Impact of Transmutation Scenarios on Fuel Transportation

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Abstract

Minor actinides transmutation scenarios have been studied in the frame of the French Sustainable Radioactive Waste Management Act of 28 June 2006. Transmutation scenarios supposed the introduction of a sodium-cooled fast reactor fleet using homogeneous or heterogeneous recycling modes for the minor actinides. Americium, neptunium and curium (MA) or americium alone (Am) can be transmuted together in a homogeneous way embedded in FR-MOX fuel or incorporated in MA or Am-Bearing radial Blankets (MABB or AmBB). MA transmutation in Accelerator Driven System has also been studied while plutonium is being recycled in SFR.

Assessments and comparisons of these advanced cycles have been performed considering technical and economic criteria. Transportation needs for fresh and used transmutation fuels is one of these criteria.

Transmutation fuels have specific characteristics in terms of thermal load and neutron emissions. Thermal, radiation and criticality constraints have been taken into account in this study to suggest cask concepts for routine conditions of transport, to estimate the number of assemblies to be transported in a cask and the number of annual transports. Comparison with the no transmutation option, i.e. management of uranium and plutonium in SFRs, is also presented.

Regarding these matters, no high difficulties appear for assemblies with limited content of Am (homogeneous or heterogeneous recycling modes). When fuels contain curium, technical transport uncertainties increase because of the important heat release requiring dividing fresh fuels and technological innovations development (MABB and ADS).

Introduction

Studies have been carried out on minor actinides transmutation scenarios under the French law of 2006 relating to the sustainable management of radioactive materials and waste. The recycling of minor actinides in a base of sodium-cooled fast neutron reactors has been studied, in homogeneous or heterogeneous modes or in a dedicated ADS stratum (Accelerator Driven System). The transport of minor actinides loaded elements is one of the technical issues under analysis: the feasibility of this operation shall be examined, pointing out all associated difficulties and uncertainties [1].

The first section provides a description of several minor actinides transmutation scenarios that have been defined. The following three sections deal with thermal stresses, the exposure to ionizing radiation as well as transport criticality. The last section provides a first evaluation of the annual transport requirements in routine conditions. The impact of the minor actinides transmutation has been assessed for the case without transmutation with the single uranium and plutonium recycling in fast neutron reactors.

Study approach and assumptions

Study scenarios

The scenarios only consider a French context, assuming a constant annual power production of 430 TW.h/year. After a first phase in which the reactors were partially replaced by EPR™ reactors, two deployment phases of the Generation IV fast reactors are considered, the first of 20 GWe from 2040 to 2050 and the second of 40 GWe from 2080 to 2100. The electrical potential of the fast neutron reactors under study is of each 1 450 MWe (core SFR V2B) and 154 MWe for the ADS (concept ADS Pb-EFIT for the European EUROTRANS project) [2,3]. The evolution of the nuclear power basis is simulated through the COSI code, in which the associated cycle plants capacities are also assessed [2]. The impact of the transmutation scenarios on the fuel manufacturing and spent fuel processing plants is also shown in [4].

Several minor actinides transmutation scenarios (MA) are considered. The homogeneous transmutation of americium, neptunium and curium is studied in fuel cores of the MOX type (option is called “Core Fuels Recycling”, Figure 1). The minor actinides content varies in the course of the scenario between 3.9 and 1.2% in equilibrium, where in this case the need exists for the manufacturing and recycling of 450 tons/year (2 760 assemblies yearly). The case of recycling americium alone is also considered with a maximum americium content of 2.9% during the scenario and 0.9% in equilibrium.

Another transmutation option consists in the recycling of minor actinides (MA) (or americium) in radial blankets («Bearing Radial Blankets», Figure 2). The bulk minor actinides (or americium) content is 20% with an irradiation time of 10 cycles of 410 Effective Full Power Days (or 10% with 5 cycles of 410 EFPD) requiring 29 tons/year or 244 assemblies yearly (or 75 tons/year and 522 assemblies yearly).

The minor actinides transmutation in ADS has also been studied, whereby plutonium was recycled in fast neutron reactors (Figure 3). The ADS fuel consists of plutonium and minor actinides oxides on an inert MgO type matrix (magnesium oxide). The manufacturing and recycling of 20 tons per year is required, which consists in 688 assemblies yearly with mean plutonium and minor actinides oxides contents of respectively33% and 40%.

Figure 1: Block diagram for homogeneous transmutation scenarios (MACF or AmCF)

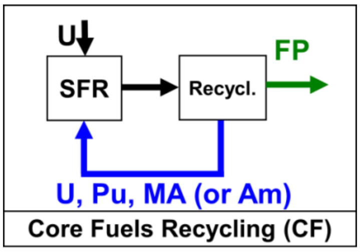


Figure 2: Block diagram for heterogeneous transmutation scenarios (MABB or AmBB)

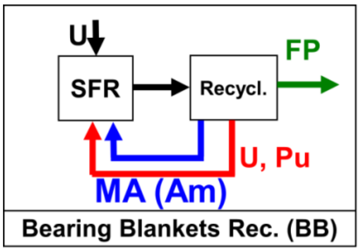
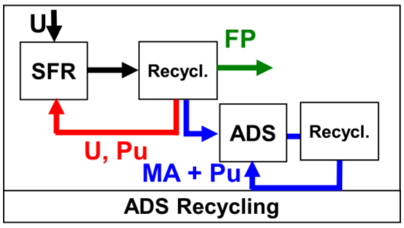


Figure 3: Block diagram with ADS stratum



Characteristics of fuels/blankets

The emission characteristics, whether thermal or neutron, of minor actinides fuels can be much more important than those of standard fast neutron reactor fuels, and even than those of pressurised water reactor fuels (UOX and MOX) which are currently manipulated. The characteristics of the fresh objects are shown in Table 1 and the characteristics of spent objects in Table 2. In the latter case, the cooling time of the assemblies may vary according to the sustained assumptions in the scenarios: this can be 5 years (a) but also reduced to 3.4 years in some cases (b). This reduction is considered necessary for certain scenarios, with the alternative to develop the reactor concept in order to have the required plutonium available for the deployment of the second fast neutron reactor phase (e.g. by using radial blankets) [1].

The most disadvantageous assemblies are those with high curium concentrations (MABB and ADS fuels). This is also valid for spent americium loaded blankets due to the great presence of curium generated by the americium transmutation.

Table 1: Characteristics of fresh fuels/blankets in equilibrium (circa 2130)

	No transmutation	Homog. Mode Core Fuels Recycling		Heterog. Mode Bearing Blankets Recycling		ADS
		AmCF	MACF	AmBB	MABB	MA
Heat Load (kW/ass.)	0.3	0.7	1.6	1.4	9.1	8.3
Neutronic Emissions (neutrons/s/ass.)	2.0E+07	3.4E+07	3.8E+09	7.1E+07	3.2E+10	1.6E+10

Table 2: Characteristics of spent fuels/blankets in equilibrium (circa 2130)

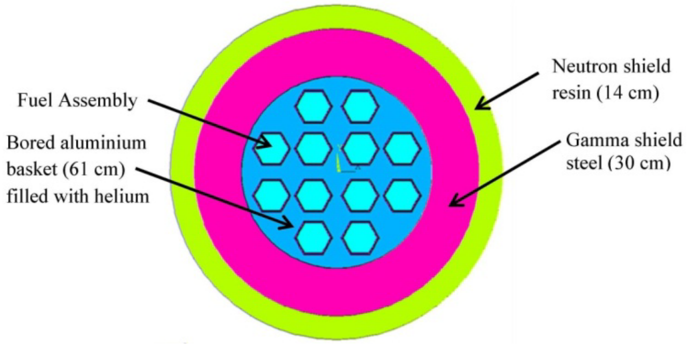
	No transmutation	Homog. Mode Core Fuels Recycling		Heterog. Mode Bearing Blankets Rec.		ADS
		AmCF	MACF	AmBB	MABB	MA
Heat Load (kW/ass.)	1.3 (b)	1.8 (b)	2.2 (b)	3.2 (a)	10.6 (a)	7.9 (a)
Neutronic Emissions (neutrons/s/ass.)	0.5E+09 (b)	1.6E+09 (b)	2.8E+09 (b)	5.3E+09 (a)	2.7E+10 (a)	1.5E+10 (a)

Study principles for transport

The feasibility of fresh and spent fuel assemblies transportation required for each transmutation scenario was studied based on the same approach. For each fuel transport a packaging type is suggested based on current concepts whereby thermal stresses, radiation protection and criticality are considered. Our study approach has not included other issues in this stage, such as mechanical resistance (assemblies' deformation), handling, containment, regulations (circulation, physical protection ...). In general, only the routine transport conditions are considered (undamaged fuel assemblies and no drop, fire, immersion or other accidental conditions). Conclusions of the study (number of fuel assembly transported per cask) would be different if these additional constraints were taken into account.

A packaging model has been defined which is used for the following calculations. This consists in a multi-layer packaging with an outer diameter of 2.13 m and a centre basket enclosing the assemblies (basket diameter of 1.21 m), and surrounded by a steel layer with a thickness of 30 cm (ensuring radiation protection), whereby this layer is covered by a 14 cm thick neutron absorbing resin layer. There is mechanical gap, especially between each assembly and the basket, as well as between the basket and the cylindrical shell: these parameters shall be discussed later as these have an impact on heat removal. Several transport capacities are considered, between one and twelve assemblies per packaging (Figure 4). Any eventual locking systems likely to reduce the number of assemblies per packaging are not considered in this analysis.

Figure 4: Schematic sectional view of a transport packaging



Thermal studies

The thermal study is aimed at defining the maximum thermal power to be removed for a fixed packaging configuration, with the restriction of not surpassing an established fuel clad temperature in order not to damage the assemblies. A modelling was performed for conductive and radiative thermal exchanges within the packaging, based on calculations with the ANSYS™ tool. In the case of multi-assemblies packaging, the same have not been modelled pin by pin due to the great amount of fuel pins, but an equivalent thermal conductivity in the assembly was considered [5]. This approach allows for the execution of parametric calculations while the most important parameters were highlighted.

It is assumed that the packaging is passively cooled by means of helium. This gas is an excellent option due to its high thermal conductivity. Sodium, in spite of its higher preference, was not opted for because of safety reasons. Also, the analysis includes the assumption that the operations to be performed in the transport are feasible, e.g. the fuel assembling in the manufacturing plant or the handling of spent fuel at the outlet of the reactor, in spite of the associated uncertainties.

An analysis was made of the impact of important parameters, such as the maximum allowed temperature for the fuel cladding, gap and material emissivity. The accepted maximum temperature for the fuel cladding depends on the material and its condition (fresh, irradiated). This is still unknown today, but the assumed range is between 450°C and 650°C for fresh assemblies and 650°C for spent assemblies, whereas the latter value is of the same magnitude as the thermal handling criteria out of sodium considered in the Phenix and Superphenix reactors [6]. This characteristic shall be determined by the chosen material of the cladding.

The mechanical gap standards for the packaging have been determined in analogy with the current transport packagings, with a 2mm gap between the hexagonal tube and the basket, and a gap of 5 mm between the basket and the shell. On the contrary, a gap reduced to zero is considered in order to identify its impact: a very significant reduced gap seems feasible and is patent-pending [7]. For the assessment of the accepted thermal power it is important to know the emissivity of the fuel cladding and hexagonal tube. Based on current knowledge of the assemblies' structures, emissivities of the hexagonal tube equivalent to 0.35 and of the fuel cladding equivalent to 0.45 are considered. Due to the importance of these properties, emissivity measurements of structure materials shall be required for optimal results.

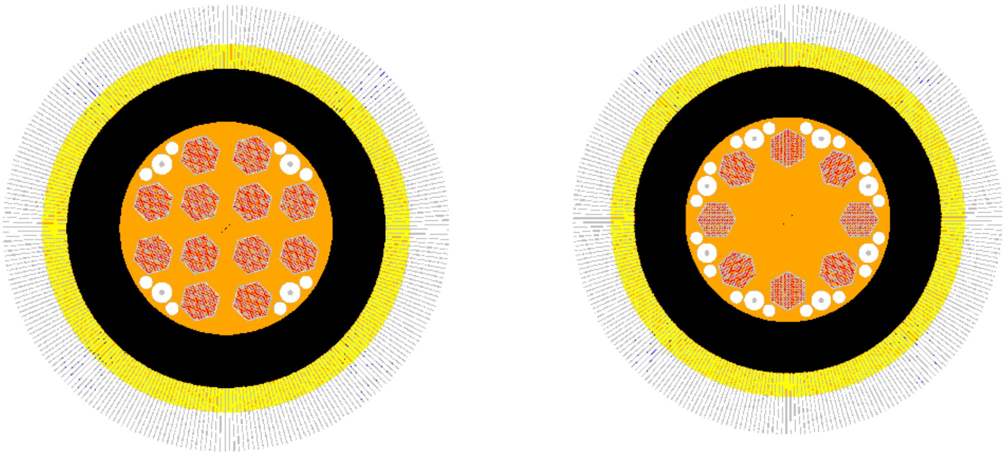
The results show that at a maximum fuel clad temperature of 450°C, the transportation of 12 assemblies with a thermal power of 2.5 kW each and with standard gap is feasible. If this value reaches 650°C, the 12 fuels must have a maximum power of 4.6 kW each. A decreased gap improves significantly the thermal constraints (respectively 3.5 and 6.6 kW). In case of one assembly transportation, thermal limit is 3.3 kW (450°C and standard gap) and can increase as far as 8.8 kW (450°C and reduced gap).

Radiation protection studies

Fuel transport must comply with regulatory dispositions with regards to ionising radiation exposure [8]. For each packaging configuration in the study, ambient dose equivalent rates were considered with regards to the fissile column and compared according to the following values: 2mSv/hr at contact and 0.1 mSv/hr at 2m from the packaging surface. Calculations were made by means of the TRIPOLI-4® code [9], in which each assembly was represented by the fissile column alone (Figure 5).

By successively considering different load types in the cask, radiation protection studies have defined the maximum number of assemblies for transportation in a packaging for each of the examined scenarios. The same have also demonstrated the impact of the basket type enclosing the fuels, as well as of the neutron absorbing resin.

Figure 5: Sectional view of a modelled packaging by means of the TRIPOLI-4® code



Basket enclosing 12 assemblies

Basket enclosing 8 assemblies

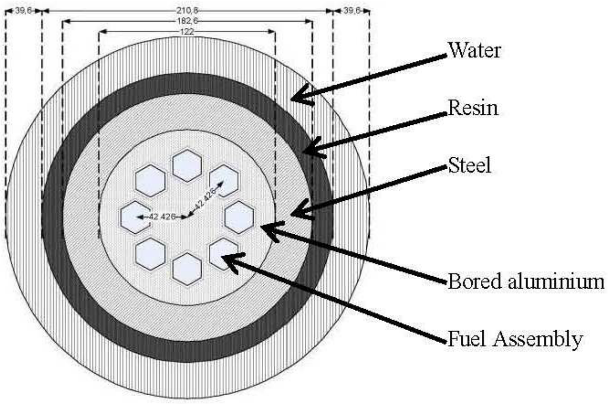
The basket of the study is made of aluminium with natural boron, although it should be evaluated whether this is feasible. With regards to the resins, the current materials may be renewed, but in view of an identical radiation protection efficiency, a material shall be selected which fits best with regards to thermal constraints due to the temperature level reached according to the transported fuels or blankets (approximately between 50 and 110°C).

Criticality study

Criticality studies have been performed in the case of fresh core fuel and ADS fuel transport, because, in a first approach it was considered that these cases would be more disadvantageous than the spent cores with regards to criticality risks. Calculations were made based upon the calculation package CRISTAL v1.2, during routine transport conditions.

The first results demonstrate that the transportation of 12 assemblies is only feasible with a guaranteed absolute absence of water in the assemblies and in the packaging, whereby this result is obtained for plutonium contents of 22% or 18%. In order to overcome such constraints (absence of water), a transport per lot of 8 with an assemblies distribution in circle is allowed (Figure 6). Also a study was performed on the transport of ADS assemblies, strongly loaded with plutonium and minor actinides, whereby a single assembly per packaging was considered. The first results show no specific constraints with regards to the presence of water or the number of fuel pins, apart from the compliance with the dimensional and media requirements.

Figure 6: Sectional view of a packaging with eight cavities



Transport results

Selected transport packaging

For each of the scenarios in the study, the selection of the transport packages was based on an iterative approach considering thermal constraints, ionising radiation exposure and criticality. The study assumed a maximum temperature of 450°C for new fuel clad, whereby the maximum temperature for fuel clad in the case of a spent blanket or assembly was not to surpass 650°C.

In the case of non-recycled minor actinides, the fresh SFR-MOX assemblies can be transported by groups of 8, in routine transport conditions. Transport with greater assemblies' number is constrained subject to criticality risk prevention.

The transportation of fresh americium loaded fuel assemblies (AmCF) used in the scenario of homogeneous americium transmutation is feasible by groups of 8. After irradiation the produced curium-244 content at 0.1% in equilibrium or 0.2% in transient phase becomes a limiting factor. The packaging capacity should be reduced to 7 in compliance with the regulatory limits for radiation exposure.

The minor actinides transmutation scenario leads to the presence of curium in the fresh assemblies (AMCF) which has a great impact on their transport. Actually, a curium content of 0.2% in a fresh assembly sets a limit due to the radiation protection criteria, resulting in the required reduction of 7 fresh assemblies in a packaging. After the passage in the reactor the objects also have to be transported by groups of 7, due to the high neutron emission.

The transport of americium AmBB loaded blankets in the heterogeneous transmutation scenario of americium alone is limited for the spent blankets, due to the exposure to ionising radiation. The transport by groups of 3 blankets is feasible.

As the curium content increases, technical difficulties become more complex. For the transport of fresh objects with a curium content of between 1.9 and 2.5% in the AMBB or with a curium and plutonium content of between 3 and 5% in the ADS fuels, the thermal emission is even prohibitive for a unit transport. The transport must be fractioned in three parts, if the maximum temperature for a fresh object cannot exceed 450°C (the fractioning level of the assembly varies according to the assumption made for the fuel clad temperature).

For AMBB blankets and spent ADS fuels the thermal emission is very high after 5 years of cooling as pointed out in Table 2. This is in excess of the value of 7.5 kW which is the threshold considered for the handling of the fuels in the reactor (the maximum allowed power for handling the assemblies is 2.5 kW, whereas research is made to increase this limit to 7.5 kW [1]). With regards to this handling constraint, an increased cooling time is thus essential: a period of 15 years would be necessary for the AMBB.

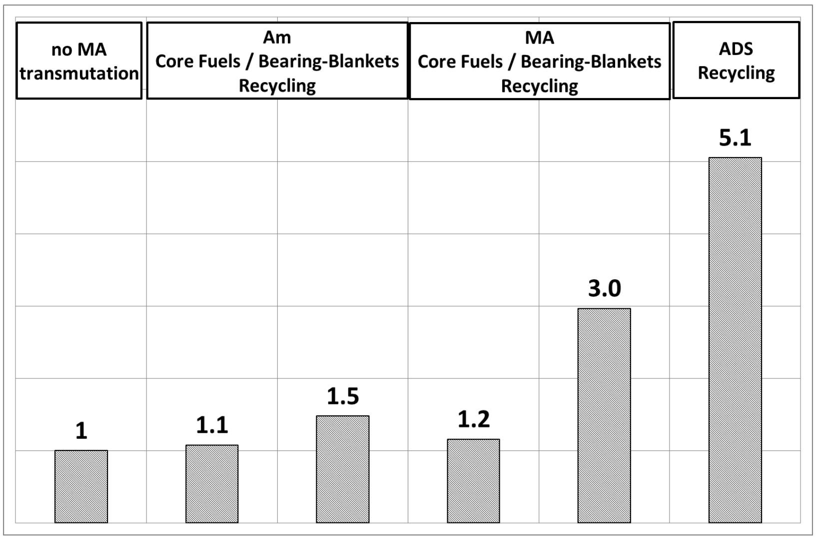
In the case of ADS fuels, a relatively low supplementary period should be considered as at the end of the scenario, the residual power is evaluated at 7.9 kW after 5 years of cooling. Even at 7.5 kW, the thermal emission remains high, imposing a unitary transport of each of the objects which requires important technological innovations for the packaging transport concept aimed at the reduction of mechanical gaps. In the absence of innovative technologies, it would be necessary to disassemble the spent fuels on each reactor into a specific cell with the implied consequences (exploitation constraints, increased costs and higher number of annual transports).

Impact of the transmutation on the number of annual transports

The analysis aims at the evaluation of the number of annual transports required for each transmutation scenario, based on the one hand, on the annual fresh fuels flux between the manufacturing plant and the reactors, and on the other hand, on the annual fuels flux between the reactors and the processing plant. It is assumed that the manufacturing and processing operations take place at the same site.

Figure 7 shows the number of annual transports assessment in equilibrium in the fast neutron reactors for each of the transmutation scenarios compared to the case without transmutation. In the latter case, the number of annual transports is 700 (fresh and spent fuels). As a comparison, today's fuel cycle balance is approximatively 200 transports per year of spent fuel (with a similar type of cask, class B). The homogeneous americium or minor actinides transmutation has nearly no impact on the annual transport quantity with a ratio of 1.1 or 1.3. The heterogeneous americium transmutation only results in a minor increase of the transport compared to the case without transmutation (ratio of 1.5). The impact of the transmutation on the transport item is clearly more significant with the increase of the curium content: the annual transport flux increases three-fold in the case of heterogeneous minor actinides transmutation and five-fold for ADS fuels.

Figure 7: Assessment of number of annual transports



While there were no technical difficulties in the americium transmutation scenarios (homogeneous and heterogeneous), this is no longer true for the fuel assemblies or blankets containing curium. It becomes more uncertain due to the quite significant thermal emission requiring either the fractioning of the fresh objects or the development of innovative packaging technologies related to thermal exchanges (MABB and ADS fuels). For each scenario in the study, the annual number of transports has been considered for the cost assessment in this item, which, although of little importance, has been integrated into the cost assessment of the transmutation. [1,10].

Conclusions

This study constitutes a first analysis of the transportation of assemblies in the case of minor actinides transmutation scenarios. Although only routine transport conditions have been considered, this study provides quantitative elements with regards to the feasibility of fresh and spent assemblies transport within the framework of minor actinides transmutation scenarios.

In the case of curium containing fuels, transport uncertainties exist with regards to the significant thermal emission requiring the fractioning of fresh assemblies and the development of innovative technologies (in the case of MABB and ADS). Compared with fuels containing curium, there are no high difficulties with regards to assemblies with limited americium content in the case of homogeneous and heterogeneous recycling. Studies on americium contained fuels, however, should be detailed so as to guarantee the industrial feasibility of their transportation.

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