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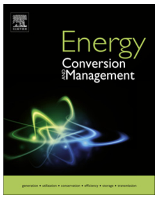

Analysis of a Spanish energy scenario with Generation IV nuclear reactors

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ABSTRACT

The advantages of fast-spectrum reactors consist not only of an efficient use of fuel through the breeding of fissile material and the use of natural or depleted uranium, but also of the potential reduction of the amount of actinides such as americium and neptunium contained in the irradiated fuel. The first aspect means a guaranteed future nuclear fuel supply. The second fact is key for high-level radioactive waste management, because these elements are the main responsible for the radioactivity of the irradiated fuel in the long term.

The present study aims to analyze the hypothetical deployment of a Gen-IV Sodium Fast Reactor (SFR) fleet in Spain. A nuclear fleet of fast reactors would enable a fuel cycle strategy different than the open cycle, currently adopted by most of the countries with nuclear power. A transition from the current Gen-II to Gen-IV fleet is envisaged through an intermediate deployment of Gen-III reactors. Fuel reprocessing from the Gen-II and Gen-III Light Water Reactors (LWR) has been considered. In the so-called advanced fuel cycle, the reprocessed fuel used to produce energy will breed new fissile fuel and transmute minor actinides at the same time.

A reference case scenario has been postulated and further sensitivity studies have been performed to analyze the impact of the different parameters on the required reactor fleet. The potential capability of Spain to supply the required fleet for the reference scenario using national resources has been verified.

Finally, some consequences on irradiated final fuel inventory are assessed. Calculations are performed with the Monte Carlo transport-coupled depletion code SERPENT together with post-processing tools.

1. Introduction

The most famous definition of sustainability was included in the Brundtland report in 1987 [1]: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. Another technical point of view about sustainability is the fact of no decreasing neither the environmental quality nor the individual one [2]. The human activities linked to sustainability are affected by three kinds of limitations: environmental, economic and social ones [3–5].

Many authors have classified the different energies in terms of sustainability [6] according to different parameters. They can be set into three: resources consumption, environmental impact and economical and technical availability. In case of nuclear energy, parameters such as no proliferation and nuclear safety should be also considered.

Regarding nuclear fission, the use of the current technology (Generation I to III+) has disadvantages in terms of resources availability for long term. An interesting option for Fuel Cycle is what is called “closed cycle” as it is the most sustainable option possible. Closed cycle means that the irradiated fuel, after being burnt and then cooled in the power plant spent fuel pool, is reprocessed as it still has around 0.6% Pu-239 and 0.7% U-235, which are the most common fissile materials. This Pu-239 is used together with U-238 to make new fresh fuel, called MOX (Mixed Oxide) fuel, to be used again in power plants. Almost 94% of the irradiated fuel is U-238, which might be reused for fresh fuel too. The rest are fission products (FP) and minor actinides (MA), which are the most radioactive components of the spent fuel. Those materials (FP and MA) are normally vitrified to manage them in a much more stable solid form than their natural one. Those wastes have been considered to be stored in a geological deep repository, to avoid human and environmental contact for thousands of years.

In terms of efficiency, the total primary energy (the natural uranium at the mine) estimated to be transformed into heat in the fission process in a once-through cycle is 0.5%. The 85% of the potential energy is still stored in the natural uranium unused in

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the process of fuel fabrication and the other 14.5% is stored in the spent fuel [7]. In terms of mass, in light water reactors with once-through cycles, only 3 kg of U-235 from each 1000 kg of natural uranium (99.3% U-238 and 0.7% U-235) are used for generating heat. In a closed cycle with reprocessing, the used resource is doubled to 1%. Therefore, there is a need of improvement in the fuel cycle as the major part of the resource is treated as a sub-product (depleted uranium) or as waste (spent fuel).

The most advanced fuel cycle strategy nowadays is not only based on spent fuel reprocessing to make new MOX fuel, but also on separation and transmutation of minor actinides and fuel breeding. The MA transmutation is meant to reduce the radioactive inventory of the spent fuel, while fuel breeding consists on generating fissile material (Pu-239) from non-fissile U-238. Actually fast reactors can produce more fuel than what they use in a cycle. The advanced fuel cycle strategy needs fast reactors as the sodium cooled one, which is the chosen system for the present analysis. The use of these reactors can wide the availability of resources for much more than 300 years, as they use very efficiently the fuel [8].

It is also important to underline the case of Thorium (Th-232) as a fuel for fast reactors. It can be transmuted into U-233, a fissile element that might be used in the actual thermal reactors. Thorium is a huge resource to be used, which is estimated to be 4.4 millions of tons among the known resources [9]. This resource can play an important role to make sure a long term development of nuclear energy, especially in countries like India [10].

Nuclear fission produces low CO_2 emissions, even taking into account all fuel cycle process (65 g CO_2/kW h), compared with other energies like thermal plants (600–1200 g CO_2/kW h), solar panels (90 g CO_2/kW h), and higher than wind or hydro power (30–65 g CO_2/kW h) [11–15].

In addition, a sustainable strategy for nuclear energy has to take into account the no proliferation and safety aspects [16,17]. In case of the no proliferation aspects, the fuel reprocessing process makes very difficult the Pu-239 isolation, as it is mixed with other isotopes such as Pu-240 and Pu-241. One advantage of a closed fuel cycle with MOX fuel is the possibility of recycling the military Pu for energy production. Regarding safety, sodium fast reactors have inherent safety characteristics due to the physical properties of the materials and the type of system (for example, pool type avoids coolant losses). There is a long experience of commercial operation with these reactors and some of them have operated for more than 35 years like Phenix, in France. However, they face some challenges in the next years for the massive implementation of this technology.

As a consequence of USA president Carter decision in 1977 [18], the United States stopped reprocessing in an attempt to limit the proliferation of nuclear weapons material. Since then spent fuel is stored intact in a repository, what is called once-through cycle.

Spain, as other countries like Canada, Finland or Sweden, followed later on that decision [19]. Before that moment Spain was reprocessing its spent fuel in other countries like France or UK. After that strategic change, the spent fuel pools of the Spanish nuclear plants slowly became full, as they were not designed to handle with the spent fuel of their operational life. Several actions were planned by the power plant owners such as re-racking the spent fuel pool or building an Individual Temporary Storage to store each plant's own wastes in shielded casks. All these expensive actions could have been avoided with a Centralized Temporary Storage (CTS). However the decision was delayed in the last years for political reasons till finally it was approved in December 2011. This storage will have enough room to cope with all the Spanish spent fuel and with the waste from reprocessing waiting in France to come back to Spain. Nevertheless, as its own name indicates, the CTS facility is a temporal solution for the high-level radioactivity wastes. Alternative technologies should be pursued to provide a definite solution to those wastes, and the reduction of the radioactive load of the wastes in fast reactors could be an interesting option to be investigated. Indeed, one feasible option is the mentioned advanced closed cycle, since the existing reprocessing plants have demonstrated the correct operability of the irradiated waste treatment and the occidental countries respect the non-proliferation treaties. These two aspects are the main reason to support the advanced fuel cycle in the study.

In this paper, a hypothetical Spanish energy scenario with sodium fast reactors is analyzed, testing if a fleet of nuclear fast reactors could solve any of the challenges that the nuclear industry is facing, such as nuclear waste management, security of supply and sustainability.

In the first part of the paper, the Generation IV reactors characteristics are briefly summarized, as they represent a step up to the nowadays Generation II and III/III+ reactors. Later on, the Spanish energy scenario is presented, introducing some sensitivity studies. Finally the detailed results and conclusions of the study are presented to show the influence in terms of energy production, resources availability and nuclear waste reduction.

2. Reactor technology description – Sodium-cooled fast reactors

The new nuclear power plant designs considered in Generation IV initiative pretend to overcome past and present design parameters in terms of sustainability, industrial competitiveness, safety and proliferation resistance. Additionally to power generation, these new designs will be used to generate industrial process heat and hydrogen production.

Sodium fast reactors meets these goals clearly and have many years of operational experience. Actually, they are in operation nowadays in countries like Japan, China or Russia and in a very short term India [20–22].

The two main advantages of SFR in terms of sustainability were explained in the introduction: the possibility of minor actinides transmutation and the capacity of breeding fuel. The main disadvantages are related with operational safety. Sodium could have a positive reactivity feedback in case of coolant voiding. This fact has a strong influence on the core design. Therefore many analyzes have been and are being done to get an optimal configuration design that avoids power excursions [23,24]. On the other hand, sodium is very reactive with water and air (oxygen), so the interfaces between those components must be reliable enough to avoid any contact in any case. Related with fuel fabrication, if transmutation of minor actinides is intended, difficulties in manufacturing (U,Pu,MA[1])O_2 should be overcome, since fuel loaded with MA is highly radioactive.

2.1. SFR core design

The SFR core design used in this analysis corresponds to the new optimized core of the CP-ESFR European Project, from the European Community's Seventh Framework Program [24]. The basic core, called CONF2, with 3600 MWth contains oxide fuel in two concentrically regions, distributed in an inner and outer region. The outer region presents slightly higher plutonium enrichment in order to flatten the radial power shape at the end of the cycle. The active region of the core has a flattened shape of about 4.7 m in diameter by 1.0 m height. There exist five different types of sub-assemblies (SA), two fuel SA with a different isotopic enrichment, two control elements with different boron carbide compositions and one radial reflector assembly. Above the fuel SA there is a sodium plenum

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[1] MA: Minor Actinides (Americium, Neptunium and Curium).