ANNEX XXIII

A FRENCH STUDY ON RADIOACTIVE WASTE TRANSMUTATION OPTIONS

XXIII-1. SUMMARY

In the frame of June 28th, 2006 waste management French Act, it was requested to obtain at the end of 2012 an assessment of industrial perspectives of partitioning and transmutation of long-lived elements. These studies were carried out in tight connection with GEN-IV systems development.

The results include the technical and economic evaluation of fuel cycle scenarios along with different options for optimizing the processes between the minor actinide (MA) transmutation in fast neutron reactor, their interim storage and geological disposal of ultimate waste. The results are analyzed through several criteria.

These scenario evaluations take place in the French context where the deployment of the first Sodium-cooled Fast Reactor (SFR) is considered in 2040. By this date, the SFR technology should be mature. Several management options of minor actinides have been studied:

- Plutonium recycling in SFR (minor actinides are sent to waste);
- Plutonium recycling and minor actinide (or Am alone) transmutation in SFR in homogeneous mode (minor actinides are mixed with reactor fuel);
- Plutonium recycling and minor actinide (or Am alone) transmutation in SFR in heterogeneous mode (putting minor actinides in radial blankets on depleted UO_2 matrix);
- Plutonium recycling in SFR and minor actinide transmutation in Accelerator-Driven-System (ADS).
- The criteria used for analysis of scenarios mentioned above should consider technical and scientific aspects, requirements for potential industrialization and public acceptance. They are listed below:
- Inventories and characterization of materials and waste;
- Impact on the waste repository (footprint, safety, etc.);
- Impact on the industrial facilities (reactors, fabrication plant, reprocessing plant, interim storage) and transportation needs;
- The impact on radiological exposure of the public and workers;
- Economic impact;
- Industrial risks.

This Annex presents an overview of the main outcomes of this study and the related assumptions made for the calculations.

XXIII-2. INTRODUCTION

The research conducted in this area is governed by the French Act of 28 June 2006 on the sustainable management of radioactive materials and waste. In Article 3, the act stipulates “an assessment of the industrial prospects of separation and transmutation systems for long-lived radioelements by 2012”.

This legal requirement was detailed in the Decree from 16 April 2008 setting the requirements for the National Plan for Radioactive Material and Waste Management (PNGMDR) which calls for the CEA to coordinate the research conducted on the separation-transmutation of long-lived radioelements. The decree recalls that a file reviewing this research would have to be submitted by the end of 2012, and states that it must include "the results of technical and economic scenarios investigation taking into account the possibilities of optimisation of long-lived high-level waste transmutation processes, their interim storage, and their disposal in a geological repository".

With this in view, the CEA set up a working group called GT-TES (Technico-Economic and Scenario Working Group) including EDF and AREVA, in order to identify the scenarios to be investigated and to develop a method to assess the impact (advantages and disadvantages) of implementing these scenarios, and particularly their technical and economic impact on industrial facilities. The GT naturally relied on ANDRA in the areas concerning geological waste disposal.

This paper is a summary of the work that the group has completed this far.

XXIII-3. SCENARIOS INVESTIGATED

In a first phase, a decision was made to select contrasting material management scenarios in order to highlight the advantages and drawbacks of the various methods considered, and to identify the major trends. It must be pointed out that these scenarios have been designed to assess the options and not to attempt to describe the final industrial reality. The assumptions connected with these scenarios are based on industrial experience transferred as effectively as possible to these new material management options; they do not preclude any future process and technological developments.

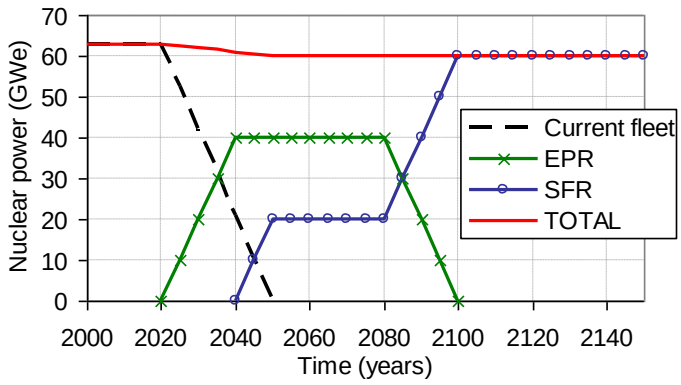


FIG. XXIII-1. Production by reactor technology.

All of the scenarios analysed in this first phase include the consideration that the current series of reactors would be renewed at constant installed capacity (60 GW(e)) generating 430 TW(e)h/year. 40 GW(e) of light water EPR^{TM}-type reactors would be deployed between 2020 and 2040, followed by 20 GW(e) of sodium fast reactors (SFR) between 2040 and 2050, see Fig. XXIII-1. The date of 2040 corresponds to a general hypothesis of a possible start of deployment of these SFRs which would also be consistent with the main renewal dates for power reactors and fuel cycle plants. The introduction of second series of 40 GW(e) SFR would take place from 2080 to replace the EPR^{TM} which by then will have reached the end of their service life. Starting in 2100, nuclear power generation capability would consist entirely of fast reactors.

Among the scenarios considering the deployment of SFRs, several differentiated alternatives have been selected:

- Recycling of plutonium only (scenario F4);
- Recycling of plutonium and transmutation of all or part of the minor actinides in homogeneous mode:
  - of all minor actinides (scenario F2A);
  - of americium alone (scenario F2B).
- Recycling of plutonium and of all or part of the minor actinides in heterogeneous mode in radial blankets:
  - of all minor actinides (scenario F1G);
  - of americium alone (scenario F1J).
- Recycling of plutonium in SFR and transmutation of minor actinides in a dedicated ADS stratum (scenario F7).

The SFR core concept considered has been developed by the CEA and French partners [XXIII-1 and XXIII-2].

The ADS model selected is the one designed for the EUROTRANS project (ADS Pb-EFIT) [XXIII-3].

XXIII-4. ASSESSMENT CRITERIA

Assessment criteria must take into account the standpoint of all the actors (scientists, industry, politicians, public, etc.), must not be redundant, and must form a coherent holistic set that is as robust as possible. The methods applied involved grouping all the questions of various stakeholders by a number of key points, and then, in a second phase, defining the indicators that serve to answer these questions. The questions are summarized and set forth as follows:

- What are the inventories and characteristics of the materials and waste produced under various scenarios?
- What is the impact under various scenarios on the features of the installations (reactors, plants, storage facilities) and the transport requirements?
- What is the impact under various scenarios on geological disposal? (geological disposal occupancy, safety, etc.)
- What is the impact under each scenario on the radiological protection of public and workers?
- What is the economic impact under each scenario?
- What is the industrial inherent risk under each scenario?

(Expertise, maturity and progressiveness of technologies introduction, flexibility of the technologies faced with potential changes in context …).

XXIII-5. SCENARIO OUTCOMES

XXII-5.1. Inventory

Contrary to a system of water cooled reactors, which inevitably produces increasing amounts of plutonium (reaching 1600 tons in 2150 for 60 GW(e) PWR fleet working on UOX fuel), a system of plutonium recycling SFR would stabilise the Pu inventory at a level of about 900-1000 tons. Stabilisation implies that SFRs operate on a break-even core, i.e., that they produce as much plutonium as they consume.

XXIII-5.1.1. Main results at equilibrium and interim period

At equilibrium period, in the case of recycling Pu alone in SFRs without MA transmutation, the minor actinide content in the irradiated fuel is about 0.4% (compared to about 0.1% in PWR-UOX fuel).

Transmutation of MA requires considering, at equilibrium:

- a content of about 1.2% of MA in the fuels in the case of transmutation in homogenous mode; in this case all the SFRs are involved; or
- one row of radial blankets containing 20% of MA in 75% of the reactors of the system; or
- the deployment of 18 ADS of 385 MW(th) in case of transmutation in dedicated reactors (an ADS with a higher power could certainly lead to more attractive performance).

Transmutation of Am alone requires at equilibrium in all SFRs:

- a content of about 0.8% in homogeneous mode; or
- one row of radial blankets containing 10% of Am .

The interim period proves to be more restrictive, because the quantity of MA to be transmuted and the number of fast reactors available are not necessarily matched. This is the case in particular between 2040 and 2080. This means that:

- in homogenous mode, having to significantly exceed the limit of 2.5% of minor actinides in the fuel ;
- in heterogeneous mode, considering two rows of blankets containing 20% of actinides until around 2100.

These results are conditioned by the assumptions made in the scenarios, and in particular the limitations associated with them. Hence, they demand further optimisation of the interim phase to try to smooth the peaks encountered which dimension the fuel cycle installations [XXIII-4].

XXIII-5.1.2. Plutonium availability

If the deployment of the first wave of SFR from 2040 raises no problem, it is important to anticipate the reprocessing of the spent fuel (cooling time reduced to 3.4 years instead of 5 years) or to alter the reactor concept in order to extract the plutonium required to deploy the second wave of SFR (using radial blanket, for example).

In these conditions, the deployment of a SFR reactor system as described in these scenarios appears feasible.

The deployment of ADS reactors is facing a plutonium deficit of about 40 tons. Loosening the limitations applied to the scenario would probably help circumvent this difficulty. Two alternatives can be examined, i.e. reducing the fuel cooling time and/or larger number of fertile assemblies.

XXIII-5.1.3. Inventories of minor actinides

– Inventory of MA in waste

The transmutation of MA helps considerably to limit their quantity in waste, because with the exception of minimal losses they are no longer automatically sent to waste.

If the non-recycling of MA means the continuous increase of their waste inventory (to reach nearly 400 tons in 2150), the transmutation of all the MA helps stabilize this inventory at around 60 tons regardless of the transmutation mode selected (homogeneous, heterogeneous or ADS). Between these two extremes, the transmutation of Am implies a moderate increase in the waste inventory due to curium and neptunium: the value that would supposedly be reached in 2150 is about 150 tons.

– Inventory of MA in the cycle

The immediate consequence of implementing the MA transmutation option is the increase of the MA quantities in the cycle inventory, as shown in Fig. XXIII-2. It should be noted that here the term “cycle” refers to all the installations of the nuclear fuel cycle where actinides are present (fuel fabrication plant, reactor, reprocessing plant, spent fuel storage). The not recycled part of MA inventory is considered to be waste and the sum of recycled and waste parts of MA constitutes the overall MA inventory. In the case of ADS, the high level of inventory in the cycle is explained as follows: although the reactor inventory is comparable with the transmutation in SFR, the short duration of the irradiation cycle due to the low power of ADS makes the inventory outside of the reactors (7 years: reprocessing + fabrication) proportionally larger. This term is considered dominant here.

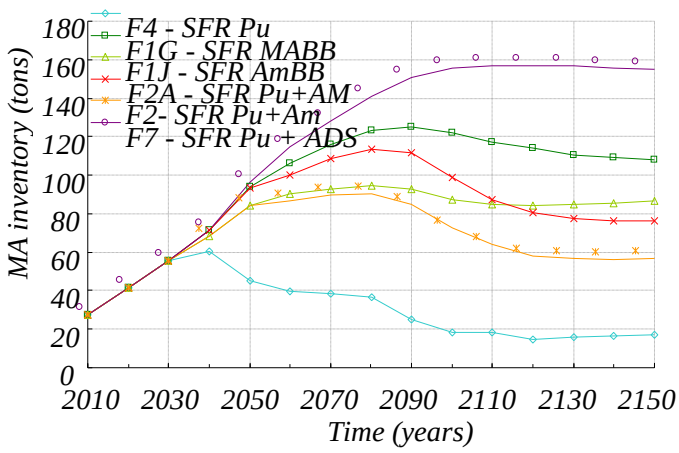


FIG. XXIII-2. Inventory of minor actinides in the fuel cycle.

XXIII-5.1.4. Scenario optimization

Transmutation in homogeneous mode:

The technical feasibility of the homogeneous transmutation remains limited to about 2.5~3.0% of MA if the design of SFR reference core with acceptable impact on reactivity coefficients is adhered to [XXIII-2]. Optimization of reprocessing strategy allows to limit the maximum MA content loaded in reactors: PWR MOX fuel assemblies are reprocessed over a longer period thus are more diluted, and since all fuels are reprocessed in "last-in-first-out" mode, the cumulated ^{241}Am production is reduced. Those changes lead to keeping the MA content below 2.5% during the transient period of SFR deployment (see Fig. XXIII-3). The same optimization gives a relative reduction of Am content (maximum is 2.0%) for the scenario with only Am transmutation [XXIII-5].

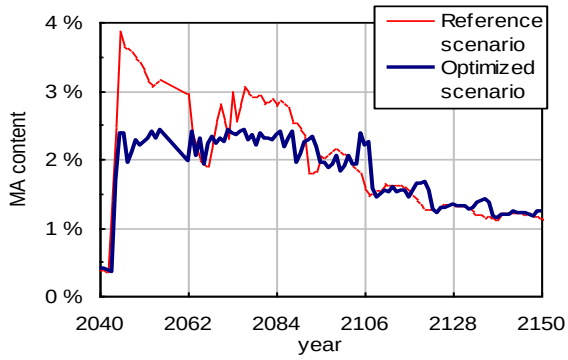


FIG. XXIII-3. Evolution of the MA content in fresh fuel.

Transmutation in heterogeneous mode:

The scenario has been optimized:

- By optimizing the reprocessing strategy (identical to the homogeneous case, see previous chapter);
- By reducing both initial Am content (from 20% to 10%) and irradiation time of AmBB (from 10 cycles to 5 cycles of 410 effective full power days (EFPD), which is the same duration as in standard fuel) to increase loading frequency. This allows to reduce Cm build-up and consequently fuel decay heat.

It remains possible to use only one AmBB row with 10% Am in the optimized scenario. The thermal power of fresh AmBB is divided by 2, although Am inventory in fuel cycle is higher as illustrated: 115 tons at equilibrium instead of around 80 tons for the reference scenario. In our study, this new scenario is called "scenario F29" [XXIII-5].

XXIII-5.2. Impact on waste

CEA asked the French national radioactive waste management Agency (Andra) to assess the impact of high and intermediate level waste as produced by various transmutation options on the size of a geological repository. Andra used repository architecture similar to that employed in the Cigéo project which is under development for current NPPs. Results allow to compare the underground footprint and the excavated volume for three scenarios (F4, F1G and F1J). The impact of the interim storage duration is also assessed. Solutions are

proposed to optimize the footprint of the repository. An analysis of the advantages and drawbacks of transmutation options is provided [XXIII-6, XXIII-7].

HLW and ILW-LLW are disposed of in separate underground zones. This arrangement offers independence in terms of (i) management of the various types of waste and (ii) phenomenological behaviour of each zone, in view of the specific characteristics of the waste type.

The repository cells are constructed progressively with waste emplacement according to a modular architecture which provides for a strict separation between mining and nuclear activities.

The underground facility includes (Fig. XXIII-4):

- a common infrastructure built prior to the operational phase of the repository;
- a disposal zone for ILW-LLW
- a disposal zone for HLW.

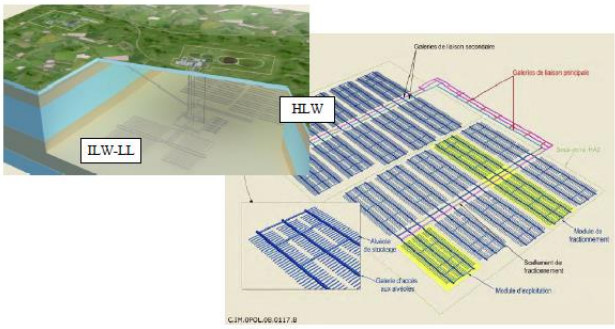


FIG. XXIII-4. Potential layout of the repository.

In the F4 scenario, the first study phase concluded that an increase of the interim storage period from 70 to 120 years would provide a gain of 25% on the footprint of the HLW zone and 7 % on the total excavated volume. The presence of americium in the waste restricts the densification of the repository because of a relatively slow decay of the thermal power due to the long radioactive half-life of americium-241.

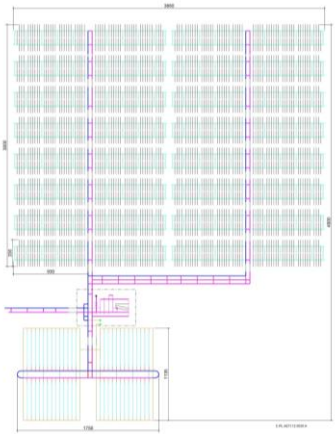
In the case of transmutation of all minor actinides (F1G), the increase of the interim storage period to 120 years allows a larger gain (60%) of the footprint of the HLW zone and 12% of the overall volume excavated.

Based on the results of the first study phase, the second study phase consisted of research of possibilities for the design optimization with the objective of decreasing the repository footprint more drastically. This second phase has considered only an interim storage period of 120 years for HLW. Indeed this assumption connected with transmutation scenarios provides a significantly higher gain than a 70 years interim storage period.

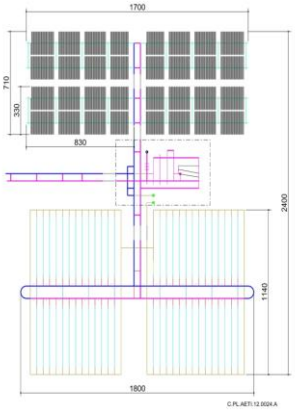
Figure XXIII-5 shows the repository layout as a result of this study.

As compared to the multi-recycling of plutonium in SFR, the transmutation of MAs connected with repository design optimization would provide:

- a reduction by a factor from 7.3 (Am) to 9.8 (MAs) of the footprint of the HLW disposal zone after an interim storage period of 120 years;
- a total reduction by a factor 3 of the repository footprint taking into account ILW-LLW and common infrastructures;
- a total reduction by a factor 2 of the excavated rock volume.



Without transmutation (F4)



Transmutation of MA (F1G)

FIG. XXIII-5. Underground repository architecture with an interim storage period of 120 years.

Along with a footprint reduction for the HLW disposal zone, the partitioning and transmutation of actinides also decrease the duration of the thermal phase. After an interim storage period of 120 years, the thermal phase is reduced to about 200 years, compared with 1000 years without transmutation.

The partitioning and transmutation of actinides do not reduce the long-term radiological impact of deep geological repository which is dominated by long lived fission and activation products (APs) with higher mobility in the geosphere (iodine-129, chlorine-36).

Under the normal long-term safety evolution scenario, the study shows that the repository densification as allowed by partitioning and transmutation does not significantly change the radiological impact of fission and activation products, despite their concentrations increase in the near field with densification.

In an altered evolution scenario such as one involving intrusive drilling, the impact of FPs and APs may increase to some extent because of the repository densification. Nevertheless this impact remains acceptable with regard to the dose limit provided by the basic safety guide issued by the French nuclear safety authority (0.25 mSv/year).

XXIII-5.3. Impact on the cycle facilities

XXIII-5.3.1. Impact on manufacturing

Powder metallurgy processes comparable to that employed in the MELOX plant can be regarded for the fuel manufacturing. Such processes include successive steps involving powder preparation, manufacture of pellets via lamination and sintering, manufacture of rods and installation of the sub-assemblies. Nevertheless, the presence of minor actinides requires reinforced shielding systems (from neutron emission and gamma radiation). Furthermore, due to the heat released by radioactive materials specific provisions should be made for controlling temperatures during the manufacture of minor actinide-bearing sub-assemblies. However, as americium and the mixture of minor actinides are less hazardous than plutonium, the criticality risk control, that can be implemented through customary control procedures, is not problematic.

Table XXIII-1 compares the thermal power and neutron emissions of the oxide powders used for fuel manufacturing. These values are standardized with respect to the SFR fuel without minor actinides.

TABLE XXIII-1. THERMAL POWER AND NEUTRON EMISSION OF POWDERS DURING MANUFACTURING (AT EQUILIBRIUM)

		MA transmutation			Am transmutation	
	F4	F2A	F1G	F7	F2B	F1J
Fuel	Fr-core	Fr-core	MABB	ADS	Fr-core	AmBB
Thermal power (W/kg)	1.5	9	55	160	3	7
Neutron emission (relative value)	(1)	(120)	(1600)	(3500)	(1.4)	(3)

It is clear that the scenarios involving the transmutation of all MA are extremely impeded by the presence of curium and particularly of the ^{244}Cm isotope. The fuel manufacturing would obviously require the construction of a shielded enclosure with remote-controlled devices. With high Cm content, development of a completely new technology will be required (more relevant for ADS option). The scenarios with transmutation of Am are less restrictive for manufacturing operations [XXIII-8].

XXIII-5.3.2. Impact on the reprocessing

Minor actinide-bearing sub-assemblies are processed in facilities designed for different types of spent fuel to be recycled (UOX, MOX, SFR). Reprocessing operations are assumed to be based on the hydro-metallurgy processes as those at La Hague, including reprocessing of ADS fuel that can be done by pyro-metallurgy. The reprocessing facility is divided into workshops. Most of the workshops are dedicated to separation of nuclear material from metal structures by placing it into solution, to separation of chosen elements via extraction with solvents, to conversion of separated elements into oxides and to conditioning of structural waste and fission products.

The scenarios including the transmutation of MA naturally involve the implementation of process for chosen elements separation. According to these scenarios, this process may involve a sequential separation (DIAMEX-SANEX), where the actinides are recovered separately, combined separation (GANEX) where plutonium and MA are extracted together, or individual separation (EXAM)where Am can be recovered selectively. All of these processes are still being developed. Their feasibility has been demonstrated at the laboratory scale, however, their industrial implementation still requires a sufficient amount of R&D.

Studies on reprocessing facilities for core fuels recycling (MA or Am) or bearing blankets recycling (MA or Am) do not show significant difficulties. But scientific and technical feasibility has to be investigated for ADS spent fuel.

Criticality constraints have been analysed in preliminary studies: additional analysis is required for specific functions such as conversion of product containing curium. Thermal and radiation constraints have also been considered: the controlling systems and biological shielding are to be reinforced, particularly during the minor actinide conversion [XXIII-8].

XXIII-5.3.3 Impact on transport

The heat released by new or spent actinide-bearing sub-assemblies can be a problem for transportation between the reactors and the fuel cycle plants (Table XXIII-2).

TABLE XXIII-2. THERMAL POWER OF NEW AND SPENT SUB-ASSEMBLIES (EQUILIBRIUM WILL BE REACHED AROUND 2130)

		MA transmutation			Am transmutation	
	F4	F2A	F1G	F7	F2B	F1J
Fuel	Fr-core	Fr-core	MABB	ADS	Fr-core	AmBB
New S/A, kW/assembly	0.3	1.3	9	7	0.6	1.3
Spent S/A, 5 years, kW/assembly	1.3	2.2	11	7	1.8	5

Therefore, impact of transmutation scenarios on fresh and spent fuels annual transportation has been evaluated. Thermal, radiation and criticality constraints have been taken into account in order to propose cask concepts for normal conditions as shown in Fig. XXIII-6.

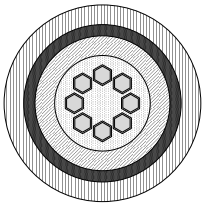


FIG. XXIII-6. Example of a cask concept for 8 S/A.

No difficulties appear for Am transmutation scenarios (homogeneous or heterogeneous). With curium in fuel, transport uncertainties increase because of significant heat release requiring fresh fuel separation and technological innovations development (MABB and ADS).

The number of canisters to be transported and the number of transport journeys required are significant factors for the scenarios assessment (Fig. XXIII-7), see reference [XXIII-8].

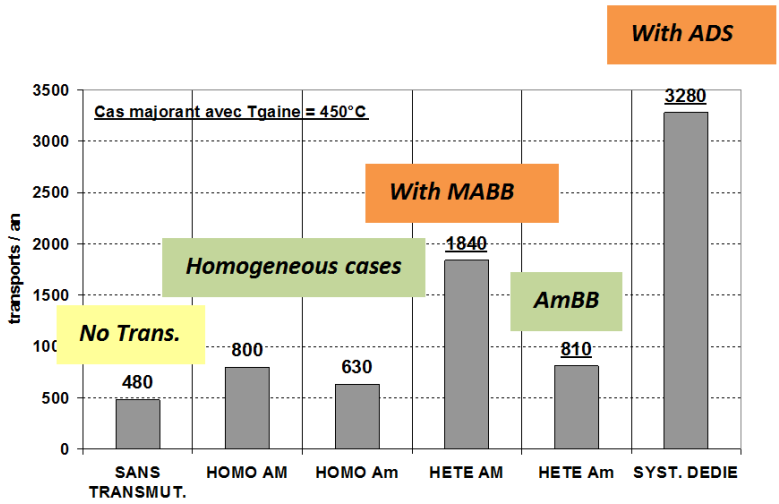


FIG. XXIII-7. Annual transport operations with fresh and spent fuel.

XXIII-5.4. Impact on the reactor

XXIII-5.4.1. Impact on the core

The homogeneous transmutation process will decrease the safety coefficients of the core more or less significantly according to the minor actinide content. A limit of 2.5 % is generally accepted for a large SFR core [XXIII-2].

In the case of the heterogeneous transmutation (MABB and AmBB), the MA to be transmuted are introduced on the periphery of the core and, even in case of its high content, their impact on the reactivity coefficients remains marginal.

XXIII-5.4.2. Impact on the fuel handling

A special biological shielding or cooling system will probably be necessary for handling sub-assemblies containing MA and particularly MABB.

The handling of spent sub-assemblies is greatly affected by their residual power. At present, there are two limits:

- For unloading S/A out of the reactor vessel, the maximum acceptable power amounts to 7.5 kW in case of gaseous environment (possible solution for the European Fast Reactor) or 20 kW in case of liquid sodium coolant being used (as in case of a transfer bucket such as on Phénix or Superphénix). Research studies have been conducted based on the possibility of increasing the last value to 40 kW;
- Concerning the S/A underwater storage, it will be necessary to clean them beforehand in order to remove all traces of sodium. At present, the maximum power for cleaning is 2.5 kW. Research work is being performed to reach 7.5 kW.

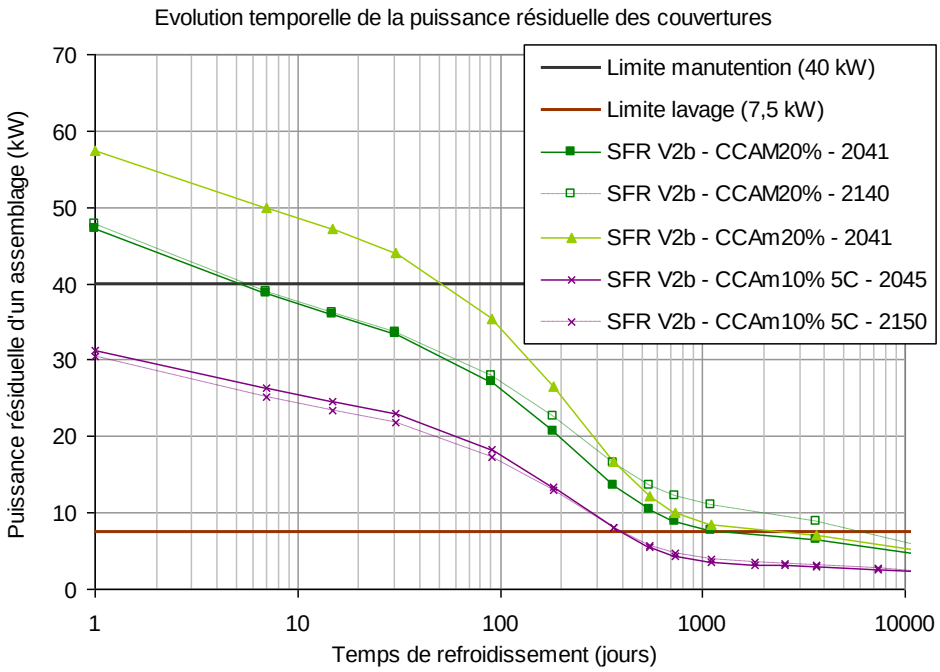


FIG. XXIII-7. Residual power of spent sub-assemblies.

Figure XXIII-7 clearly shows the impact of the MA bearing blankets implementation. Even considering a transfer in sodium, the AmBB with 20% of Am could not be unloaded out of the reactor vessel before approximately fifty days. Therefore, providing a storage area inside the vessel appears to be a compulsory requirement.

Cleaning of the MABB and AmBB with 20% of MA or Am could not be envisaged at least for 15 and 7 years, respectively, or probably later since the uncertainty concerning residual power has to be taken into account. This means that an intermediate storage area (outside of the reactor vessel) in sodium is necessary and must be sized accordingly.

The optimization of the AmBB concept as explained in paragraph 1.4 allows to reduce these drawbacks (AmBB, 5 cycles instead of 10 cycles with 10% of Am). In this case, there will be no technical impact on the reactor vessel.

XXIII-5.4.3. Impact on the external storage

The external storage is a buffer used to store the new assemblies temporarily before loading and to store the spent assemblies while waiting for their decay heat to become compatible with the washing device. The size of the external storage depends on precise knowledge of the decay heat of spent fuel assemblies and on the allowable power of the washing device. To account for these different uncertainties, two wrapper values were chosen for the washing device power: 7.5 and 4 kW. With this hypothesis and with the value of the decay heat (see Fig. XXIII-7), the size of the external storage and the cooling delay for different types of assemblies can be defined. The results are given in Table XXIII-3.

The size assessment of the external storage shows the impact of both decay heat and washing device, especially in the case of low, allowable power of the washing device. In the worst case, it would be necessary to wait for 60 years before washing, which reveals the very long life time of the external storage of about 120 years that includes 60 years of reactor life time plus 60 years of the last fuel assemblies cooling [XXIII-9].

TABLE XXIII-3. MAIN FEATURES OF THE EXTERNAL STORAGE

Allowable power of washing device	7.5 kW		4 kW	
Fuel	years	Number of positions	years	Number of positions
Only Pu fuel	0.5	242	1.2	362
AmBB 20%	7	310	60	928
MABB 20%	15	382	60	928
AmBB 10%	1.1	248	3	572
Homogeneous MA/Am (at equilibrium)	0.6	242	1.5	543

XXIII-5.4.4. Impact on reactor availability

The introduction of minor actinides leads to an increase in the number of actions during refuelling, such as reshuffling or increasing movement of the MA assemblies. Therefore, the reactor availability is slightly reduced. Results of the handling time assessment with the CEA

tool OCTET showed its increase by one equivalent day at every reloading operation. As the opening-and-closing time is 400 days, the availability is reduced by 0.25% [XXIII-9].

XXIII-6. ECONOMICS

The purpose of these studies is not to raise issues about the economics of the nuclear industry in France and in the world. Therefore, providing power production costs in absolute terms is meaningless, as these depend on the particular industrial and marketing conditions under which the plants will be constructed. Besides, several fuel cycle related processes will need new technology development and subsequent industrial assessment, which increases cost evaluation difficulties. Comparing production costs in relative terms appears to be sufficient for the task conducted in this paper which consists of a simple inter-comparison analysis of different scenarios.

The comparison of the levelised costs of electricity per MWh for each scenario is planned to be carried out when the equilibrium is reached (when a total SFR fleet is deployed). For the computation of cycle costs in the levelised cost of electricity per MWh, each step of nuclear fuel cycle (front end and the back end) was taken into account. For each step, the unitary cost and, for discounting purposes, the time interval in regard to the fuel irradiation time were evaluated.

Two sets of discount rates have been chosen in order to assess the results sensitivity to this parameter:

- The first case is representative for a “private estate” economic approach. The discounting is performed with a rate of 8 % over the first 30 years and 3 % afterwards [XXIII-6];
- The second case corresponds to a “public” or “public interest" economic approach. The discounting is performed with a rate of 4 % over 30 years, which then decreases to 2 %.

In the first approach (referred to as approach A) economic calculations were carried out with a unit cost database for reactors and cycle operations. In this database, the operating costs are assessed similarly to those of existing facilities while assuming advanced cost-saving methods use. The second approach (referred to as approach B) does not account for the advanced developments considered in approach A due to the fact that they might not provide suitable industrial solutions (due to modified regulations, for instance). Furthermore, approach B is based on hypotheses which are much more cautious in relation to certain major parameters (which are not clearly understood) such as, e.g., the plant availability factor (Kd).

XXIII-6.1. Results of approach A

Table XXIII-4 presents the average production costs for the different scenarios. An index of 100 has been allocated to the average production costs for 2120-2150 (representative of the fleet at equilibrium) of scenario F4 (without any transmutation). The index 100 does not represent the same value for the two sets of discount rates.

TABLE XXIII-4. STANDARDIZED PRODUCTION COSTS (RELATIVE UNITS)

Scenarios	Discounting rate of 8%-3%		
	Total	Reactor	Cycle
Without MA	100	94	6
Heterogeneous all MA	106	96	10
Heterogeneous only Am (20%, F1J)	104	95	9
Heterogeneous only Am (10%, F29)	105	95	10
Homogeneous all MA	108	95	12
Homogeneous Am	105	95	10
In ADS	126	116	10
Scenarios	Discounting rate of 4%-2%		
	Total	Reactor	Cycle
Without MA	100	91	9
Heterogeneous all MA	107	92	14
Heterogeneous only Am (20%, F1J)	105	92	13
Heterogeneous only Am (10%, F29)	107	92	15
Homogeneous all MA	109	92	17
Homogeneous Am	106	92	13
In ADS	124	110	14

With the selected hypotheses, approach A shows that:

- The cost overrun related to the transmutation in SFR would amount to around 4 to 9 % overall. As for the cycle alone, cost overruns could reach 50 to 60 %. However, the cost overrun for the reactor item would not exceed 2 %;
- There would be no large distinction from an economic viewpoint between the homogeneous and heterogeneous transmutation options;
- Only the transmutation in the ADS could generate a significant cost overrun of around 26 %.
- It has also been observed that the relative order of merit of the scenarios is only slightly affected by the choice of discount rate due to the fact that the cash flow chronologies are very similar for different scenarios.

A sensitivity study indicates that the most important items are SFR investment and operating costs, and then to a lesser degree, fuel reprocessing and manufacturing costs. The same conclusions apply to the 4%-2% discounting rate.

XXIII-6.2. Results of approach B

The economic calculations have been modified and more penalizing values have been used, particularly concerning the items which have been identified as important in the sensitivity analysis. Different values have been chosen compared to approach A for three types of reasons:

- There are technical divergences leading to different cost assessments;
- There are different philosophies, particularly concerning future requirements regarding safety and radiation protection. It is assumed that the technological developments will not be able to deal with such matters;
- There is a greater caution concerning certain aspects which are not clearly understood at this stage (Kd, etc.).

Figure XXIII-8 compares the results of Approaches A and B.

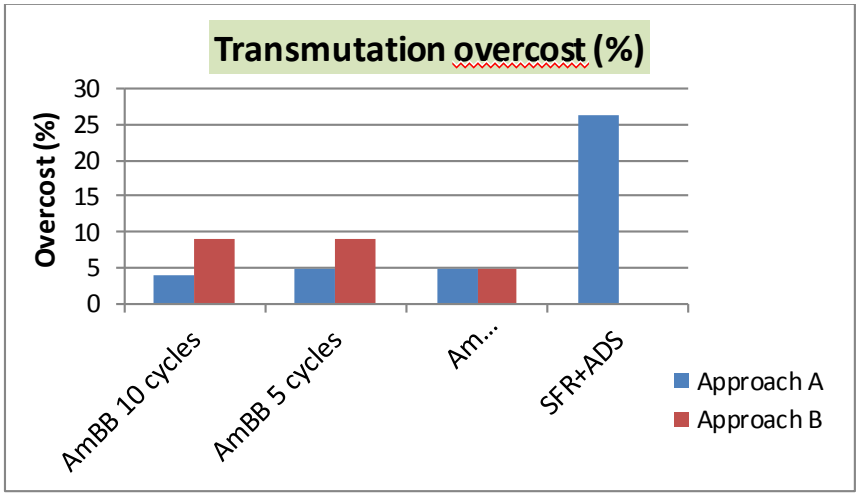


FIG. XXIII-8. Transmutation overcost between approaches A and B.

The cost overrun related to the transmutation in SFR would amount to around 4 to 9 % overall and around 26% in the case of ADS. So, except ADS, the economy is not very discriminating for the transmutation option.

XXIII-7. TECHNOLOGICAL MATURITY, FLEXIBILITY, PROGRESSIVITY

All of the scenarios described in this paper refer, to various degree, to processes or technologies which have not been implemented industrially at present or, in some cases, are still concepts.

The maturity of the processes and technologies to be implemented in the different scenarios is a major parameter which is required for understanding technical and economic risks related to the different options. Nevertheless, risks will be limited if the selected options provide sufficient flexibility and if new technologies are implemented progressively. For

instance, processes which are continuously updated through successive addition of new functions involve less risks than processes requiring dedicated facilities, which are, in most cases, not easily adaptable to new options.

It is obvious that these risks will be all the more high as the technologies employed will not be mature. This is the case for the scenario involving the transmutation of minor actinides in ADS. Although significant progress has been made regarding the feasibility demonstration, ADS are complex systems which development requires the design of high-technology components and which feasibility cannot yet be guaranteed.

For all of the scenarios described in this report it is assumed that the 4th generation SFRs will be implemented as from 2040. The feedback from fifteen years' expected experience with the ASTRID prototype operation would contribute to gaining technological maturity for SFR and fuel multirecycling. Furthermore, the experience which has already been gained with this type of reactor can be used today to improve the understanding of the uncertainties remaining in this field, which will certainly pay off in terms of costs, deadlines or implementation rates.

The technological maturity of the cycle operations for the transmutation of MA has not been reached and still requires a sufficient amount of R&D, specifically regarding the transmutation scenarios of all of the minor actinides. As expected, the presence of minor actinides at the manufacturing and reprocessing steps will cause design modifications for dealing with radiation protection and thermal problems. The transmutation of curium raises design constraint issues for all of the facilities.

The progressivity and flexibility of the options might be the key factors for their industrial development. The progressive addition of americium in the blankets involves much less industrial risk than, for instance, the combined extraction of plutonium and minor actinides with a homogeneous recycling in all of the fuel flow in the nuclear fleet. A progressive implementation of the options as they become technically mature and economically acceptable will always be a safer solution from an industrial viewpoint than the drastic introduction of innovative and technically challenging options.

XXIII-8. CONCLUSIONS

The studies carried out in collaboration with EDF, AREVA and Andra have allowed to obtain many important and objective results on a set of defined scenarios and with an improved and satisfactory methodology related to the advantages and drawbacks of MA transmutation options and consequences on fuel cycle plants.

Only the transmutation of all minor actinides through multi-recycling operations in SFR allows to stabilize their inventory over time. This involves two elements which must be identified:

- The transmutation of minor actinides significantly reduces their inventory in the geological repository due to the fact that they are no longer transferred to the waste packages. The amount of minor actinides in the waste is essentially determined by the quantity which is already present when the transmutation is implemented;
- The immediate consequence of reduction of the minor actinide content in the waste is an increase of the MA inventory in the cycle (reactors and plants). As transmutation is a relatively slow process, the minor actinides accumulate in the facilities prior to reaching an equilibrium level. The calculated inventories vary from 60 to 160 tons according to the transmutation concepts. It should be noted that, at the same time, the plutonium inventory amounts to around 1,000 tons.

Reducing of the thermal load of high-level waste packages due to the transmutation of americium greatly decreases the underground area covered and the excavated volume of the high-level waste disposal modules without calling in question the performance and safety of the repository. The transmutation of Am and MA would result in a reduction by a factor from 7.3 (Am) to 9.8 (MAs) of the footprint of the HLW disposal zone after an interim storage period of 120 years, a total reduction by a factor 3 of the repository footprint taking into account ILW-LLW and common infrastructures.

As can be expected, calculations reveal high contents of minor actinides at the fuel manufacturing and reprocessing steps which will demand significant design modifications for dealing with obvious thermal and radiation protection problems. The complexity of the operations carried out during the operating phase (loading / unloading, interim waste storage, transport) will also be increased. Scenarios involving the transmutation of all minor actinides are extremely impeded by the presence of curium and the implementation constraints often exceed the scenarios where only americium is transmuted by one order of magnitude.

Economic studies have been conducted on the different scenarios in order to determine the transmutation impact on electricity production costs. They show that the cost overrun related to the transmutation process could vary between 5 to 9% in SFR and 26 % in the case of ADS with the assumptions made.

The transmutation of curium raises design constraint issues for all facilities whereas its impact on reduction of high-level waste zone is low compared to the impact of Am transmutation.

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