FAST REACTORS DEPLOYMENT STRATEGY. SOME CONSTRAINTS AND CONSEQUENCES.

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ABSTRACT

Assuring energy supply, environmental protection, economic feasibility, proliferation issues and safeguards of the nuclear materials, imply the development and deployment of innovative reactors (Generation III/III+ and Generation IV) and the development of innovative concepts for the nuclear fuel cycle closure with the aim of an acceptable cost energy production, reduction of waste volume and long term radiotoxicity. This paper examines the role of the fast reactors in the nuclear fuel cycle, starting from physical considerations and till to the consequences of their deployment. Particular attention was paid to the solution of the potential lack of Pu, as well as to the consequences of the Pu build-up with respect to the proliferation resistance issues. The environmental impact of the Minor Actinides transmutation has been examined. The uncertainties of the neutron cross sections, on the transmutation of Minor Actinides, were also taken into consideration.

1 BACKGROUND

Despite the NPP accidents and the uncertainties related to the public acceptability, projections show a significant increase of the nuclear energy demand in the next future, especially in the countries of emerging economy. The use of the nuclear energy, able to substitute fossil fuels at acceptable costs, is strongly related to two critical aspects of nuclear power production:
- potential catastrophic risks, and
- the radioactive wastes management,
whilst important consequences on the Uranium resources and associated fuel cycle components availability (the contribution of the Thorium cycle until now is insignificant) are expected.

GEN III/III+ commercial reactors are expected to be the choice for nuclear power expansion in short term, while the long-term solution of a sustainable closed fuel cycle requires fast reactors deployment. The recent history of NPP accidents reaffirms that enhanced safety performances are required to minimise the potential catastrophic risks, while the high-level radioactive wastes (HLW) reduction implies Partitioning & Transmutation (P&T) techniques for both minor actinides (MA) and long-lived fission products (LLFP). Generation-IV Initiative studies have demonstrated that in long term advanced fast reactors are needed to meet both enhanced safety behaviour and improved environmental impact. New characteristics and requirements concerning the reactor cores and the associated fuel cycles are typical issues in the Generation-IV innovative nuclear systems, and it’s commonly accepted that issues involved in the transition from the open to a sustainable closed fuel cycle have to be completely understood and further extended investigation is required.
2 NUCLEAR REACTORS AND NUCLEAR FUEL CYCLE

The potential contribution of the nuclear energy to the energy demand depends essentially on the answer on the sustainability of the nuclear fuel cycle, intended as the set of scientific, technological, economical and socio-political steps necessary to ensure a safe energy supply, constant in time. Figure 1 shows the scheme of a generic nuclear fuel cycle.

![Figure 1: Schematic view of the nuclear fuel cycle.](image)

Three main steps in chronological sequence are recognized, as well the central role of the reactor. Simple considerations, like probability of capture and of fission, displayed in the Figures 2, [1], highlight the diversity on the design (and operation), as well the diversity of the role of thermal reactors and fast reactors within a chosen fuel cycle.

![Figure 2: Neutron capture and fission probabilities, for $^{232}$Th, $^{238}$U, $^{233}$U, $^{239}$Pu, respectively](image)

Actually, the typical fissile isotopes $^{235}$U, $^{239}$Pu, of the most exploited fuel cycle (U, Pu):

$$ ^{1}_{n_0} + ^{238}_{92}U \rightarrow ^{239}_{92}U \rightarrow ^{239}_{93}Np \rightarrow ^{239}_{94}Pu, \quad ^{1}_{n_0} = \text{neutron} $$

show a wavering trend: in the thermal spectrum prevail the fissions of $^{235}$U with accumulation of $^{239}$Pu, while in the fast spectrum the fissions of $^{239}$Pu prevail and therefore a consumption of $^{239}$Pu itself.

Neutron balance considerations for the same fuel cycle show the difficulty of the use of a thermal reactor in a "closed" fuel cycle, of course possible, but not without significant technical-scientific and economic penalties, and the necessity of deployment of the fast reactors for the "closure" of the fuel cycle. In effect, if $\sigma_{\text{fis}}$ and $\sigma_{\text{cpt}}$ are the fission and capture cross sections respectively, for each absorption event in fissioning nucleus:

$$ \sigma_{\text{fis}} / (\sigma_{\text{fis}} + \sigma_{\text{cpt}}) = 1/(1 + \alpha) \quad (1) $$
is the fission event probability and, if \( n \equiv \) neutrons produced per fission event, then:

\[
\eta = n / (1 + \alpha)
\]  

(2)

is the number of neutrons produced per neutron absorbed. Taken into consideration that L neutrons are lost from the system (including the parasitic captures) and that 1 neutron is required for the chain reaction (corresponding to 1 destroyed fissile nucleus), the following neutrons balance condition is obtained [2]:

\[
\eta - 1 - L \geq 1
\]  

(3)

where: \( \eta - 1 - L \) is the number of neutrons captured in the fertile nuclei, i.e. the number of fissile atoms created per fission event, called "conversion ratio", is:

\[
CR = \eta - 1 - L
\]

or [3]:

\[
CR(r, t) = \frac{\sum^{\text{Fis. Prod}}_{\text{captures}}(r, t)}{\sum^{\text{Fis. Dest.}}_{\text{Absorptions}}(r, t)}; \quad \text{or} \quad CR = \frac{\int_{0}^{T_{\text{fuel}}} dt \int_{\text{Core}} dV \sum^{\text{Fis. Prod}}_{\text{captures}}(r, t) dr}{\int_{0}^{T_{\text{fuel}}} dt \int_{\text{Core}} dV \sum^{\text{Fis. Dest.}}_{\text{Absorptions}}(r, t) dr}
\]  

(4)

where: \( \sum^{\text{Fis. Prod}}_{\text{captures}}(r, t) \) and \( \sum^{\text{Fis. Dest.}}_{\text{Absorptions}}(r, t) \) \( = \) capture and absorption macroscopic cross sections, respectively of fissile produced and of fissile destroyed. Figure 3, from [1], displays the behaviour of the parameter \( (\eta - 1) \) for the \( ^{235}\text{U} \) and \( ^{239}\text{Pu} \) nuclei

![Figure 3: \( ^{235}\text{U} \) and \( ^{239}\text{Pu} \) parameter \( (\eta - 1) \) behaviour](image)

showing that at the reactor's energies of interest, the \( ^{239}\text{Pu} \) satisfies the neutron balance condition, given by the formula (3), especially in the fast neutron spectrum. Combining in appropriate way the mixture of fissile nuclei in order to increase the value of the parameter \( \eta \), it becomes possible to burn uranium more efficiently (roughly by a factor of 60, while the Generation-II reactors fuelled essentially with \( ^{235}\text{U} \) exploits less than one percent of the energy potentially available from uranium) extending also the Uranium resources, which contributes to the sustainability of the nuclear fuel cycle.

The fast reactors can also burn long-lived actinides, especially the Minor Actinides (MA) which are recovered from used fuel out of ordinary reactors. This ability is a characteristic feature of fast reactors and it is due to their neutron economy and to the spectral behavior of neutron capture and fission reactions of minor actinides. Indeed, Figure 4 displays the spectral behaviour of the parameter alpha, i.e. the ratio \( \sigma_{\text{capt}} / \sigma_{\text{fiss}} \), showing an appreciable fission probability starting in the fast spectrum region: \( E_{n} \geq 0.1 \) MeV; in the thermal spectrum only transformations, by nuclear reactions, of the MA are feasible. For each absorption event in fissioning nucleus: \( 1/(1 + \alpha) \) is the fission event probability, while \( \alpha/(1 + \alpha) \) is the capture
event probability, i.e.: \((1+\alpha)\) is the number of neutrons necessary for fission, while \(\alpha\) fissioning nuclei are transformed into fertile nuclei; each of them requires one supplementary neutron to “becomes” again fissioning nucleus. Since from each fission event \(\nu\) neutrons are produced, the maximum number of neutrons available for transmutation is:
\[
\nu - 2(1 + \alpha),
\]
In the real reactors from the neutrons balance it follows that neutron losses (by capture and leakage) are greater of 0.20 neutrons per fission, i.e.: the maximum number of neutrons available for transmutation is:
\[
\max\{n_{\text{transmutation}}\} \leq \nu - 2(1 + \alpha) - 0.2
\]  \hspace{1em} (5)
For the \((U, Pu)\) fuel cycle typical values of \(\nu\) and \(\alpha\) parameters are: \(\nu \approx 2.87, \ \alpha \approx 0.36\) for

\[
\text{Figure 4: Minor Actinides } \alpha = \frac{\sigma_{\text{cpt}}}{\sigma_{\text{fis}}} \text{ ratio spectral behaviour.}
\]
LWR, and \(\nu \approx 2.98, \ \alpha \approx 0.14\) for FR, or:
\[
\nu - 2(1 + \alpha) - 0.2 \approx -0.05 \quad \text{for thermal spectrum},
\nu - 2(1 + \alpha) - 0.2 \approx +0.5 \quad \text{for fast spectrum},
\]
showing again the difficulty of the thermal reactors to be deployed for MA transmutation, not without some technical and economical penalizations.

3  FAST REACTORS DEPLOYMENT

The methodology concerning the sustainability of the nuclear fuel cycle obviously does not refer to a single reactor, but on one or more groups of reactors to support a choice of energy supply. It is therefore based on energetic and physical considerations, with the aim to identify the processes, parameters, roadmaps, bottlenecks, etc., useful in establishing the validity and feasibility of an energy choice and the appropriate technological solution. An iterative process, among energetic scenario studies and reactor design studies, allows the convergence on the most performing solution, satisfying all the constraints. Appropriate computational tools, like: COSI6, [4], for scenario studies, ERANOS2.2, [5], for core design and FISPACT, [6], for irradiation/post-irradiation analysis, have been used.

3.1  Nuclear Materials Demand

Independently of the nature of the chosen cycle, namely: open or closed, \((Th, U)\) or \((U, Pu)\) fuels, thermal and/or fast reactors deployment, it’s obvious that in order to satisfy a given
energy demand the continuous availability of the loading nuclear materials is required, for the whole duration of the scenario. In case of an energy demand scenario which includes the deployment of the fast reactors, the scenario sustainability is extended to the availability of the necessary Pu to load the fast reactors fleet. This availability does not depend only on the Pu production in the thermal reactors, but could require specific choices regarding both the whole fuel cycle components and the design of the fast reactor itself.

To better highlight this situation, an appropriate scenario has been identified, [7]. Figure 5 shows the energy demand shares among the different reactor types, as well the different reactors deployment strategy. GEN-II reactors, working till 2050, will be replaced by GEN-III/III+ reactors since 2020, while GEN-IV FRs are deployed, starting from 2040, with a pace of about a plant per year until 2100, the complement energy production being ensured by GEN-III+ reactors. After that date GEN-IV reactors replace the GEN-III+ fleet, foreseen to work till 2160. FRs core reference configuration is characterized by unitary Breeding Ratio (Break-even core) without MA recycling, and 5 years cooling time.

Figure 5: Energy distribution / reactor type.

Figure 6 shows the Pu margin for the different configurations of the FRs in the scenario, while Table 1 provides the minimum Pu margin for the considered FR configurations.

Table 1: FRs Pu margin performances.

<table>
<thead>
<tr>
<th>Core</th>
<th>Recycling MA</th>
<th>Cooling Time</th>
<th>Pu margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Break-even (Green)</td>
<td>No</td>
<td>5 years</td>
<td>~ 0 tons</td>
</tr>
<tr>
<td>Break-even (Cyan)</td>
<td>Yes</td>
<td>5 years</td>
<td>~ 325 tons</td>
</tr>
<tr>
<td>Break-even (Blue)</td>
<td>No</td>
<td>2 years</td>
<td>~ 895 tons</td>
</tr>
<tr>
<td>Breeder (Red)</td>
<td>No</td>
<td>5 years</td>
<td>~ 1330 tons</td>
</tr>
</tbody>
</table>

At the same cooling time, the FRs core reference configuration (previously defined) does not sustain the scenario, while MA recycling and breeder FR configurations allow the sustainability of the scenario; moreover cooling time reduction provide sustainability solution. This option does not regard the core design; it concerns an action on one of the nuclear fuel cycle components. Indeed, the same gradient of the Pu margin gain, between reference and reduced cooling time configurations, indicates identical core performances.

3.1 Proliferation Resistance

Limiting ourselves to the aspects of the core design, the possible solutions to ensure sufficient amounts of Pu for the sustainability of the energy scenario namely: Pu and/or MA recycling or fertile assemblies "deployment" strategy, introduce several problems related to proliferation resistance and physical protection (PR&PP) aspects.

It does not concerns only the huge amount of Pu, equivalent to a high number of "Significant Quantity" units, and its management starting from the transportation, the
reprocessing and the fabrication of the new fuel. It concerns also the quality of produced Pu, or its isotopic composition. It is a “Reactor Grade” Pu (RG) with "intermediate" PR characteristics. Indeed, it is characterized by a fissile content higher than 60% and a \(^{238}\text{Pu}_{94}\) content lower than 1%, equivalent to "weak" resistance with respect to the proliferation, but shows a "strong" resistance with respect to the proliferation due to the high content of \(^{240}\text{Pu}_{94}\) which is higher than 30%, [8].

The same analysis has shown that independently from the energy share (high or low energy demand scenarios) Pu content and quality are not so different. Moreover, MA homogeneous recycling does not affect significantly the Pu composition, excepting the \(^{238}\text{Pu}_{94}\) content that increases of about 5 times, contributing to the improvement of the PR response through the increase of the heat rate.

3.2 Environmental Impact

The irradiated fuel discharged following the refueling strategy contains significant amounts of MA i.e. Long-Lived Waste of high activity. Their impact in terms of radiological loading and decay heat in the temporary and/or permanent radioactive waste disposal, represents an important problem which still has not an easy and immediate solution. The sustainability of the nuclear fuel cycle, beyond the production of enough Pu margin to load the FRs fleet, would require their recycling in nuclear reactors which, as already highlighted, can't be that fast reactors.

In case of the FRs break-even core configuration at 2 years cooling time, the homogeneous recycling of MA reduces the amount of MA to be sent to the disposal from about 1520 to 8 tons while the MA amount in the other fuel cycle components increases from about 113 to 303 tons, [9]. During a period of 150 years a total reduction of the MA amount by a factor of about 5, has been evaluated, while the reduction of the MA to be sent to the disposal is of about 2 orders of magnitude. For different energy demand scenarios, results close to the previous ones will be obtained.

This reduction, of about 2 orders of magnitude, is useful not only in terms of waste management but also in terms of proliferation resistance due to the considerable reduction of Np. For an energy demand scenario of 800 TWhe, the homogeneous recycling of MA in the same FR break-even core configuration allows a Np reduction: from about 250 tons to about 30 tons, as shown in Figures 7a and 7b.

Of course there are also some "contraindications" connected to the half-life of the isotopes of Cm and their cross sections from one side, and some other aspects related to the safeguards. The first involves an accumulation of Cm for time steps of the order of some centuries, and this imposes some considerations about the approach of the partitioning &
transmutation of the MA, while the second is due to the fact that the detection of $^{239}\text{Pu}_94$ is "masked", in terms of detection sensitivity, by the presence of $^{241}\text{Am}_95$. These difficulties of detection are due to a substantial overlapping of electron, gamma and neutron emission spectra, without taking into account the considerations regarding the uncertainties of the measurements.

3.3 Impact of the Uncertainties

There are various sources of uncertainties. For the closing of the nuclear fuel cycle, which requires the deployment of fast reactors, the transmutation of MA is an important step and the most significant nuclides of interest because of their consequences are:

- $^{241}\text{Am}$ and $^{244}\text{Cm}$, for what concerns decay heat and radio-toxicity for ingestion;
- $^{244}\text{Cm}$, for what concerns the neutron source for the spontaneous fission;
- $^{241}\text{Am}$, $^{242}\text{Am}$, $^{242m}\text{Am}$, $^{243}\text{Am}$ and $^{243}\text{Cm}$, for what concerns the gamma dose in manufacturing plants.

Considering only the neutron cross sections of fission and capture, the current degree of uncertainty can be considered acceptable in terms of the impact on the neutron source and the decay heat of the waste at repository. In fact, recent evaluations, [10], indicate percent values of the order of a few units:

$^{237}\text{Np}$: 0.5;  $^{238}\text{Pu}$: 1.0;  $^{241}\text{Am}$: 0.1;  $^{243}\text{Am}$: 0.9;  $^{244}\text{Cm}$: 2.9

for a combined total value (including other actinides) of 3.3%.

Assessments of the uncertainties for nuclides and reactions and origin different from the fission and capture cross sections (i.e. decay constants, fission yields, energy released, etc.) are subject of further investigation.

4 REMARKS

A safe management of the HLW, is mandatory in the pursuing a sustainable development of the nuclear energy in both Generation-IV and SNE-TP Initiatives. Reactor Physics and neutrons economy considerations show that the sustainability of the nuclear energy and waste minimization can be achieved by closed fuel cycle option. The realization of the nuclear fuel cycle closure, through FRs, is tightly connected with their deployment, which implies some constraints. The Pu availability is the main issue, while its lack during the cycle can be avoided adopting appropriate operative conditions for the different components of the associated fuel cycle, like:

- by cooling time reduction,
- by use of axial or/and radial blankets,
- by MA recycling, or
- by a combination of above options.

The cooling time is an important parameter for a sufficient Pu margin assuring the FRs deployment; this option does not affect the reactor core design both for break-even core and MA-bearing core in homogeneous recycling.

The rise of the breeding gain by axial or/and radial blankets introduction in the FR cores allows the production of the missing Pu, assuring the sustainability of the scenario especially in case of high energy share scenario. Proliferation issues condition strongly this option.

The MA homogeneous recycling is feasible with an increase of the core breeding gain, allowing the FRs deployment and a strong reduction of the TRU elements to be sent to the repository. Cm buildup and Pu safeguard issues have to be taken into consideration.
In addition, the knowledge of the fuel equilibrium composition plays an important role to conceive the fuel cycle, to foresee mass balances, to face PR&PP issues, to design the reactor, while the reactors should be designed according to the associated fuel cycle; not vice versa. Finally, changing Na-coolant to Pb-coolant not significant variations of the results would be expected.

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REFERENCES


