HYBRID NUCLEAR CYCLES FOR NUCLEAR FISSION SUSTAINABILITY

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Abstract

Nuclear fission can play and must play an important role in paving the road to Energy Sustainability. Nuclear Fission does not produce CO_2 emissions, and it is already exploited at commercial level with the current NPP (Nuclear Power Plants). Most of them are based on LWR reactors, which have a very good safety record. It must be noted, however, that all LWR (including the advanced or evolutionary ones) have some drawbacks, particularly their ***very poor efficiency in exploiting the natural resources of nuclear fuels***. In this paper, an analysis is presented on how to maximize the energy

actually generated from the potential contents of fission natural resources. The role of **fertile-to-fissile breeding** is highlighted, as well as the need of attaining a very high **safety performance** in the reactors and other installations of the fuel cycle. The proposal presented in this paper is to use advanced and evolutionary LWR as energy-producing reactors, and to use subcritical fast assemblies as breeders. The main result would be to increase by two orders of magnitude the percentage of energy effectively exploited from fission natural resources, while keeping a very high level of safety standards in the full fuel cycle.

Breeders would not be intended for energy production, so that safety standards could rely on very low values of the thermal magnitudes, so allowing for very large safety margins for emergency cooling. Similarly, subcriticality would offer a very large margin for not to reach prompt-criticality in any event.

The main drawback of this proposal is that a sizeable fraction of the energy generated in the cycle (about 1/3, maybe a little more) would not be useful for the thermodynamic cycle to produce electricity. Besides that, a fraction of the generated electricity, between 5 and 10 %, would have to be recirculated to feed the accelerator activating the neutron source. Even so, the overall result would be very positive, because more than 50 % of the natural resources could be exploited with such a cycle, using very safe reactors. This percentage is much higher than the actual value for the once-through cycle (0.5 %) and the value for multiple Pu recycling in the MOX scheme (1 %). Moreover, thorium could also be exploited through fertile conversion into U-233 in the subcritical breeders.

The separation between energy production (to be done in LWR) and nuclear breeding (to be done in subcritical hybrids) presents a scenario with very appealing safety features and a high potential for an efficient utilization of all natural resources of

uranium and thorium, that account for 10^{24} J, i.e., 25 Gtoe, which is 35,000 times as large as the annual production of Nuclear Energy nowadays, and about 2,500 times as large as the total annual energy consumption all over the globe.

Keywords: Nuclear fuel cycle, Energy Sustainability, Breeders, Accelerator Driven Systems.

1. INTRODUCTION AND BACKGROUND

Nuclear fission can play and must play an important role in paving the road to Energy Sustainability. The massive deployment of Renewables will require some decades, and the same can be said about Nuclear Fusion. It will not be easy to reach a fully commercial level in both cases. For the time being, Renewables are highly subsidized in all the countries where they have achieved a sizeable power [1]. Nuclear Fusion is receiving very high R&D budgets because it also conveys very appealing features as a long-term energy source. Nevertheless, Fusion R&D programs, even under the so-called Fast-Track Fusion scheme [2,3].

Current CO_2 emissions per year are about 1 % of the total atmospheric contents [4-7]. This means that the CO_2 concentration will double its value in one century, unless emissions are cut down or new CO_2 traps are implemented.

Nuclear Fission does not produce CO_2 emissions, and it is already exploited at commercial level with the current NPP (Nuclear Power Plants). Most of them are based on LWR reactors, which have a very good safety record. Even in the case of very severe accidents, as the one happened in Three Miles Island –2 (TMI-2) in 1979 [8], they have shown a very robust safety performance.

It must be noted, however, that all LWR (including the advanced or evolutionary ones) have some drawbacks, particularly their very poor efficiency in exploiting the natural resources of nuclear fuels.

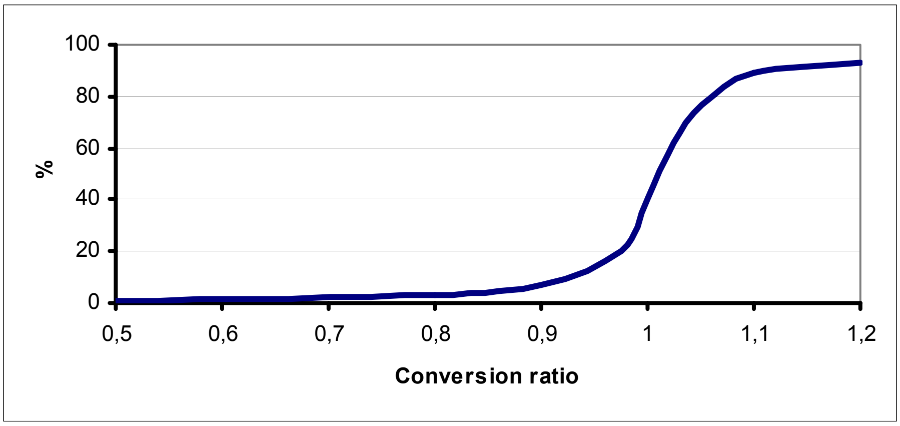

Figure 1. Percentage of natural resources utilization as a function of the conversion ratio (CR)

In figure 1, the percentage of energy utilization is depicted as a function of the reactor conversion ratio, which is the fundamental parameter in this context (see definition below, Eq.(1)).

As fissile nuclei are the fundamental ones for the chain reaction, the afore-mentioned conversion ratio, CR, is a key parameter to characterize a nuclear reactor. It is defined as

$$\mathrm{CR} = \frac{\text{Rate of production of fissile nuclei}}{\text{Rate of destruction of fissile nuclei}} \tag{1}$$

As fissile nuclei are produced by fertile captures, the conversion ratio can be expressed as follows

$$\mathrm{CR} = \frac{\sigma_{cu}\,U}{\sigma_{ap}\,P} \tag{2}$$

where U stands for the concentration (or for the inventory) of fertile nuclei, P stands for the concentration (or for the inventory) of fissile nuclei, and σ_{cu} and σ_{ap} are the average cross sections for fertile capture and fissile absorption (fission plus capture).

As can be seen in figure 1, fast breeder reactors (FBR) with a conversion ratio larger than 1 can achieve a very high percentage of energy utilization. In fact, the fissile material inventory in a FBR becomes larger at the end of an operation cycle than at the beginning of it. So, it can feed a new reactor with the excess of fissile material, once reprocessed. Of course, spent fuel reprocessing is needed to recover the fissile nuclei and the fertile ones. Fission fragments must be separated for being properly confined until they decay down to naturally occurring radioactive levels (what happens after 500 years, in round numbers). Minor actinides (MA) are also present in the spent fuel, and are particularly important for the long-term radiotoxicity of the nuclear waste [9].

All these features have been discussed and reviewed several times in national and international programmes, particularly in the INFCE initiative (International Nuclear Fuel Cycle Evaluation, 1978-1980). INFCE [10] was mainly oriented to hamper the deployment of the so-called Plutonium economy

In the last years, new initiatives on Nuclear Waste Transmutation were proposed [11-13] in order to reduce the long-term radiotoxicity of the wastes by eliminating a high fraction of the transuranics (TRU) from the spent fuel, before its final disposal.

This was one of the main reasons to launch the Generation 4 program and Forum [14], aimed at making it possible a new, more ambitious phase of Nuclear Fission Energy in the mid and long term.

Anyhow, new reactors would be needed for Nuclear Fission to be a true element in Energy Sustainability. More attention should be paid to proliferation resistant features, because the UREX+ method [15] produces a stream of Pu/Np that could be considered not totally safe for non-proliferation purposes [16].

2. NUCLEAR FISSION SUSTAINABILITY

There is a common view on the criteria that must guide Nuclear Fission Sustainability. They are the following ones:

- Non-proliferation
- Operational safety of nuclear installations
- Minimization of nuclear waste radio-toxicity
- Efficient use of nuclear fission raw materials
- Economic competitivity

In this analysis, lessons learned from nuclear accidents are very important. In this context, the Chernobyl accident is of paramount importance, because the very high power attained during the accident destroyed all the confinement barriers and spread a very large inventory of radioactive products in a very large area. As recognised in the official information of the Soviet Union authorities after studying the accident [17, 18], operator mistakes and safety violations led to a catastrophic accident because of the positive reactivity coefficient associated with the cooling water [19].

Undermoderation is a key criterion for reactor stability [20] and it must also be applied to Fast Reactors (where the molten metal has some slowing-down effect [21]).

The operational experience on LWR (that presumably will still be better in advanced and evolutionary LWR) and the physics of these reactors are a true guarantee that reactivity trips yielding prompt-critical states and extremely high power surges can not happen.

However, these reactors are not useful at all for efficiently exploiting the natural nuclear resources. This drawback can be overcome by including another neutron system (or reactor) in the fuel cycle, in order to produce the fissile material needed for feeding the burner reactors (i.e., energy-producer reactors). Of course, this second type of reactors can be called converters, because they convert fertile nuclei (as U-238) into fissile nuclei (as Pu-239). They must have very good safety features, particularly concerning criticality accidents. In this context, a subcritical system activated by an intense neutron source could be an appropriate choice. A subcritical reactor needs an external source in order to keep the value of the neutron flux. Without the source, the neutron flux vanishes, because the reactor by itself is unable to maintain the chain reaction.

Several proposals [22-47] can be found in the literature and they convey different types of mechanisms .The closest choice for activating an intense neutron source seems to be an accelerator particle beam impinging into a suitable target [42, 48-51]. Spallation reactions are the richest ones in neutron generation, particularly with a target made of heavy nuclei, where the beam protons will impinge. On the contrary, they are the dirtiest reactions because of the very many spallation products produced [52-58].

In the ower corner of the nuclides chart we find lithium-deuterium stripping reactions [55], with a very low production of radioactive nuclei (mainly tritium). For spallation reactions, protons in the range 500 MeV through 1 GeV seem adivisable, while lithium targets can work with deuterons in the range of 30-50 MeV, but higher energies are also advisable [59].

The main objective of this paper is to assess the overall performance of this hybrid fuel cycle, which is depicted in figure 2, and can represent a contribution to Nuclear Fission Sustainability.

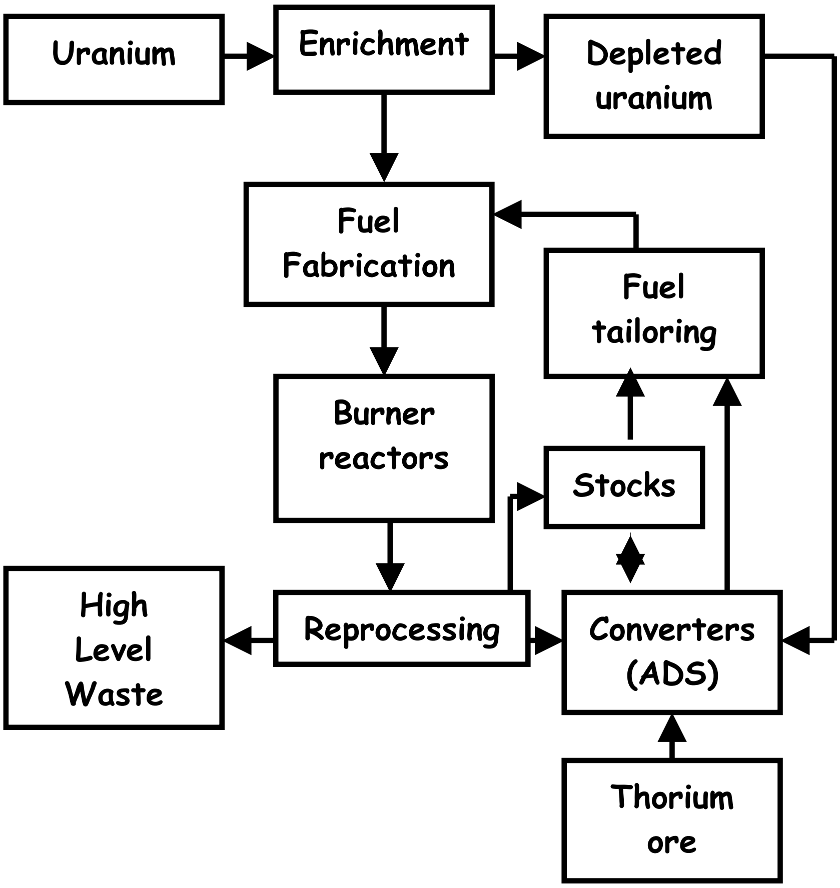

Figure 2. A sketch of the hybrid nuclear fuel cycle. Useful energy is produced in burner reactors (LWR and the like) while subcritical reactors (typically, ADS) are used as fissile fuel factories (converters).

3. THE HYBRID NUCLEAR FUEL CYCLE

Capture cross sections in the fertile nuclei (U-238 and Th-232) have very peculiar and well-known features, as a function of the neutron energy [60, 61]. For thermal energies, the cross section value is high, but much lower than the fission cross section of the fissile materials. In the epithermal and intermediate energy region (between 1 eV and 10 keV, approximately) the capture cross sections have many resonances and they go down very strongly for higher neutron energies.

In a Fast Reactor, a suitable energy shape is tailored in the neutron spectrum (by means of an adequate composition in the fuel and the coolant, and adequate volume fractions for each material) so that the neutrons are very poorly moderated.

As depicted in figure 2, two types of reactors would be needed to close this nuclear fuel cycle. On the one hand, burner reactors would be responsible for producing the required energy. In our approach, these reactors would be LWR type.

The second type of reactors would produce the nuclear conversion, and could be fed either from reprocessed fuel, or from depleted uranium, or natural thorium. Those breeders would be subcritical and would need an external neutron source, as already said. In order to assess the potential of this type of hybrid cycles for exploiting the nuclear fission natural resources.

4. NEUTRONIC CHARACTERIZATION OF A HYBRID REACTOR

A hybrid can be considered a subcritical blanket surrounding a source where Q neutrons per second are born. A fraction ζ of the fusion-born neutrons reach the blanket, which is made of a fissile material (P), a fertile material (U), and other nuclei such as structural materials and the coolant. The fuel composition will be characterized by E which stands for the fissile to fertile concentration ratio.

$$E = \frac{P}{U} \tag{3}$$

A simple subcritical accounting [47] leads to the following calculation of the total number T of neutrons disappearing in the blanket, through absorption or leakage, per source neutron

$$T = \zeta \frac{\psi^{*}}{1 - k} \tag{4}$$

where ψ^* is an importance factor [62]

The physical interpretation of ψ^* can be derived from the reciprocity principle between direct and adjoint fluxes and sources [20]

$$(\psi^{+}\ S) = (S^{+}\ \psi) \tag{5}$$

The adjoint source S^+ can represent either a definite cross section or the function 1/v, which enables one to relate the importance function ψ^+ either to a reaction rate or to the number of neutrons produced in the reactor.

The basic parameters chosen to characterize the blanket neutronics are

ν'= mean number of secondary neutrons per multiplicative reaction (in most of the hybrids, this will be very close to ν, the number of neutrons per fission);

η' = mean number of secondary neutrons per absorption in the fuel (accounting for all types of fuel nuclei, not only for fissile ones).

x = probability of a neutron in the blanket to be absorbed in the fuel;

z = the probability of an absorption in the fuel to be a fertile capture.

Any relevant integral magnitude of the hybrid can be expressed in terms of the former parameters. For instance, the effective multiplication factor k

$$k = \eta' x \tag{6}$$

and the breeding ratio B (i.e. the conversion ratio (eq. 1) of this reactor, that would be larger than 1)

$$B \geq \frac{z}{1-z} \tag{7}$$

where the equality holds for $\sigma_{cU}=\sigma_{aU}$, that is when the rate or multiplicative (fission) reactions in the fertile material U is negligible. In general, it will be so, because most of the neutron multiplication reactions will take place in the fissile nuclei.

On the other hand, these parameters are interrelated through

$$z + \frac{\eta'}{\nu'} \leq 1 \tag{8}$$

the equality being fulfilled for $\sigma_{cp} = 0$, i.e., when all the fissile absorptions are multiplicative reactions. In suitable hybrid reactors working as converters, more than 80 % of the absorptions will convey neutron multiplication.

The value of those parameters will depend on the fuel composition and the spectrum. As a very rough estimate, for a thermal blanket with uranium it can be fitted to

$$\eta' = \frac{2.1E}{E + 0.01} \tag{9}$$

and for a fast blanket (with plutonium)

$$\eta' = \frac{3E + 0.006}{E + 0.03} \tag{10}$$

On the other hand, the fuel composition and the breeding ratio can be related through a spectral index w, defined as follows

$$w = \frac{\sigma_{cU}}{\sigma_{aP}} = EB \tag{11}$$

where E and B have been defined in eqs. 3 and 7. It is worth quoting that for thermal spectra w ~ 0.01 (or even smaller); for epithermal spectra, w ~ 0.05, and for fast ones, w ~ 0.1 or even larger. It is possible to obtain higher w figures with intermediate spectra generated by incomplete moderation.

One of the main consequences of last equation is the definition of the maximum fissile to fertile ratio E* achievable in a breeding regime ($B \geq 1$), which is equal to the spectral index:

$$E^* = w \tag{12}$$

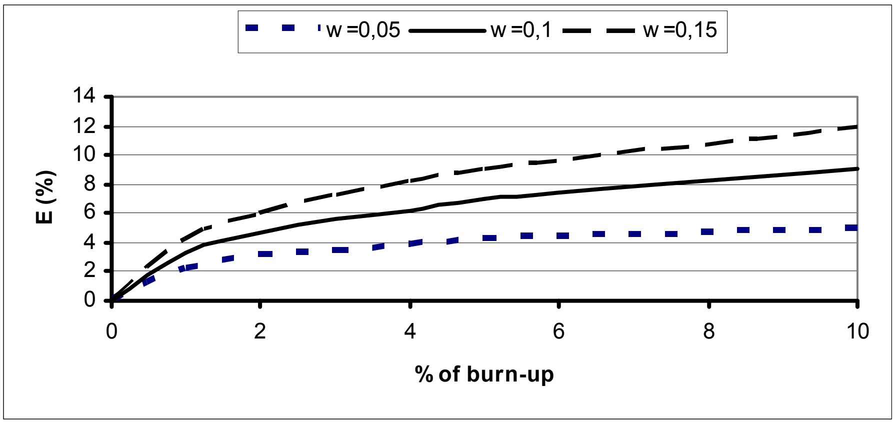

Figure 3. Fissile to fertile ratio (E) evolution along burnup as a function of the spectral index w

4.1. Fissile production (Breeding)

If ε stands for the number of fertile captures produced per source neutron, we have

$$\varepsilon = \frac{\zeta\psi^*}{1-\eta' x} zx \tag{13}$$

and taking into account Eq.(8),

$$\varepsilon \approx \frac{\zeta\psi^*}{1-\nu'(1-z)x} zx \tag{14}$$

$$\left(\frac{d\varepsilon}{dz}\right)_{\nu' x} = \frac{\zeta\psi^*(1-\nu' x)x}{(1-\nu'(1-z)x)^2} \tag{15}$$

It is clearly observed that the sign of the derivative depends on (ν′x-1). For ν′x >1, the derivative is negative, i.e., ε increases as z decreases, but the minimum value of z is bounded because criticality is attained at

$$z_{\min} = \frac{\nu' x - 1}{\nu' x} \tag{16}$$

As $z \rightarrow z_{\min}$, ε tends to infinity, but this is an asymptotic behaviour related to the mathematical fact that the neutron flux in a critical reactor tends to infinity if it is neutronically fed by an external source.

Of course, this situation is utterly impossible, because the power would also be infinite.

4.2. Neutron subcritical multiplication

The most important reaction in this subject is fission, which yields Q_f~ 200 MeV per reaction. We must also include the capture contribution with Q_c ~ 6.5 MeV and the (n,2n) and (n, 3n) energy-consuming reactions with $Q_{n,2n}$ = -6 MeV and $Q_{n,3n}$ = -12 MeV.

If γ stands for the energy muyltiplication in the blanket per unit of source energy, then

$$\gamma = \frac{Q_f}{Q_s}\zeta\frac{\psi^*}{v}\frac{k}{1-k}\frac{1+\frac{Q_{n,2n}}{Q_f}\frac{\Sigma_{n,2n}}{\Sigma_f}+\frac{Q_{n,3n}}{Q_f}\frac{\Sigma_{n,3n}}{\Sigma_f}+\frac{Q_c}{Q_f}\frac{\Sigma_c}{\Sigma_f}}{1+\frac{2}{v}\frac{\Sigma_{n,2n}}{\Sigma_f}+\frac{3}{v}\frac{\Sigma_{n,3n}}{\Sigma_f}}+1 \qquad (17)$$

In the usual cases where fission dominates both energy and neutron multiplication, it can be written

$$\gamma = \zeta\frac{\psi^*}{v}\frac{\eta' x}{1-\eta' x}\frac{Q_f}{Q_s}+1 \qquad (18)$$

which tends to infinity as the blanket approaches criticality ($\eta' x = 1$). Safety requirements, particularly subcriticality margins, set the maximum k allowable, and therefore the maximum energy multiplication factor.

4.3. Effective fissile production

Taking into account that a light water reactor yields a discharge burnup (in percent) very close to the feed enrichment (in percent as well) in a once-through cycle, the potential energy can be defined by Q_f (200 MeV) times the number of fissile nuclei produced, ε. Hence, the support ratio would be

$$S = \frac{Q_f}{Q_s}\frac{\varepsilon}{\gamma} = \frac{\xi\,\psi^{*} z\, x\, \nu' Q_f}{\xi\,\psi^{*} k\, Q_f + \nu'(1-k) Q_s} \tag{19}$$

which is expressed in terms of the basic parameters of the blanket and the source.

When the energy balance in the hybrid is dominated by the blanket (because k is not very far from 1) an upper limit of S can be found, which corresponds to

$$S = \frac{z\nu'}{\eta'}$$

In fact, this is only true for k=1, but it gives a general indication of the importance of the blanket parameters.

If Eq. (8) is taken into account for the simplest case of $\sigma_{cp}=0$, it holds

$$z = 1 - \frac{\eta'}{\nu'} \tag{20}$$

and the Support ratio becomes

$$S = \frac{\nu' - \eta'}{\eta'} \tag{21}$$

For a fast spectrum subcritical blanket, one can have $\nu'=3$ and $\eta'=1$. This means that S will be close to 2. If neutron parasitic captures are taken into account, this value can decrease by 10 % or so. It is important to note that this value of η' includes all types of neutron absorptions in the fuel isotopes, both fissile and fertile ones.

The former value indicates that a breeder can produce fissile fuels for LWR reactors with a total power twice as large as the breeder power.

From this general calculation it could be said that natural resources utilization could reach 65 % with this scheme, instead of 0.5 or 1 %.

5. SUMMARY AND CONCLUSIONS

Current and anticipated LWR present very robust safety standards, but they are not suited for an effective exploitation of the natural resources, which needs fertile-to-fissile breeding. This can be achieved in a Fast Breeder Reactor (and less probably, in a Thorium Thermal Breeder) but safety analysis on those reactors, particularly FBR, identified some major problems in connection with reactivity trips and nuclear-thermal-hydraulic feedback. Those risks were analyzed in the INFCE initiative, which was a serious blow against the Breeder development [10].

Theis proposal [66] is based on using LWR for electricity generation (as burner reactors) and subcritical hybrid blankets, driven by intense neutron sources, as breeders. Those breeders would not be intended for energy production, so that safety standards could rely on very low values of the thermal magnitudes, so allowing for very large safety margins for emergency cooling. Similarly, subcriticality would offer a very large margin for not to reach prompt-criticality in any event.

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