endeavors to draw the technical and resources balance between underground actinides management and surface actinides management.

2. The industrial fuel management system for the current LWR fleet

2.1. Nuclear production

There are currently 58 PWR reactors operating in France representing 63 GWe and designed on standardized PWR reactors series. EDF aims at increasing the lifetime of its Gen II reactors over 40 years. Besides, EDF is currently building the EPR reactor, a 1650 MW unit, on the Flamanville site.

2.2. The current fuel cycle: spent fuel and back end

Since the French fuel cycle was already presented in detail in [2], the reader is invited to consult this reference. In the 1970s, in order to preserve varied options for the future, including the development of FR's, the decision was taken to develop a closed fuel cycle based on reprocessing of spent fuel and retrieving plutonium and uranium at La Hague plant operated by Areva NC. High Level Waste (fission products and minor actinides – HLW) is confined into glass canisters and reusable nuclear materials – plutonium and uranium – constitute a potential energy resource to be recycled. The nuclear spent fuel reprocessing and recycling in France has reached the stage of mature industrial practice and represents a first step towards the sustainability of nuclear power while assuring a secure treatment and conditioning of HLW and preserving resources of fissile and fertile fuels. The main figures of the current fuel cycle at equilibrium are presented in [2]. From 2010 on, EDF envisages increasing from 850 tons to more than 1000 tons the quantity of spent fuel reprocessed every year so that the annual amount of MOX fuel will increase up to 120 tons. Today, twenty-two 900 MW-class PWRs are licensed for MOX fuel and a licensing procedure is under way for two extra reactors. The spent MOX will be reprocessed in the future: it constitutes a resource of nuclear fuel for the long term that can be reused especially in future FR's to meet future energy needs. This strategy gives time and can be extended for the years to come, over the next decades, while preparing for future options.

2.3. The French Act of June 28, 2006 on "a sustainable management of nuclear materials and radioactive waste"

As for the management of long lived and high activity nuclear waste, after 15 years of research and studies of different options, the Act of June 28, 2006 established a national strategy for managing nuclear materials and radioactive waste. A stepwise program for long lived waste management (high and medium activity) is defined along various approaches: a retrievable geological repository as a reference solution (authorization decree in 2015, beginning of operation in 2025); the creation of new facilities for interim storage in 2015, the pursuit of research on partitioning and transmutation (P&T). More precisely, for P&T, the Act requests the assessment of industrial prospects of Gen IV systems and ADSs (Accelerator Driven Systems) for presentation to the French Parliament in 2012. The assessment should account for the potential benefits of P&T (i.e. minor actinides – MA – recycling or not) for the long term management of HLW and also for their impact on future fuel cycle facilities and reactors operation in terms of safety, radiation protection and costs. The Act foresees the commissioning of a prototype (reactor and cycle) in 2020 which triggers R&D on a new generation of FR's and advanced

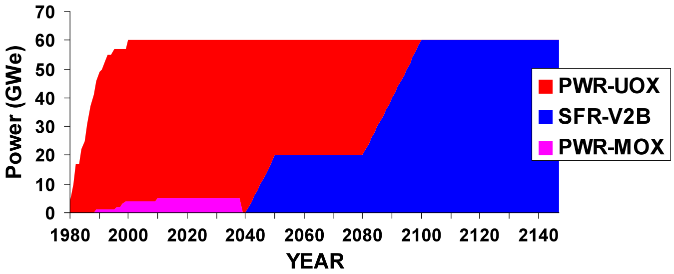

Fig. 1. SFR deployment scenario.

recycling modes (with or without MA). Besides, it states that, whichever chosen strategy for the management of waste, industrial interim storage of spent fuel and deep geological disposal remain necessary.

2.4. To transmute all the minor actinides or americium only?

Scenario studies compare many transmutation options. In particular, one has the choice to transmute all the MA: Am, Cm, and Np, or Am only.

Np transmutation is not of a real interest. This actinide is not mobile under the chemical conditions in the French geological site for the repository: so, it has no environmental impact. Its decay heat is low and there is no real benefit on the underground repository area.

As for Cm transmutation, due to Cm short half-life (18 years), it has a weak impact on the underground repository area. The only significant gain would be on the waste radio-toxicity in the repository, but on the one hand, this gain is variable along time and it is not different from the gain obtained with Am alone transmutation after 100 000 years; on the other hand, radio-toxicity is a questionable indicator as we will see in Section 4.2. As for drawbacks, Cm handling in the fuel cycle is very hazardous: in particular, the thermal load and the level of neutron sources at fuel fabrication stage are very high as compared to the FR MOX standard fuel fabrication. Besides, the decay heat and neutronic sources of spent MA bearing fuel are very high: this has a huge impact on fuel handling and the power plant availability as well as the transportation of spent fuel. That is why EDF is in favor of considering in research scenarios transmutation of Am only and to dispose of Cm in the geological repository after an interim storage for decay heat. Thus, in this article, only Am transmutation research scenarios are considered although we also perform the studies of scenarios where all MA are transmuted for comparison and checking purposes.

3. Characteristics of the various transmutation scenarios

The principle of the study is to define a reference scenario of FR deployment without MA transmutation, and to compare it to other scenarios built on the same frame, but with various Am transmutation options.

3.1. The plutonium reference case

The reference case (scenario S_ref) is based on EDF prospective view of the transition between its current nuclear fleet and a GEN IV FR fleet throughout the 21st century, as shown in Fig. 1.

The current reactors renewal starts as from 2020, with GEN III PWR (EPR type). GEN IV FR deployment is supposed to start in 2040, and the Pu mono-recycling in PWR to stop a few years earlier. With a kinetics of 2 GWe replaced each year, and an installed nuclear power fixed at the current level, 60 GWe, 20 GWe are replaced in 2050. The fleet is then composed of two thirds of GEN III PWR, and one third of GEN IV FR. GEN III PWR are then replaced by FR's as from 2080, and the fleet is thus entirely composed of FR's in 2100. All MA are vitrified with the fission products.

The GEN IV FR concept used has been developed by the CEA and is known as SFR V2B [3]. Its core (Fig. 2) contains 453 Fuel Assemblies (FA), with ∼16% mean Pu content, for a 3600 MW thermal power. The total core inventory is 74 tons (heavy metal). This design is characterized by a breeding gain a little more than zero, allowing iso-generation, without any fertile blanket. The core residence time of the fuel is 7 years (5 cycles lasting 410 equivalent full power days with an 81% loading factor). The ex-core time is also 7 years (assumption we also used for PWR fuel): 5 years of minimum cooling time before used fuel reprocessing, and 2 years after, before the loading in core. Thus the deployment of SFR V2B requires about 17 tons of Pu per GWe. The Pu necessary to feed the 20 GWe of SFR deployed between 2040 and 2050 is first extracted from UOX and PWR MOX used fuels. The SFR MOX fuel reprocessing is supposed to start only when the stock of PWR MOX used fuels is completely exhausted (i.e. in 2059, see Section 5.1).

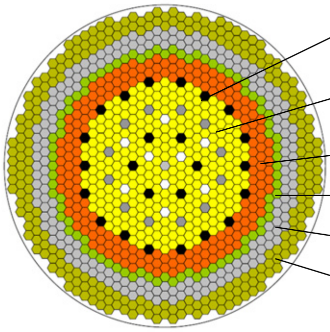

Fig. 2. SFR V2B core with AmBB's (heterogeneous scenario).

3.2. The Am transmutation scenarios

The Am transmutation scenarios are based on the same framework. Two main options are considered: the homogeneous transmutation (scenario S_hom), the Am being mixed with the Pu in the standard SFR fuel, and the heterogeneous transmutation, the Am being mixed with depleted U in radial blankets disposed outside the fissile core [4].

The main advantage of the heterogeneous option is to reduce the number of Am fuel bearing assemblies with respect to the homogeneous one, more currently studied. Fig. 2 shows the position of 84 Am Bearing Blanket assemblies (AmBB's in green).

A homogeneous transmutation core would necessitate 453 Am bearing FA's. Taking into account the different loading schemes of homogeneous FA's and heterogeneous AmBB assemblies, it is possible to show that the homogeneous scenario requires an Am bearing FA flux 5 to 10 times higher than the heterogeneous scenario (1300 Am bearing core assemblies per year versus 120 to 300 AmBB assemblies per year in the case of 20 SFR V2B reactors loaded).

These Am bearing assemblies will have to be fabricated in remote control plants, requiring maintenance and repair with telemanipulators or robots. Reducing their output and size will therefore be a big advantage, from a technical point of view to begin with. It can also be argued that the safety demonstration while not impossible in homogeneous cores will be more difficult not so much because of neutronic parameters [5] but because of gas production in the actinides bearing FA's. The drawback of this choice is to raise the Am content of Am bearing assemblies. A 20% content is required to limit the required number of AmBB's while efficiently transmuting the Am. AmBB irradiation time is 14 years, to ensure a convenient transmutation rate (35%), and the AmBB assemblies have to be rotated 180° after half of this time.

In the case of the homogeneous option, all the FR's are supposed loaded with standard assemblies in order to keep the Am content as low as possible. In the case of the heterogeneous option, the fraction of FR's equipped with AmBB's is not fixed, and depends on the amount of Am to transmute and the numbers of FR's available. Two options can then be considered:

- All Am contained in the used assemblies reprocessed from 2038, when FR fuel fabrication starts, have to be transmuted in AmBB's, meaning that all the FR's have to be loaded with AmBB's if necessary (scenario S_het); in this case, reduction of repository surface area due to lower heat content is considered more important than the difficulties of loading all the FR's with AmBB's and running the fabrication plants at high flux.
- Only a fraction of the SFR's, for instance 50%, is loaded with AmBB's (scenario S_het_50%). In this case, the penalty of loading all the FR's with AmBB's and running larger fabrication plants at high flux is considered greater than the benefits of repository surface reduction due to lower underground heat content. The number of FR's used for transmutation is reduced by half, and the Am which cannot be loaded in the reactors when partitioning starts in 2038 is sent directly to the waste stream.

The SFR's adapted to the Am transmutation are called FR 1500_{Am}. The other FR 1500_{Pu} are pure Pu breeders and do not have the special equipments necessary for AmBB loading. This option projects in the future the current LWR EDF fleet where only 24 reactors out of 58 have the MOX loading capability from the technical and licensing point of view. For the first order calculations a 60 GWe fleet around 2100 is composed of 40 FR's 1500. Those data are valid for research scenarios. In industrial practice, EDF does not consider Am partitioning from PWR MOX fuels in 2038. MOX fuels can be industrially reprocessed with an adapted PUREX process.

The last scenario we considered is based on the scenario S_het, but with a different assumption about the date of implementation of the Am transmutation, putting it off from 2040 to 2080, date of the second phase of SFR massive deployment. The first motivation for this assumption is to propose a more progressive scenario. Indeed, SFR deployment at an industrial scale is really a big challenge. Am option, requiring to implement advanced reprocessing, and to fabricate and handle a more complex fuel, is another big technical challenge, thus it seems more realistic to postpone its implementation to a later date, when SFR fleet is strongly installed, and the closure of the fuel cycle with SFR used fuel reprocessing is well established.

In addition, by doing so, we limit the Am transmutation to Am issued from SFR used fuel: in that case, GEN IV FR's would minimize their own HLW production, and we consider that the MA produced before, especially by PWR MOX fuel, will be sent to the repository. Besides, restraining the Am transmutation to the Am produced by the SFR fleet makes possible to limit the proportion of SFR's loaded with AmBB's, almost at 50% like in the S_het_50% scenario, as we will see in Section 5.2.1.

4. Simulation tools and methodologies

4.1. Simulation tools

Two tools are used for the complete simulation of a scenario. Firstly, the scenario simulation code TIRELIRE-STRATEGIE [6] simulates the operation of the nuclear fleet and the associated fuel cycle facilities. Then, exploiting the results of this simulation (i.e. for each year, uranium consumption, the mass flows, fuel inventories and isotopic compositions in all fuel cycle facilities, and the number of HLW packages together with their thermal power outputs, etc.), our final HLW repository model calculates the minimal repository area requested for disposing of the waste packages. The vitrified waste package repository design is issued from the ANDRA 2005 report [7]. The area minimization process is driven by the temperature constraint fixed by ANDRA: the temperature in the clay layer must be kept below 90 °C. Repository thermal calculations used for this optimization are performed with the SYRTHES code, developed by EDF R&D Division [8].

4.2. Detailed criteria for comparisons of scenarios

MA transmutation is a complex process and the number of criteria to assess can be very large, which can finally result in an inefficient assessment. So, criteria selection is an important step of scenario studies. The main criteria chosen are the following ones: inventories and characteristics of materials and waste induced in the different scenarios (in the fuel cycle including reactors and in the geological repository); facilities characteristics and transportation needs; impacts on geological repository (underground area, safety); impact on radiation protection of citizens and workers; economical performance (cost of each scenario); impact on power plant (safety, availability, cost); industrial risk; fuel resources consumption. One of the criteria very often emphasized to justify transmutation is the potential radio-toxicity of waste. It is actually a criterion very difficult to deal with and not so pertinent. The radio-toxic inventory of a waste quantity corresponds to the dose received by a set of people who would have ingested this waste quantity. It is a theoretical indicator which has a real meaning only if there is a path from the waste to the set of people. In the case of the geological repository, for the site considered in France, MA are not mobile and so do not move out of the repository. In fact, ANDRA, in charge of the repository studies, has performed a safety assessment: it shows that the environmental impact is due to the fission and activation products and is very low, between one and two orders of magnitude under the regulatory limit. Indeed the dose at the outlet stays below one microsievert per year, even at its maximum reached after $\sim$500 000 years in the normal evolution scenario and below one microsievert per year, maximum reached after 25 000 years, in the altered evolution “borehole” scenario. The main contributors for vitrified waste are ^{129}I and ^{36}Cl. Pu isotopes play a role only in case of the altered evolution “borehole” scenario, but their contributions are at least three orders of magnitude below (maximum reached after 100 000 years). No MA contributions are quoted at the outlet [7]. Therefore EDF does not consider potential radio-toxicity as a pertinent indicator to justify MA transmutation unless the French safety regulator after the advice of its standing advisory group (“*Groupe Permanent Déchets*”) requires it for technical reasons not foreseen at this stage.

5. Detailed results and consequences on fuel disposal

5.1. Reference scenario

The cumulated amount of Pu requested for feeding a fleet of 60 GWe of SFR V2B is about 1070 tons (Fig. 3). Its repartition is 500 tons in core, 150 tons in fabrication facility, 370 tons in used assemblies waiting for cooling, and a few tens of tons of Pu separated and stored as a reserve for fabrication. To get such a Pu mass in 2100, it is necessary to make use of fertile blankets during all the transition period (they are not useful later, the last one being reprocessed in 2101). Lower axial blankets are enough, but they must be loaded in all the SFR's operated during the transition period. On the whole, 2700 tons of fertile blankets are needed, producing about 130 tons of Pu.

In order to get 350 tons of Pu necessary to deploy the first 20 GWe of SFR's, it is necessary to increase the amount of reprocessed used fuel to a maximum value of 1200 tons per year, of which 270 tons originate from PWR MOX fuel in 2050 (Fig. 4).

The ratio $Pu/U + Pu$ in that case is slightly higher than the 20% limit currently admitted in the La Hague facility. The reprocessing of the SFR MOX fuel starts in 2059. Therefore, it would be possible to use the same reprocessing technology until this date, facilitating the transition towards the SFR fuel cycle. After 2055, all the PWR used fuel is exhausted, and the annual mass of SFR MOX fuel to be reprocessed each year is stabilized at about 450 tons per year.

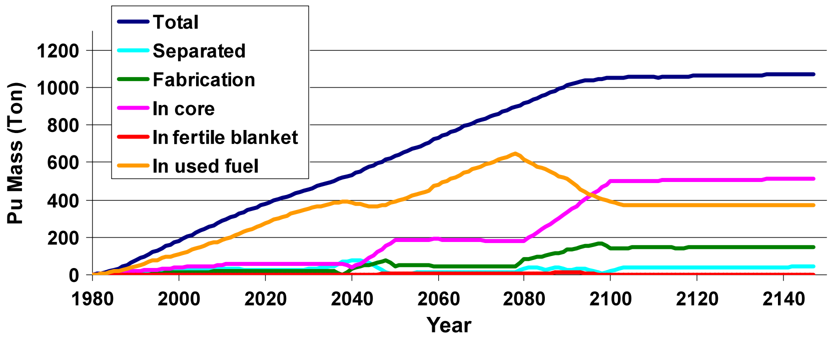

Fig. 3. Reference scenario, Pu mass inventories in the fuel cycle.

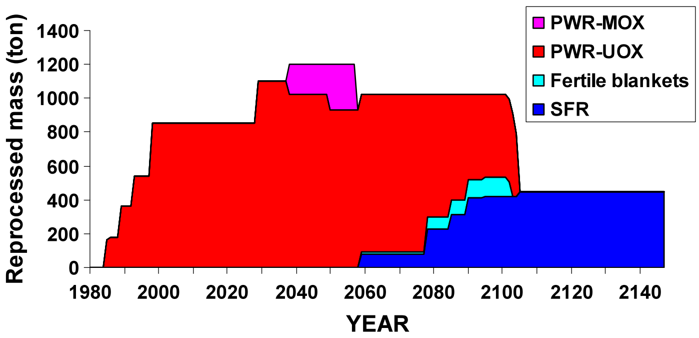

Fig. 4. Reference scenario, reprocessed fuel masses (TMLi).

Table 1
Plutonium and minor actinides' inventories in 2150.

Scenario		S_ref	S_het	S_het_50%	S_het_2080	S_hom
Am content	Equilibrium Maximum	–	CCAm 20% Am	CCAm 20% Am	CCAm 20% Am	0.8% Am 2.8% Am in 2040
Pu (tons)	Cycle Waste	1070 20	1240 25	1200 25	1150 23	1120 30
MA (tons)	Cycle Waste	18 390	105 155	95 210	95 232	55 155

5.2. Am transmutation scenarios

5.2.1. Plutonium and minor actinides' inventories

The Pu content has been adjusted in the case of the reference scenario in order to ensure the Pu iso-generation. Am transmutation increases the breeding gain, of the fissile core in case of homogeneous transmutation, or by the Pu production in the AmBB's in case of heterogeneous transmutation, but it is not enough to do without the fertile blankets. In order to simplify the simulations, we kept for all the scenarios the same assumption about using 2700 tons of fertile blankets during the transition period. Table 1 summarizes the results obtained at the end of the scenario (2150). Due to their higher breeding gain, the transmutation scenarios feature higher Pu cycle inventory at equilibrium than the reference one, the extra Pu being stored. At equilibrium, the Am content in the case of homogeneous transmutation is 0.8%, but there is a peak at ∼3% at the beginning of SFR deployment in 2040, due to the important amount of Am accumulated in the PWR used fuel (especially the MOX ones).

Considering the heterogeneous transmutation scenarios, S_het assumes the transmutation of all the Am issued from the used fuel reprocessing, and thus requires to load AmBB's in all the SFR's available between 2064 and 2090. After this date, the proportion of reactors equipped with AmBB's decreases progressively (with some oscillations) towards the equilibrium value, 55%, which is not reached before 2200 (Fig. 5).

In the case of the other heterogeneous options, S_het_50% imposes a 50% proportion, while S_het_2080 starts the Am transmutation in a situation already close to the equilibrium, thus limiting the proportion around 50%. Of course, it means that a significant amount of Am has been vitrified during the transition period: 55 tons in case of S_het_50%, 80 tons in case of S_het_2080. On the other hand, almost all the Am issued from the SFR used fuel reprocessing is transmuted.

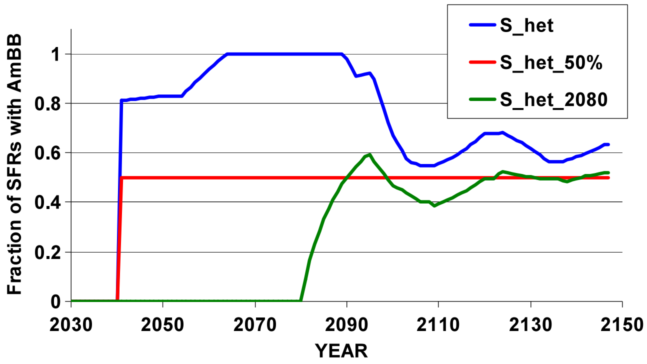

Fig. 5. Proportion of SFR V2B equipped with AmBB.

Table 2
TRU inventories (waste and total).

Scenario		S_ref	S_het	S_het_50%	S_het_2080	S_hom
TRU (tons)	Waste	410	180	235	255	185
Reduction	Waste	1	2.3	1.7	1.6	2.2
TRU (tons)	Total	1500	1355[a]	1400[a]	1440[a]	1310[a]
Reduction	Total	1	1.11	1.07	1.04	1.15

[a] For the transmutation scenarios, we did not take into account the extra Pu due to the over-breeding.

Table 3
Transmutation impact on total vitrified waste package number, and on total repository area.

Scenario	S_ref	S_het	S_het_50%	S_het_2080	S_hom
Vitrified HL package (total number)	141 000	141 000	141 000	142 000	140 000
Vitrified HL package disposal area (normalized area $S_{ref} = 1$)	1	0.55	0.66	0.71	0.57
Total repository area (HLW + MLW + underground common installations)	1	0.69	0.76	0.80	0.7

Am transmutation results in a significant increase of the MA inventory (mainly Am) in the fuel cycle: 55 tons in the case of homogeneous transmutation, around 100 tons in the case of heterogeneous transmutation, compared to less than 20 tons in the case of the reference scenario.

Am transmutation allows a significant reduction of the amount of MA sent to the final disposal. The repository TRU (TRansUranium elements) inventory is about 400 tons in 2150 in the case of the reference scenario, ∼180 tons in the case of S_het and S_hom scenarios (reduction factor higher than 2) (Table 2). The performance of S_het_50% and S_het_2080 scenarios is lower, with a reduction factor above 1.5.

On the other hand, if we consider the TRU total amount, both in cycle and repository, it is important to note that the reduction factor is very limited, due to the huge amount of Pu in the fuel cycle.

5.2.2. Impact on waste disposal

The total number of vitrified waste packages produced in the various scenarios is almost the same, a little more than 140 000 (Table 3). Am transmutation brings no benefit with respect to this parameter. It is due to the fact that the glass content is imposed by criteria related to fission products, not actinides (we have assumed that the current criterion limiting at 10^{19} the maximum α decay per gram of glass, integrated over the first 10 000 years of cooling, will be released beyond 2×10^{19} α/g according to CEA R&D work [9], and thus will have only a marginal impact on the glass fabrication). Thus the number of glass canisters is practically proportional to the energy produced, which is the same for all the scenarios, with a rate of around 2 glass canisters per TWhe.

If the number of waste packages is the same, their heat power is quite different, according to their Am content. Considering a waste canisters' interim storage lasting 60 years before their disposal, the underground area needed by a waste package issued from SFR MOX reprocessing is decreased by ∼50% if the Am is transmuted. The reduction of the total repository area, including access drifts, compacted waste packages issued from the fuel structures compaction, or glass canisters issued from used fuel reprocessed before 2040, is smaller.

For research purposes only, we considered a unique repository for the whole duration of the scenarios. In the case of the reference scenario with no Am transmutation, its global area should be around 30 km^2. Thanks to Am transmutation (scenarios S_hom and S_ het), the area needed for the glass canister would be reduced by ∼45%, and the total repository area by 30%. If only half of the SFR's are loaded with AmBB's (scenario S_het_50%), these areas are reduced respectively by 33% and ∼25% and by 30% and 20% in case of the scenario postponing the transmutation to 2080. It must also be noticed

Table 4
Power and dose (contact and 1 m) for the fresh SFR assemblies and AmBB in 2040.

	SFR (2040)	SFR_hom (2040)	AmBB
Power (kW/assembly)	0.7	1.13	2.7
Contact dose (mSv/h)	14.8	19.3	70
Dose at 1 m (mSv/h)	0.5	0.80	2.9

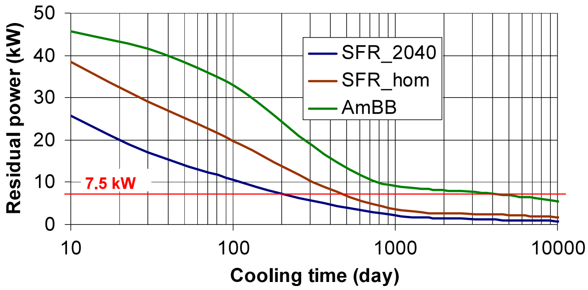

Fig. 6. Assemblies residual power evolution versus cooling time.

that the repository area reduction will be best effective at the beginning of the 22nd century, the reduction factors discussed above being obtained in the 2150 time frame.

6. Technical balance between underground actinides' management and surface actinides' management – a methodological approach

We first present here partial technical elements for the handling interfaces of AmBB assemblies between fabrication plants, the inside of the reactor vessel, the other power plant systems and the reprocessing plant. Am in fresh fuel results in increasing its power, neutron and gamma activity, hindering and complicating its fabrication and handling.

These consequences are enhanced in the case of AmBB, with 20% of Am: Am homogeneous transmutation is the option presenting the more limited impact, as illustrated by Table 4: with ∼3% of Am when the transmutation starts in 2040, the assembly power is increased by 60%, and the total dose (neutron + gamma) at the bare assembly contact by 30% (but 60% at 1 m) with respect to the SFR V2B standard fuel. Nevertheless, the shielding would have to be reinforced both for fabrication and handling, including the reception and temporary storage at the power plant, and the need to use shielded cells for the MOX fabrication will have to be carefully investigated. On the other hand, shielded cells and remote control are very likely to be necessary for the AmBB fabrication, with a dose 5 to 6 times the one of the FR MOX assembly, with also an increase of the fuel power density by a factor 6 with respect to the standard fuel. AmBB handling, transport and reception would require strong shielding measures.

Fig. 6 shows the evolution with respect to the cooling time of the power of the irradiated assemblies. Maximum power currently admitted for discharging assemblies of the core is 20 kW, but R&D work in progress increases expectations that this value will be increased to 40 kW. However, AmBB would still require 40 days of cooling before being unloaded. Before shifting the used assemblies to the reprocessing factory in a shielded cask, it is necessary to wash them, which requires a power less than 7.5 kW: it takes almost 10 years of cooling for AmBB residual power to decrease below this limit, and this should be done in an external storage tank filled with sodium so that operation of the reactor will not be hampered. This is, so far, the major costly step in the reactor facility for heterogeneous Am transmutation. In a previous paper [10], we have proposed that an external sodium storage tank should be used for increasing the lower structures inspection capabilities of an industrial prototype. It is expected that design modifications and successful R&D on visualization techniques under sodium will allow for commercial FBR's 1500_{Pu} inspection of the lower mechanical structures without the need for core unloading in an external sodium storage tank.

The feasibility of used AmBB transport over a long distance is not proven. Designing a cask even for transporting only one AmBB each time is a real technical challenge, taken into account its high level of residual power, of power density, but also of neutron emission (∼20 times the one of standard SFR V2B assemblies) which would impose to reinforce the radiological protection with the consequence to increase the difficulty to efficiently evacuate the heat and to limit the fuel clads temperature at a level ensuring their integrity. The reference solution in our heterogeneous transmutation studies is to let the AmBB assemblies cool down for 10 to 40 days inside the reactor vessel, store for ∼10 years in an external sodium storage tank, wash and then cool down in a water pool at the reactor site until transport to the reprocessing site is feasible. For a site with 2 reactors and common sodium storage, this concerns less than 200 AmBB assemblies in a time frame of 14 years.

The case of homogeneous transmutation looks easier, nevertheless the residual power is doubled, and the neutron emission multiplied by a factor of 4 with respect to a standard SFR V2B assembly. Moreover, the number of used Am transmuting

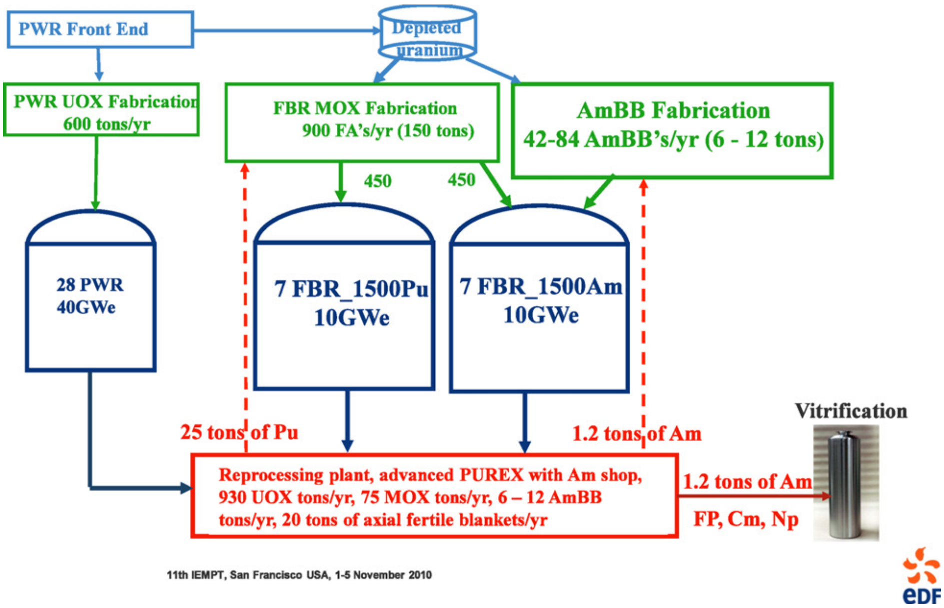

Fig. 7. Schematic diagram of the complete fuel cycle facilities in 2064 for the S_het_50% scenario.

assemblies to be handled and transported each year is more than an order of magnitude higher than in case of heterogeneous transmutation.

It is therefore evident that further R&D work is necessary to reduce the scope of the technical options even for the single S_het_50% scenario chosen to illustrate the methodology of technical and economical balance between underground repository cost reduction and above the ground extra investment. Questions raised during this technical comparison will have to be answered in the scientific and technological phases of the R&D programs. A classical example concerns the scientific milestones of the R&D programs for partitioning and fabrication:

- the partitioning of Am from a high activity solution with 100 to 200 g of Am in the back extraction solution, all other actinides being sent to the HLW stream;
- the demonstration of the fabrication capability of 10 FR pins containing each 100 to 200 g of Am.

The corresponding fabrication milestone in the technological phase is the extrapolation to several (10 to 30) fuel assemblies containing between 250 and 300 such fuel pins.

As for the repository area, Table 3 shows that a gain of 24% with respect to the S_ref scenario could be reached in the S_het_50% scenario with only half of the FR's loaded with Am, and transmutation starting in 2038. It is then theoretically possible to calculate a reduction in investment costs of the underground repository facilities induced by transmutation. On the other hand, transmutation will require investing in above the ground facilities. Economic evaluation is not possible at the present stage of transmutation research. On the other hand, and provided that the scientific feasibility of the major fuel cycle processes is achieved, it is possible to draw process flow sheets and define complexity factors for the process functions and equipments with respect to current industrial facilities of similar type. Both process flow sheets and complexity factors have to be validated in the technological feasibility phase. Taking the S_ref scenario as a reference case, one should define complexity factors for the supplementary facilities above the ground:

- the 20 FR's 1500_{Am} altered with respect to 20 FR's 1500_{Pu} in the reference S_ref scenario;
- the fabrication plant for AmBB assemblies, the reference being the FR MOX and fertile blanket plant for 40 FR's 1500_{Pu}, corrected for minor output flux differences when only 20 FR's 1500_{Pu} are used in the S_het_50% scenario;
- the modified reprocessing plants for Am partitioning and AmBB assemblies reprocessing. The reference facilities include the MOX FR reprocessing plant, operating around 2060;
- the interfaces between the 3 main functions: reactors, reprocessing, fuel fabrication in the case of AmBB assemblies.

We illustrate graphically these supplementary facilities in Fig. 7 for the S_het_50% scenario, in the 2060 time frame. We recall that the main hypothesis of this scenario is the small flux of Americium Blanket Bearing assemblies (AmBB's) in the specialized shop which will use fabrication technologies far more complex than those in actual Melox plants.

One would wish to know rapidly rough investment estimates. Even more important than those estimates which will not be known for at least 15 more years are the R&D resources which will be needed to consolidate the complexity factors and in particular investment in new R&D facilities. For the heterogeneous scenarios of Am transmutation with a limited annual flux of AmBB assemblies at the industrial scale, R&D resources should be invested first in determining through reactor experiments and post irradiation exams the maximum feasible content of Am in the AmBB assemblies. Next, R&D resources should be invested in overcoming the 7.5 kW limit of FA's residual power before sodium washing and designing long distance transport casks at high thermal load.

7. Conclusions

For a utility like EDF, the most important objective in the 2006 waste law framework is to start bringing down from 2025 onwards its glass logs produced between 1980 and 2040 with the Marcoule and La Hague vitrification processes. They amount to several tens of thousands of glass logs with several tens of tons of minor actinides. Thus reducing the waste potential radio-toxicity underground is not a repository criterion for EDF unless the French safety regulator after the advice of its standing advisory group requires it.

Several (industrial) research scenarios are studied for partial or total transmutation of Am in order to evaluate the benefits, mainly the heat load reduction in the repository and the drawbacks. Heterogeneous transmutation is preferred in research to reduce the size and complexity of AmBB assemblies fabrication plants. Reduction factors of 5 to 10 for the annual fabrication fluxes with respect to the homogeneous transmutation case are obtained. The penalty is the high thermal power of these fuel assemblies and the more difficult handling techniques at all interfaces, in particular the fuel handling system above the reactor vessel. The other power plant systems, the external facilities and the transport also have to be considered in the analysis. Projecting 2009 industrial practices with MOX fuel in PWR's, only half of a hypothetical 22nd century fleet of FR's is equipped with Am transmutation capabilities and operated in that regime. Sensibility studies are performed by shifting beyond 2080 the beginning of the Am transmutation regime.

Further R&D work is needed to consolidate the numerous technical data, to progress in the evaluation of process flow sheets for the surface facilities and to raise the power limits at critical interfaces.

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