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Nuclear fission sustainability with hybrid nuclear cycles

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Abstract

An analysis is presented on the main requirements to develop nuclear fission in the context of social, economic and environmental sustainability. This analysis is mainly focused on maximizing the energy actually generated from the potential contents of fissionable 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 light water reactors (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 fissionable natural resources while keeping a very high level of safety standards in the full fuel cycle.

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 renewable energy sources 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 either case. For the time being, renewable sources are highly subsidized in all the countries where they have achieved a sizeable power [1]. This is a mandatory policy to foster their development, and it is justified for the long term advantages that renewable sources will convey in meeting the global energy demand. 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], will still require several decades to reach an industrial level.

It is obvious that fossil fuel combustion contributes to increasing the CO_2 inventory in our atmosphere, thereby enhancing the greenhouse effect. 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 reduced or new CO_2 traps are implemented.

Nuclear fission does not produce CO_2 emissions, and it is already exploited at the commercial level with the current NPP (Nuclear Power Plants). Most of them are based on LWR (light water reactors), which have a very good safety record. Even in the case of very severe accidents, as the one that happened in Three Mile Island – 2 (TMI-2) in 1979 [8], they have shown a very robust safety performance, and radioactive products have always been kept inside the confinement barriers almost 100%. Radiological effects around Western World nuclear power plants have always been very much below emergency levels. This was also true in the fire (initiated in a turbine) that destroyed Vandellós I NPP in 1989 (in Tarragone, Spain). In that case, the reactor was a gas cooled reactor (GCR), and it was not affected by the fire neither directly (thanks to the quenching and prevention systems) nor indirectly (because the emergency core cooling system fully fulfilled its objective of maintaining the integrity of the fuel and fuel cladding).

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Indeed, the experience gained in the operation of more than 400 commercial reactors, most of them LWR, is a sound reason to consider nuclear fission as a key element for electricity production for many decades to come. Moreover, evolutionary or advanced LWR are already available with improved safety and commercial standards. Those improvements come from a suitable feedback of the acquired experience in the design and operation of the existing reactors. In summary, those reactors are very interesting for satisfying the energy needs in the coming decades.

It must be noted, however, that all LWR (including the advanced or evolutionary ones) have some drawbacks, particularly in their very poor efficiency in exploiting the natural resources of nuclear fuels. In the once through cycle based on uranium, the fraction of primary energy (contained in the nuclei) converted into useful heat is of the order of 0.5%. The rest of the energy remains in the depleted uranium (about 85%) and in the spent fuel (about 15%). Even in the case of recycling, considering the useful fraction of the spent fuel in a mixed oxides (MOX) scheme (a mixture of plutonium and uranium oxides), the percentage of exploited energy does not exceed 1%. This means that LWR are not very good tools for energy sustainability because they can not exploit the natural resources in an efficient way.

In Fig. 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)). It is worth remembering that 99.29% of natural uranium is U-238, which does not undergo fission when irradiated by thermal neutrons. U-235, which undergoes fission by reacting with thermal neutrons, only accounts for 0.71%. Additionally, all the available thorium is Th-232. Like U-238, it does not undergo fission by the action of thermal neutrons. The reason for that is nuclear parity, and it is rooted in the very nature of the nuclear force. Heavy nuclei with Z even and A odd, as U-235, U-233 or Pu-239, undergo fission with thermal neutrons, and they are generally called fissile material. On the contrary, heavy nuclei with Z even and A even, do not undergo thermal fission. However, they can suffer the so-called fertile capture, which yields a fissile nucleus. Namely, U-238 capture of a neutron produces Pu-239, and Th-232 capture of a neutron produces U-233 (in both cases, after two consecutive beta decays, once the neutron capture takes place).

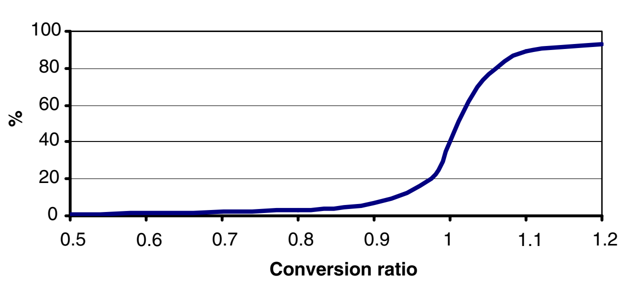

Fig. 1. Percentage of natural resources utilization as a function of the conversion ratio (CR).

Nuclear parity is, therefore, a main feature for fission. 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:

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

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). In general, there could be several fertile nuclei and several fissile ones, and the total rate of each reaction has to be properly calculated by taking into account the concentration of each type of nuclei. Moreover, cross-sections have to be properly averaged with the neutron flux energy shape because cross-sections do depend quite a lot on neutron energy.

As can be seen in Fig. 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. So, it can feed a new reactor with the excess fissile material, once it is 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 to naturally occurring radioactive levels (which 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 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 because of the risks related to proliferation and nuclear safety. Indeed, INFCE halted the USA fast breeder program. Although other programs, notably the French one, continued in that field, by the year 2000, the LMFBR (Liquid Metal Fast Breeder Reactor) development had been stopped to a large extent, and the French Super-Phenix reactor had been switched off.

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. Such a possibility could be seen as a complementary action to uranium and plutonium recycling in suitable reactors (breeders). Nevertheless, breeder reactors