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DU COMBUSTIBLE NUCLÉAIRE AUX DÉCHETS : RECHERCHES ACTUELLES

FROM NUCLEAR FUELS TO WASTE: CURRENT RESEARCH

Nuclear power plant types and the management of plutonium and minor actinides – in search of fuel cycle flexibility

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Abstract Transuranics management concerns all NPP types, because of the specifications for a sustainable development. Multiple recycling is mandatory. Neutronic abundance can be obtained in fast spectrum, or by adding external neutrons or (temporarily) with additional ^{235}U. The LWRs can control the plutonium inventory and significantly reduce the amount of transuranics transferred to the geological repository, thanks to the use of innovative nuclear fuel in a limited part of the NPP fleet. HTR adapted to transuranics burning can help. In the future, in addition to the liquid metal FBR, a strategy based on a gas cooled technological line and advanced fuel opens a second path towards fast spectra. Strategies for defining the optimal mix of reactor types in the nuclear fleet at a given time and demonstrating the fuel cycle flexibility are under study. ***To cite this article: J.-B. Thomas, C. R. Physique 3 (2002) 783–796.***

NPP design / fuel cycle / plutonium / transmutation / sustainable development / breeding / fast reactors

Filières nucléaires et gestion du plutonium et des actinides mineurs – la recherche de la flexibilité du cycle

Résumé La gestion des transuraniens concerne toutes les filières nucléaires, du fait des spécifications associées à un développement durable. Le recyclage multiple est impératif. L'abondance neutronique peut être obtenue en spectre rapide, grâce à des neutrons externes ou (temporairement) par l'ajout d'^{235}U. Les réacteurs à eau ordinaire permettent de maîtriser l'inventaire de plutonium et de réduire significativement les quantités de transuraniens transférées au stockage géologique, grâce à la mise en œuvre de combustibles nucléaires innovants dans une fraction limitée des réacteurs du parc. Des HTR peuvent servir d'auxiliaires de transmutation. Dans le futur, à côté des RNR-ML une stratégie fondée sur une ligne technologique à caloporteur gazeux et des combustibles innovants ouvre une seconde voie vers les spectres rapides. Les stratégies permettant de définir la combinaison optimale de filières dans un parc nucléaire à un instant donné et de démontrer la flexibilité

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du cycle sont à l'étude. ***Pour citer cet article : J.-B. Thomas, C. R. Physique 3 (2002) 783–796.***

conception de filières nucléaires / cycle du combustible / plutonium / transmutation / développement durable / surgénération / réacteurs à neutrons rapides

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1. Principles

1.1. Criteria for sustainable development

In order to contribute to long term development, nuclear strategy must be based on systems (NPPs and fuel cycle plants) with the following characteristics:

- cost effectiveness, particularly reduced investment costs and construction time;
- optimized safety and a simplification of the safety demonstration;
- cleanliness, by reducing the production of radiotoxic long-lived wastes, essentially transuranics (TRU): plutonium (Pu) and minor actinides (MA): Np, Am, Cm. This is not based on a risk assessment of geological repository but rather on a precautionary measure taken upstream.
- frugality (zero loss), by saving natural resources: uranium and thorium;
- resistance to proliferation, by keeping a 'zero motivation' level for proliferation by means of nuclear energy;
- ability to enter new energy markets: heating, desalination, thermo-chemistry (particularly hydrogen production), leading to optimal use of nuclear energy.

The strategy to establish in order to reach these objectives concerns all NPPs and fuel cycle plants. The reactor fleet can be made of:

- NPPs of one single type with all the required qualities;
- an optimal combination of several types of reactors. The fleet can comprise a majority of systems optimized for energy production, with the help of some systems dedicated to a specific function, so the fleet could meet all the criteria mentioned above.

The reactor technologies must be optimized with an international perspective including the dynamics of needs, resources, existing nuclear power, cost and time of innovation, etc.

1.2. Adaptation potential from the physics point of view

1.2.1. *The neutron is the instrument of flexibility*

It allows radioactive long-lived nuclei to be transmuted. Concerning TRUs, in order to substitute their short lived nuclei, the approach could be to push them towards fission, at the end of a more or less long capture chain, depending on the spectrum. The fast spectrum is the most favorable.

It allows fissile nuclei to be regenerated through fertile capture, thus ensuring 'frugality'. Here again, the fast spectrum is the most favorable.

1.2.2. *In fast spectrums, fission generates many neutrons*

This is the source of a '*high nuclear output*' which is to fission what high temperatures are to thermodynamics and chemistry.

Within this framework of energetic neutrons, fission simultaneously offers the burning of TRUs and regeneration of fissile nuclei, thus cleanliness and frugality.

1.2.3. *Additional neutrons*

These can also be found:

- with uranium 235, therefore by consuming natural uranium, which is not a 'sustainable' solution, but allows the proven systems to be used to their utmost capacity;
- by 'buying' these neutrons with re-circulated energy, taken from the fission energy itself. This process is 'sustainable' but costly and results in developing sophisticated systems within the framework of nuclear process (i.e. fusion, spallation, fission) synergy. This leads to ADS (Accelerator Driven Systems) or to fusion–fission hybrid systems.

1.2.4. *To sum up*

Everything is possible from the physics point of view, but technological and economic constraints limit the domain of reasonable options. The following criteria must be respected:

- cost criteria;
- technical logic criteria, particularly:
  - the fact that recycling is mandatory;
  - the fact that advanced partitioning and the separation of elements (and sometimes even of some isotopes) are necessary to reach some extreme objectives, which in turn leads to questioning the usefulness and value of these objectives.

1.3. Consequences: research for a balanced outlook on topical issues

1.3.1. *Mutliple recycling is necessary in the average to long term*

- For the optimal management of natural resources (uranium and thorium).
- For the management of the TRU inventory (reduction, then probably increase, so as to supply with plutonium a future regenerator or breeder fleet burning the depleted uranium).
- For the reduction of radiotoxicity in the long term.

1.3.2. *Plutonium (and thorium)*

- Plutonium (and ^{233}U) operate as *catalyzers* of the complete burning of natural uranium and thorium; they are present in a useful flow of recycled matter, but it is the reserve of natural uranium and/or thorium which is burned.
- For plutonium, the fast spectrum is necessary to reach breeding. For an intermediate or thermal spectrum, plutonium has a degraded neutron balance, which places it even under ^{233}U, sometimes ^{235}U. From this point of view, the Th/^{233}U couple is more 'tolerant': the number of neutrons emitted for a neutron absorbed by ^{233}U, related to the energy of the incident neutron, is more stable than that of ^{239}Pu, without attaining the same performance in a fast spectrum. This could enable the long-term use of proven, cost efficient and safe reactor types, even though these can not be easily adapted to the fast spectrum. In this regard, the technical and economic potential of the thorium based fuel cycle should be assessed, keeping in mind that the use of the Th/^{233}U couple brings in powerful emitters of energetic γ.
- In thermal spectrum, multiple recycling can be ensured by adjusting the supply of ^{235}U and by reducing the fertile capture in ^{238}U.
- Lastly, if neutrons were missing in the end (still through the impossibility of establishing a fast neutrons reactor technology with all the required features) to ensure fissile nuclei regeneration, these neutrons could be produced by tapping some fission energy and by generating external neutrons through spallation (ADS) and fusion (hybrid systems). These systems, already studied in the past, would benefit from the progress made since on neutron sources and the coupling of nuclear systems.

1.3.3. *Minor actinides (MA)*

This collective name conceals different levels of usefulness and difficulty. It includes:

- americium (Am): its recycling up to a reasonable level seems useful and difficult;

- curium (Cm): its recycling raises very difficult fuel and cycle problems. Moreover, the half-life of ^{244}Cm (which makes up about 90% of the Cm generated by the LWRs) is of only 18 years and produces ^{240}Pu;
- neptunium (Np): its recycling does not appear to be mandatory nor too problematic.

Therefore, the ranking of MAs must be investigated further and their disposal options optimized.

- Concerning their transmutation by fission:
  - in fast spectra: the neutron balance keeps them burning by their own fission;
  - in thermal spectrum: additional ^{235}U is required and the multiple recycling methods of plutonium could be extended to the most important MAs.
- Common problems in the basic or specialized NPPs which can be used for transmutation will probably determine the practical feasibility of MA transmutation. These are essentially:
  - fuel design for transmutation, highly loaded with MAs (particularly Cm);
  - strategic choices associated to advanced partitioning versus homogeneous recycling;
  - efficient separation performances and associated trade-offs, concerning cost, ultimate waste, doses to the fuel cycle plant personnel.

1.4. Summary

- Multiple recycling will be mandatory in the more or less long term.
- The separation strategy and performances are structuring.
- In fast spectrum, the 'high nuclear yield' simultaneously ensures the transmutation of TRUs by fission and the regeneration of fissile nuclei by fertile capture. The nuclear system thus becomes 'omnivorous': it is 'frugal' (it burns ^{238}U) ; it is 'clean' (it fissions TRUs).
- In thermal spectrum, multiple recycling applied to some MAs requires additional ^{235}U.

1.5. Consequences on the solutions

1.5.1. *Polarization in the solution space and 'interpolations'*

Several approaches can be used, combining the qualities of the different NPP types of the electronuclear fleet available at a given time. These approaches show two poles and intermediate combinations:

- based on the existing and well-proven nuclear systems, and through the evolution of NPPs and of nuclear fuel: a LWR fleet, the multiple recycling with innovative fuels, additional ^{235}U and the implementation of separation;
- based on a fast neutron reactor type assumed to be cost effective, by performing homogeneous multiple recycling;
- in symbiotic systems composed of a basis of optimized NPPs and a minority part of auxiliary systems devoted to the transmutation of MAs or TRUs.

1.5.2. *Scheduling issues*

These are essential to ensure the best transition from the present solutions to the improved solutions of the future. The related chronology involves the lifetime of the existing facilities, the synchronization between NPPs and adapted fuel cycle plants, the evolution in the consumption of natural resources depending on the history of the installed NPP power supply, the conversion factor (from fertile to fissile nuclear materials), the management of spent fuel inventories and the length of (out of pile) cycles.

1.5.3. *All nuclear system types are concerned by cycle flexibility*

Particularly, recycling operations should be achieved first in the most proven systems, as far as they are able to implement them cost effectively. For example, as long a competitive fast reactor is not yet available, multiple recycling of plutonium and of *some* actinides could be done in LWRs or HTRs.

Moreover, each element of the 'tool box' must be used to its utmost capacity and depending on the needs at a given time. The role can thus change over time. For example, a competitive fast reactor can be introduced in an existing fleet mainly consisting of LWRs in order to ensure, firstly a recycling and transmutation function for TRUs, before progressively taking over all the functions of the LWRs.

1.5.4. *The main evaluation themes*

These will be '*fuel cycle flexibility*', and overall technico-economic assessment. Actually, strategic conditions are generally the determinant factor. These should be taken into account to judge the robustness of the scenarios studied.

2. Elements of a solution: implementation and schedule

2.1. Short term solutions making the most of the present nuclear fleet and of 'evolutionary' systems

2.1.1. *Description*

These solutions are based on using LWRs (which provide nearly 90% of the electricity produced by NPPs in the world) and the reprocessing technologies presently used. The main objective is to demonstrate the ability to control the plutonium inventory while limiting the increase of the MA inventory. The instruments used for this strategy, for example in the APA fuel concept (Fig. 1), are as follows:

- multiple recycling;
- more or less advanced partitioning;
- adjustment of ^{235}U enrichment (while respecting a 5% limit in present conditions);
- the use of non-fertile matrices to avoid regenerating plutonium;
- the development of advanced fuels aimed at locally optimizing plutonium burning and at concentrating plutonium in a reduced fraction of the LWR fleet, devoted to recycling.

For example, in the EPR, for a ^{235}U enrichment of less than 5%:

- the plutonium mass flow and isotopic composition equilibrium can be obtained, by means of multiple plutonium recycling, with 30% of the plants loaded with APA assemblies, each assembly containing 33 kg of plutonium;

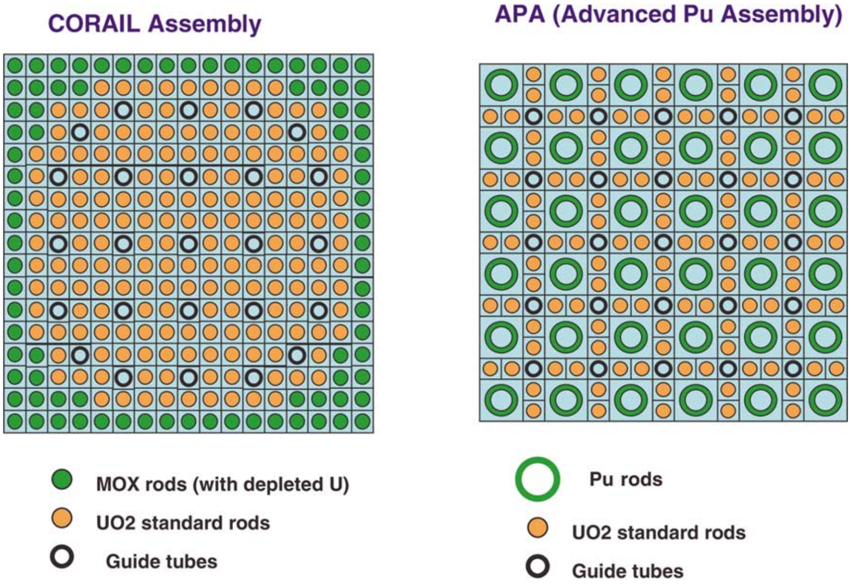

Figure 1. New subassemblies for Pu recycling in LWR.

- the equilibrium of Pu + Am and Cm (which makes up an envelope, in terms of usefulness and feasibility) can be obtained by loading 38% of the plants with APA fuel, with about 30 kg of plutonium and 10 kg of minor actinides per assembly.

The plutonium inventories at equilibrium, after a few cycles, are reduced to less than 250 tons and the plutonium inventory without use is nearly nil. The inventory at equilibrium in Am and Cm is of several dozen tons. The TRU flux towards the waste is considerably reduced as long as the separation during reprocessing is highly efficient.

Such a strategy leads to degrading the isotopic composition of the plutonium at equilibrium.

The characteristic times to approach equilibrium are of several dozen years, which means about the lifetime of a NPP generation.

These performances are accessible with the most innovative version of APA fuel (annular version), using all the room for manoeuvre provided by the concept. Feasibility and technico-economic optimization studies of the concept are underway in France, along with associated technological developments. After these studies, it is possible that an intermediate version of the APA be selected for an average term application (initially oriented towards the EPR whose ‘cleanliness’ would be enhanced). Such a choice would represent a compromise between the performances on the one hand, and the cost, development and implementation time on the other. Another concept, which could be put sooner into industrial operation for the multiple recycling of plutonium, is provided by the CORAIL design (Fig. 1), with lower performance in terms of plutonium concentrations in LWR cores.

In the choices to be made, the fuel cycle feasibility and cost will be predominant factors, when considering the use of existing processes or even of existing facilities.

2.1.2. *Summary*

This concerns:

- the performances reached:
  - equilibrium reached for major interest TRUs;
  - significant reduction of masses and of radiotoxicity concerning geological repository;
- increased ‘cleanliness’ of evolutionary NPPs, such as the EPR, thanks to innovative fuels such as the APA;
- the mandatory nature of recycling and of an efficient reprocessing.

2.1.3. *Later evolution*

The notion of fuel cycle flexibility takes into account the use of natural resources. This can, in the long term, lead to increasing the regeneration of fissile nuclei through fertile capture in LWRs and consequently, hardening the spectrum by reducing the moderation ratio. Such a scenario could be a transition phase towards replacing LWR with hardened spectrum reactor types, thus mobilizing a higher plutonium inventory.

2.2. The advantages of HTR type reactors with thermal or epithermal spectra

2.2.1. *Description*

The HTR belongs to the ‘fourth generation’ likely to be implemented in the next twenty or thirty years. From the fuel cycle and safety viewpoint, the HTR advantages are largely due to the particle based fuel. In a GT-MHR type core (designed to burn excess military plutonium), the fissile nuclei are very diluted in the core. The fuel particles do not contain fertile matter, which prevents plutonium regeneration. The specific power is high, despite the low power density, which allows a fast burning of TRUs. A high burnup (typically $2/3$ for LWR plutonium) can be reached in a few years, leading some proponents to a once through cycle strategy (with a limited long-term reduction of residual radiotoxicity). Inversely, the possibility of conventional particle fuel reprocessing, even though it has been studied since the beginning of the HTR concept with a perspective of closed thorium–^{233}U cycle, must be re-assessed in the present industrial context, under present regulations. Another potential of particle fuel, to be further assessed, is loading the particles with 100% 'transmutation' kernels without fertile matrices and adapting the local self-shielding of resonances to specific objectives.

2.2.2. *The implementation schedule of HTRs*

Launching a series around 2020–2025 means HTRs would take part in the renewal and likely increase in nuclear power, maybe even open new fields of application, including hydrogen production. In the long term, the technological line of gas cooled reactors with a high thermo-dynamic yield can evolve towards a hardened or fast spectrum, providing high nuclear output, this being the key to cleanliness and frugality, in uranium-transuranics cycles. This phase is not simply a continuous evolution but requires major technological and design progress. Lastly, when assuming that this transition to a very fast spectrum would be too penalizing in terms of cost-effectiveness, the long term use of thorium–^{233}U cycle would more easily ensure 'isogeneration', or even limited breeding with an intermediate spectrum. This would probably lead to somewhat 'heavy' fuel cycle technologies.

2.2.3. *Confinement and refractory qualities of particle fuels*

These are enhanced in reactors cooled by an inert gas such as helium, since the coolant does not attack the fuel, even in an accident situation, at very high temperatures. However, the favorable properties of particle fuel can also be used in other systems and provide them with an advantage, limited by the more aggressive behavior of the coolant.

2.3. Future nuclear systems: evaluation of their average term potential

This potential can only be evaluated within the framework of a 'reactor-cycle' strategy and by the analysis of scenarios considered on the international level (markets, development and acceptance of solutions):

- Multiple recycling is a must.
- The evolution towards fast spectra providing high nuclear output is a natural and reasonable tendency. This evolution will occur to the pace of technological and design progress, solving the additional problems resulting from the physical and material restrictions due to the fast spectrum option. Nuclear energy should advance by sharing technological progress with other state of the art industries, thus reducing the selection, development and feedback costs.
- The innovative concept of integrated sites, which includes energy producing reactors and recycling operations, must be evaluated.
- The choice between homogeneous recycling and advanced partitioning includes a strategic part concerning the appropriateness of separating transuranics, even within the framework of tightly integrated operations on the reactor site. It also depends on the composition of the reactor fleet at a given time, as well as on the reprocessing and 'transmutation fuel' technology availability.
- The burnup is of utmost economic importance, in a multiple recycling perspective. A range between 5% and 25% of fission for the heavy nuclei seems to define the area to explore in terms of initial feasibility and of further progress.
- The list of candidate reactor types is shown in Fig. 2. The analysis of this technological 'compass rose' diagram results in two main conclusions:
  - LWRs, which produce nearly 90% of all nuclear energy worldwide, can make progress, particularly by the use of innovative fuels, in order to increase the cycle flexibility, all the while remaining competitive and benefiting from the exceptional feedback which drives constant improvement;
  - the technological line of gas-cooled reactors is based on a mature concept (the HTR), which could be started up in about twenty years. This technology could evolve towards fast spectra, with inherent difficulties, different from those encountered in metal liquid technology, the latter already having operating references. Opening a second pathway to fast spectra in the gas cooled reactor line

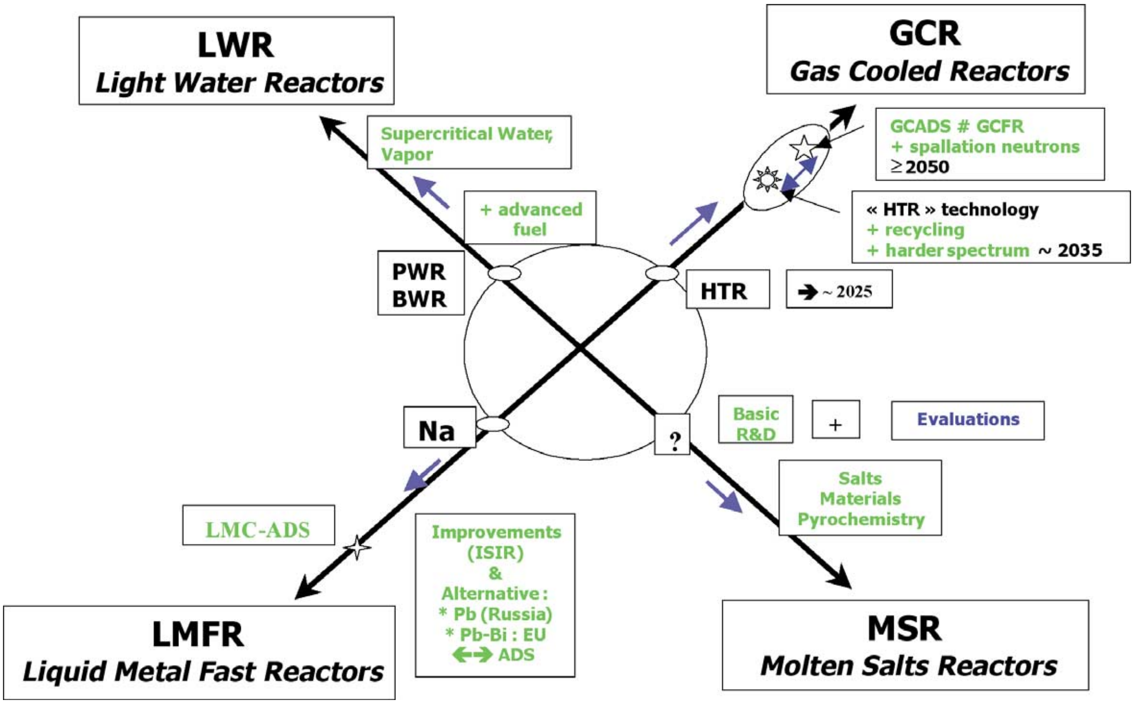

Figure 2. Future nuclear energy systems: CEA technology roadmap.

therefore provides interesting perspectives. The difficulties associated with gas cooled reactors are likely to be partly solved thanks to the technological and material progress made in all of the high temperature industries. Indeed, the gas proposed (sufficiently pure helium) does not bring specific failure modes: it is chemically inert, it is transparent to neutrons, does not participate in corrosion-activation processes and does not drastically transmit thermal shocks. As for the difficulties inherent to this technology and concentrated on the core, the fuel is the main enabler. The constraints in the fuel design due to fast neutron fluxes and the cost of reprocessing are thus the main issues. Lastly, the transparency of helium to neutrons makes core design easier (particularly for the void coefficient which is very much reduced);

- In 'fast' version, the high concentration of fissile nuclei in the core leads to different safety solutions from those of a thermal spectrum reactor. A 'defense in depth' architecture is required to reduce the risk of core meltdown and energetic criticality events to the residual risk level.

The safety system, fuel and containment design must thus be simultaneously treated with a design-safety integrated approach, using the 'lines of defense' method.

2.4. Optimized nuclear fleet: combinations, scenarios

2.4.1. *Influence of criteria*

- Physics lead to fast spectra.
- Safety must take into account the specific constraints of fast spectra.
- Advanced partitioning, assumed to be accepted and efficient, extends the possibilities of designing 'symbiotic' nuclear fleets made up of specialized plants, helping a basic NPP type optimized for energy production to fulfill complementary functions and to open new application fields. In particular, the concentrated management of TRUs or of MAs in a separated recycling loop (or 'stratum')

reduces the burden for the basic reactors in the fleet and for the associated fuel cycle facilities. An economic criterion results in minimizing the proportion of complex and costly reactors of the fleet and consequently, in using basic NPPs to recycle a maximum amount of plutonium. In the case where this NPP is with thermal spectrum, one is led to a double strata scenario. Since the fast spectrum is better for TRU fission and that a core loaded with MAs is lacking delayed neutrons and Doppler feedback, the ADS becomes the natural tool associated to the second stratum. The ADS can then, with a reduced power fraction in the fleet (5 to 10%, thus minimizing additional costs), ensure the fission of Am and Cm. This looks to be the best option for using the ADSs.

These few examples show the diversity of the possible combinations. The following analysis is aimed at illustrating representative scenarios rather than making an unlikely forecast on actual evolutions.

2.4.2. *Elements for an 'asymptotic' solution*

These would be based on both perennial and conventional solutions (without introducing thorium or the 'massive' buying of external neutrons). This solution is based on a fast spectrum reactor type:

- An 'ideal' option is the success of the 'future reactor' with fast spectrum, high temperature and a simple architecture, presently designed as a fast gas cooled reactor. This NPP type offers the possibility of homogeneous multiple recycling in a homogeneous (monotype) fleet. The key problems influencing such a success are:
  - – the fuel: burnup in fast spectrum and reprocessing costs;
  - – reaching a reduced investment cost;
  - – the success of the integrated optimization approach: design–safety. The main problems are due to the removal of decay heat at low pressure and the practical exclusion of fusion-compaction of the core and of re-criticality. Defense in depth is necessary.

  A design approach consists in, based on a given vessel:
  - – concentrating the fissile nuclei in the core so as to obtain a fast spectrum without reducing too much the specific power, adjusting the core power density to safety constraints;
  - – determining the gains in internal and external regeneration which can be profitable during the facility lifetime, without creating penalizing material fluxes at reprocessing;
  - – deciding on a burnup which ensures a reasonable compromise between spectrum hardness and cost effectiveness;
  - – designing a balanced core (probably heterogeneous).
- In the case where this ideal system cannot be achieved in a single generation, symbiotic systems can globally have an equivalent level of criteria satisfaction while preparing the evolution towards a homogeneous fleet of cost effective fast reactors. Such a fleet could combine mostly LWRs, a minority (increasing) of GCRs and, for example, a small fraction of ADSs in a second stratum.

An interesting option consists in developing from the start a flexible GCR design, of conventional unit power (about 1 Gwe) and compactness, with a defense in depth safety architecture, allowing the spectrum to change over its lifetime. This GCR-F (for flexible) is a possible approach in view of the development time needed and of progress in fuels dependent on experimental feedback. The time needed could be of several decades starting with current pin fuels or particle fuels.

2.4.3. *Transition from the present world fleet to asymptotic solutions*

The transition period under study goes from 2020–2025 to 2050–2075:

- A direct transition is possible from LWRs to a fleet composed of cost-effective fast neutron reactors (for example, GCR-Fs). This scenario shows increasing and significant requirements in plutonium to supply this fleet. This means that the flexibility of LWRs also be considered as an option, as in a return towards increasing conversion factors, thanks to a tight under-moderated core lattice and to a spectral shift principle.

- The transition can be made more progressively and associate in the long term LWRs and different transmutation dedicated systems, such as:
  - GCR-Ts with thermal or epithermal spectra, with a high burnup, a high specific power (and a rather low power density), which could be started up around 2020–2025. These reactors would operate as plutonium and minor actinide burners (typically Am);
  - ADSs being implemented later (beyond 2040, if not 2050), to burn minor actinides and ‘some plutonium’ in a second stratum;
  - molten salt reactors would potentially be started up later, after a basic R&D phase;
  - GCR-Fs starting up around 2035–2040 due to progressive development based on the HTR concept. These could then operate temporarily as plutonium or TRU burners, then as plutonium regenerators, as a minor component making up a quarter or a third of the fleet power. Then, once these are economically optimized and once there is substantial operation feedback and an advanced fuel, these would take over the LWRs for all the functions. A challenge to new reactor types is that the testing and optimization phase should already be economically profitable. This is even more difficult for versatile, adaptive systems.

It is to be noted that from a physics viewpoint, a concept such as the EFR (sodium cooled FBR), fully meets the cleanliness and frugality criteria.

In such scenarios, the availability date of innovative solutions is crucial. The tentative schedules under consideration are as follows:

- current design modular HTR: ~ 2025; GCR-F: ~ 2035; ADS: > 2040; Molten salt: to be determined;
- for cycle processes coherent with the partitioning strategies adopted and with the innovative fuels, the schedule is even less well defined, whether this be for hydro-metallurgical or pyrochemical type processes. The efficiency and cost of these processes will influence the global feasibility and cost effectiveness as much as the qualities of the reactors.

2.4.4. *Futuristic systems*

These are essentially spallation–fission (ADS) and fusion–fission hybrid systems providing fission with external neutrons. The potential role of ADSs seems to be associated to the control of a fast spectrum core devoted to MA fission, with a limited quantity of plutonium and natural or depleted uranium. Any attempt to open a larger portion of the market to these systems to burn most of the plutonium (a task which can be carried out in critical reactors) comes up against the additional costs associated to the concept: cost of the accelerator, the beam current, the spallation module, the coupling and protection elements, lowering the availability of the system due to the limited reliability of accelerators and to the renewal of consumable components, increased operation costs.

As for fusion–fission hybrid systems, this is an even more futuristic vision. However, the progress underway on fusion sources with Q factors (ratio between fusion energy produced and energy injected in the plasma) close to 5, results in recalling the exceptional quality of the neutrons in D–T fusion (14 MeV neutrons) versus fission or spallation neutrons. At such energy levels, heavy nuclei such as ^{238}U and ^{232}Th are fissile and generally the ratio of the number of neutrons produced to the number of neutrons absorbed is about 5.

In the very long term, the synergy in nuclear fields (fission, spallation, fusion) could therefore help fission to solve neutron balance problems.

2.5. Elements of a summary: towards fuel cycle flexibility

2.5.1. *How could the composition of a reactor and fuel cycle plant fleet be optimized over time?*

Based on the assumptions defined by the competent organizations on primary energy consumption, *the value and the cost of regeneration performances and time needed for recycling* must be determined, depending on the nuclear power evolution forecast.

French scenarios have or will soon be studied:

- within the framework of the Charpin–Dessus–Pellat study [1], firstly, which confirmed the mandatory aspect of recycling;
- within the framework of Future Nuclear Systems programs of the CEA, led in collaboration with French industrial partners for the preparation of the future.

2.5.2. *An example*

An example illustrating the possible evolution of a nuclear fleet is:

- the current PWR fleet is relayed by the EPR; advanced fuels allow a multiple recycling of plutonium and possibly of interesting minor actinides. Along with the EPR, the future could lead to considering advanced BWR concepts;
- starting in 2025 the 'GCR technological line' would be first implemented with thermal or epithermal spectra cores with a high specific power. These cores could be devoted to burning plutonium or minor actinides within a limited fraction of the fleet;
- starting in 2035, the transition to GCR-Rs would begin. These reactors, supposed to be cost effective as soon as they appear or after a feedback phase, could operate, for a time, as TRU burners and then as Pu regenerators. As soon as this phase in which GCR-Rs are installed in about one fourth or one third of the system, they would mobilize a significant amount of plutonium;
- beyond 2050 and depending on the pressure on natural resources, a transition would be made towards GCR-Rs with a core-blanket concept ensuring isogeneration or even breeding.

A strategy of GCR-F type converting the GCR-T into GCR-R as soon as fuel will allow, would best exploit R&D as well as the investments made in the first phase. Cycle flexibility depends on, for both GCRs and LWRs, the adaptability of the NPPs. NNPPs deprived of such adaptability would be submitted in the average term to a risk of obsolescence versus cycle constraints. A technico-economic analysis is necessary in order to evaluate this risk, by integrating the gains and losses on reactor lifetime forecast. The choice of safety options, through safety system architecture and plant performance rating, is at the heart of this analysis. The GCR versions with passive decay heat removal, of limited unit power and limited power density, must be assessed with this in mind.

2.5.3. *Summary*

The most important is to adopt a *flexible strategy*, thus robust versus context evolutions.

3. Associated research and development: contents, method – role of simulation

3.1. The key topics

These concern:

- The fuel, with an optimum to be determined between burnup, spectrum quality and reprocessing costs, all the while ensuring:
  - a good thermal quality (cold fuels);
  - refractory qualities (gain in output, increased resistance against core meltdown and re-criticality), resistance to compaction (especially important in fast spectra);
  - FP confinement at high temperatures.

  The microstructured fuels with local confinement offer interesting perspectives:
  - by their performances;
  - in development: they are 'hyper-modular'. The 'Representative Elementary Volume' is small and they are composed of thin layers, which makes it easier to use simulation and homogeneous irradiation by ions. These different aspects help to accelerate the selection stages. Conversely, a statistical approach is necessary.

Moreover, at this microscopic level, the sphere 'without weldings' seems to be a good pressure vessel. Embedded particle fuels are thus an interesting candidate, even if the concept lacks data on the lifetime in fast spectrum and on the reprocessing costs.

- Recycling, with hydro-metallurgical and pyrochemical processes. The choices concerning the front end, with different physico-chemical options, broaden the range of candidate materials.
- The NPPs, particularly the GCR technological line opening a second pathway to fast spectra.

3.2. A simulation project for nuclear energy is underway at the CEA

This project aims at accelerating the transfer from physical knowledge to design calculations tools.

- It is based on physical modeling, numerical simulation and 'smart experiments', rightsized, greatly instrumented and using calculation for their definition, their control and interpretation. Everything that can be transposed by calculation must allow the reduction of the size and time of experimental simulation, the improvement of the definition of experimental plans and the focus on the interpretation of poorly understood or poorly represented phenomena.

  Such an approach is especially necessary for fuel, whose development has generally been based on semi-empirical methods, justified by the value of the result reached and the extreme difficulty of the simulation approach. Today, the current method seems to have reached its limits when compared to the ambition of the new objectives.
- The program includes several stages: from the basic disciplines to integrated numerical simulation (change from microscopic to 'macroscopic' in space and time); coupled numerical simulation (coupling of disciplines: neutronics, thermalhydraulics, thermomechanics, chemistry, for example).
- In the nuclear fuel case, it must closely associate the progress in nuclear material science (including the irradiation effects) and the specifications of fuel innovation.

As for particle fuel, whose interest is high for nearly all the NPP types, their small size fosters an approach through numerical and experimental simulation. In order to achieve this breakthrough, the investment and sharing of an experimental and numerical tool box to simulate and explore the irradiation effects on materials and microstructures is necessary. Beyond this, the models stemming from this R&D should be quickly integrated in the simulation tools for nuclear cores and structures.

4. Conclusions

TRU management concerns the design of all nuclear system types, because of the specifications for a sustainable development. In this perspective, plutonium acts as a catalyzer, enabling the complete burning of natural uranium. The possible use of thorium in the future does not reduce the importance.of this issue.

Multiple recycling is mandatory as confirmed in France by the Charpin–Dessus–Pellat study [1] and as is illustrated by the currents reflections on the international Generation IV Forum.

Neutronic abundance is necessary to obtain the fuel cycle flexibility. It can be obtained in fast spectrum, or by adding external neutrons or (temporarily) with additional ^{235}U.

LWRs such as the EPR can control the plutonium inventory and significantly reduce the amount of transuranics transferred to the geological repository, thanks to the use of innovative nuclear fuel (such as the APA) in a limited part of the NPP fleet. HTR adapted to transuranics burning can help.

In the future, in addition to the liquid metal FBR, a strategy based on a GCR-F concept opens a second path towards fast spectra, based on the assets of a gas cooled high temperature technological line and of advanced fuels. Three areas – keys to the success of GCR-Fs are fuel, fuel cycle and the approach to safety design.

There are thus promising paths for an 'ideal' reactor or in a symbiotic nuclear fleet to satisfy the specifications set for a sustainable development. Strategies for defining the optimal mix of reactor types in the nuclear fleet at a given time and for demonstrating the fuel cycle flexibility must take into account the worldwide dynamics of needs, resources, R&D, etc.

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On the scientific and technical level, a simulation program should accelerate R&D, particularly for fuel whose progress is a key to success, both for LWRs and innovative nuclear systems.

References

[1] J.M. Charpin, B. Dessus, R. Pellat, Economic Forecast Study of the Nuclear Power Option, Commissariat Général du Plan, Paris, July 2000.

Discussion

Question de J.-M. Loiseaux

Dans l'optique d'un développement du nucléaire au niveau mondial, ce qui correspondrait à un développement de réacteurs à neutrons rapides, un problème apparaît, c'est celui de disposer de suffisamment de plutonium pour démarrer rapidement une production d'énergie à partir de RNR (U–Pu ou Th–Pu) ; Pouvez-vous commenter sur cette remarque ?

Réponse de J.-B. Thomas

Si on multiplie par 3 à 6 la puissance nucléaire installée, on devra probablement le faire d'abord avec des réacteurs éprouvés et déjà compétitifs de type REP ou REB. Il faudra amortir le choc de croissance de la consommation de matières fissiles. Le multirecyclage y contribuera, et peut-être avec des facteurs de conversion croissants, par exemple avec des cœurs sous-modérés. La durée du recyclage sera également un paramètre important. D'autres voies sont possibles, comme une filière à caloporteur gaz et spectre progressivement durci et/ou l'utilisation du couple thorium–^{233}U qui permet d'accéder à l'iso-génération sur une plage de spectre assez large. Au cours de tels scénarios, des quantités significatives de plutonium et/ou d'^{233}U seront produites (c'est déjà le cas dans les cycles ouverts actuels) et la relève progressive par des RNR refroidis par des métaux liquides ou un gaz sera possible. Enfin, avec les facteurs de conversion atteints et une pratique éprouvée du multirecyclage, l'uranium naturel restant (en grandes quantités, mais plus coûteux que l'uranium actuellement extrait) serait fortement valorisé et pourrait donc être exploité de façon raisonnable, évitant tout blocage des ressources. L'abondance du thorium offre également une assurance.

Commentaire de R. Dautray

Je n'ai là rien à dire que me faire le témoin d'un lointain passé, mais J. Horowitz disait « chaque fois que la fusion bute sur un obstacle, elle fait appel aux systèmes hybrides fusion/fission » ; mais les problèmes demeurent : régénération du tritium, technologie des matéraux, etc.

Question de H. Métivier

Prenez-vous en compte les modifications qu'il faut apporter pour les protections des travailleurs si l'on utilise la filière thorium ?

Réponse de J.-B. Thomas

Il faut d'abord noter qu'un des intérêts des filières thorium réside dans l'abondance des ressources et le fait que le couple thorium–^{233}U peut accéder à l'iso-génération sur une plage de spectre assez large.

En ce qui concerne les problèmes de radioprotection, il y a 30 ou 40 ans le cycle thorium a été écarté en partie en raison du rayonnement γ supérieur à 2 MeV qui compliquait fortement les opérations de fabrication et de transport du combustible recyclé. Aujourd'hui, on se trouve confronté à des problèmes similaires avec le cycle uranium, du fait notamment de ^{238}Pu, de ^{241}Am, etc. Parallèlement, des progrès considérables ont été faits en matière de télé manipulation et robotique. Il ne serait pas absurde de « revisiter » le cycle thorium.

Question de É. Brézin

Qu'en est-il de la durée de vie des matériaux avec des neutrons de 14 MeV ?

Réponse de J.-B. Thomas

Les conditions d'irradiation sont différentes de celles que l'on rencontre en fission. Des expériences ont été imaginées dans des installations conçues tout exprès comme IFMIF. Dans les conditions réelles d'exploitation, c'est toujours la combinaison des « agressions » thermomécaniques, chimiques et d'irradiation qui conditionne l'intégrité des structures et la durée de vie. Actuellement, des éléments de réponse séparés concernant cyclage, corrosion, fluage, etc., sont élaborés. En termes d'expérience globale, ITER apportera un début de réponse, mais restera nettement en dessous de la fluence accumulée prévue dans un réacteur de puissance. L'étape DEMO s'en rapprochera.