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Prospective scenarios of nuclear energy evolution on the XXIst century over the world scale

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ABSTRACT

Different world scenarios of nuclear energy development over the XXIst century are analyzed in this paper, by means of the EDF fuel cycle simulation code for nuclear scenario studies, TIRELIRE – STRATEGIE.

Two nuclear demand scenarios are considered, and the performance of different nuclear strategies in satisfying these scenarios is analyzed and discussed, focusing on the maximum deployable capacity and the natural uranium consumption. Both thermal-spectrum systems (Pressurized Water Reactor, PWR, and High Temperature Gas-cooled Reactor, HTGR) and different designs of Fast Breeder Reactor (FBR) are investigated. A sensitivity analysis on the FBR deployment date, Breeding Gain and fuel cycle options is also presented.

1. Introduction

On December 31, 2005, the world nuclear installed capacity was equal to 368 GWe (441 reactors), for an electricity production of about 2600 TWhe in 2005. Additionally, 22 GWe were under construction, mainly in ex-USSR and Asian countries.

Many analysts forecast an increase of the nuclear energy share over the rest of this century (both for electricity and hydrogen production) because of the well-known probable reduction of electricity production by means of fossil resources, as a consequence of their increasing price due to exhaustion and the attempt to reduce greenhouse gas emissions. In this context, the natural uranium availability clearly becomes a central issue to ensure long-term sustainability to nuclear energy, but great uncertainties on the evolution of the uranium price over the next decades remain. These issues are at the origin of the debate whether the open or the closed fuel cycle will be the predominant strategy worldwide.

In this paper, which objective is to bring a modest contribution to this debate, two scenarios of nuclear energy on the XXIst century are modeled. The analysis of these scenarios allows calculating the impact of strategic choices concerning the nuclear fuel cycle on key-parameters like the uranium consumption, waste production and installed capacity. Many studies were carried out in the past on this subject (Ono et al., 2003; Massara et al., 2006b, 2007).

More specifically, this paper presents an inter-comparison of the performance of different fuel cycle strategies (based on Pressurized Water Reactor (PWR), High Temperature Gas-cooled Reactor (HTGR) and Fast Breeder Reactor (FBR)). This paper will address only the uranium–plutonium cycle, completely mastered on the industrial scale. Concerning the FBR technology, only the most mature on the industrial scale is considered (Na-cooled), but the main reactor and fuel cycle options (Breeding Gain, BG, ex-core fuel time, Minor Actinides, MA, handling strategy, deployment date) are checked and assessed, taking care to cover all the “reasonable” range of variation of these parameters. In order to reduce the scope of cases to be studied, three FBR deployment *kinetics* will be formulated and analyzed: one intermediate – that we consider the most likely to occur – and two extreme (fast and slow). The Pu availability being of primary importance in defining the maximum starting-up kinetics of FBR, two cases will be considered: either the FBR's maximum starting-up kinetics is limited by the Pu availability in the fuel cycle, or FBR start-up could also be realized by means of enriched uranium. Advantages and drawbacks of each solution will be detailed in the paper.

The results of this study, which was carried out by means of the EDF fuel cycle simulation code for nuclear scenarios analysis, TIRELIRE – STRATEGIE, will be focused on “physical” results (nuclear installed capacities, natural uranium consumption, radioactive material inventories and mass flows between the nuclear reactors and the associated fuel cycle facilities – i.e. fuel fabrication and processing, intermediate cooling, final geological disposal); hence, no economical considerations, which are the object of future studies and would of course strongly affect the development of the scenario, will be presented in the paper.

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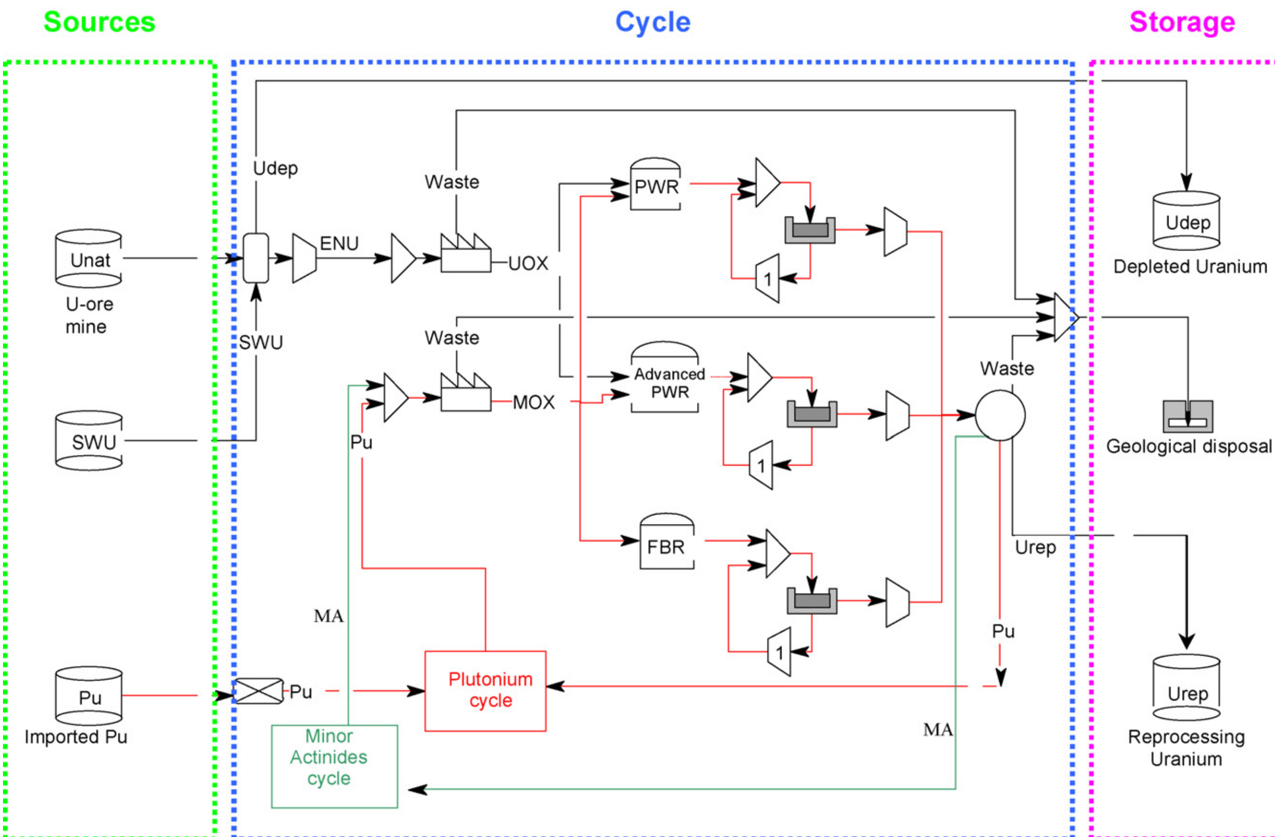

Fig. 1. Schematic illustration of the nuclear fuel cycle.

2. The EDF fuel cycle simulation code TIRELIRE – STRATEGIE

2.1. General features

TIRELIRE – STRATEGIE (Massara et al., 2005a) is a calculation code aimed at simulating the operation of a nuclear fleet and the associated fuel cycle facilities over a long period of time (decades, even centuries). It is used to analyze the consequences of strategic choices related to the nuclear fleet composition (reactors and fuels) and other fuel cycle facilities features. A template nuclear fuel cycle modeled in TIRELIRE – STRATEGIE is shown in Fig. 1.

TIRELIRE – STRATEGIE allows nuclear scenarios simulation to comply with industrial requirements (such as spent UOX and MOX reprocessing capacity limitation, interim storage capacity, cooling time before reprocessing, delay for fresh fuel fabrication, losses during reprocessing or fabrication, number and characteristics of reactors being reloaded for each year) and to take into account strategic choices (i.e. type of reactors and fuel management used for the nuclear fleet renewal, minor actinide incineration rates, interim storage management).

2.2. Detailed description

The main parameters defining the dynamics, year per year, of a nuclear scenario in TIRELIRE – STRATEGIE are basically:

- The nuclear fleet installed capacity (in GWe), which is related to the electricity production via the average fleet load factor;
- The installed capacity of each nuclear system type (i.e. PWR, FBR, HTGR, etc.);
- A priority level associated to the deployment of each nuclear system type;
- Maximum introduction rate for the total fleet and for each reactor type;
- MA (Np, Am and Cm) rate at fuel fabrication and losses at reprocessing for all actinides and for each reactor type;
- Reprocessing rate for each fuel type;
- Spent Nuclear Fuel (SNF) cooling time before reprocessing and delay for fresh fuel fabrication, for each reactor type.

Each reactor type is characterized by:

- Maximum lifetime;
- Core Heavy Metals (HM) mass and the HM mass reload (taking into account its reload batch size);
- Fuel type which can be charged in each reactor type (i.e. UOX, MOX, Pu on Th support for advanced PWRs);
- Fuel irradiation time;
- Parameters specifying the models for the calculation of the discharged fuel isotopic composition (*evolution model*) and the Pu content for fresh MOX fuel (*equivalence model*). The evolution and equivalence models are different for PWR and FBR (cf. Fig. 2) and will be presented in the following sections.

The code calculates the power capacity to be installed every year, on the basis of the total power demand and the number of decommissioned units, if any. This power demand will be satisfied by the reactor types taken into account in the current scenario, according to their priority level and their maximum introduction rate: i.e. if the priority is 1 for PWR, 2 for FBR and 3 for HTR, then PWR will be deployed up to their maximum deployable power. When this limit is reached, the next reactor type in the priority order will be considered (in this case FBR) and so on.