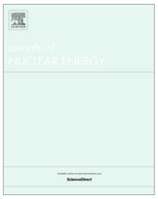
Annals of Nuclear Energy 70 (2014) 240–247

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



Analysis of advanced European nuclear fuel cycle scenarios including transmutation and economic estimates

Iván Merino Rodríguez, Francisco Álvarez-Velarde *, Francisco Martín-Fuertes

CIEMAT, Avda. Complutense, 40, 28040 Madrid, Spain

ARTICLE INFO

Article history:
Received 9 August 2013
Received in revised form 11 March 2014
Accepted 16 March 2014
Available online 11 April 2014

Keywords:
Fuel cycle
Advanced reactor
Transmutation
Energy cost
Cost uncertainties

ABSTRACT

Four European fuel cycle scenarios involving transmutation options (in coherence with PATEROS and CP-ESFR EU projects) have been addressed from a point of view of resources utilization and economic estimates. Scenarios include: (i) the current fleet using Light Water Reactor (LWR) technology and open fuel cycle, (ii) full replacement of the initial fleet with Fast Reactors (FR) burning U–Pu MOX fuel, (iii) closed fuel cycle with Minor Actinide (MA) transmutation in a fraction of the FR fleet, and (iv) closed fuel cycle with MA transmutation in dedicated Accelerator Driven Systems (ADS). All scenarios consider an intermediate period of GEN-III+ LWR deployment and they extend for 200 years, looking for long term equilibrium mass flow achievement.

The simulations were made using the TR_EVOL code, capable to assess the management of the nuclear mass streams in the scenario as well as economics for the estimation of the levelized cost of electricity (LCOE) and other costs.

Results reveal that all scenarios are feasible according to nuclear resources demand (natural and depleted U, and Pu). Additionally, we have found as expected that the FR scenario reduces considerably the Pu inventory in repositories compared to the reference scenario. The elimination of the LWR MA legacy requires a maximum of 55% fraction (i.e., a peak value of 44 FR units) of the FR fleet dedicated to transmutation (MA in MOX fuel, homogeneous transmutation) or an average of 28 units of ADS plants (i.e., a peak value of 51 ADS units).

Regarding the economic analysis, the main usefulness of the provided economic results is for relative comparison of scenarios and breakdown of LCOE contributors rather than provision of absolute values, as technological readiness levels are low for most of the advanced fuel cycle stages. The obtained estimations show an increase of LCOE – averaged over the whole period – with respect to the reference open cycle scenario of 20% for Pu management scenario and around 35% for both transmutation scenarios. The main contribution to LCOE is the capital costs of new facilities, quantified between 60% and 69% depending on the scenario. An uncertainty analysis is provided around assumed low and high values of processes and technologies.

1. Introduction

The efficient design of strategies for the long-term sustainability of nuclear energy requires the study of transition scenarios from the current fuel cycle to a future one with advanced technology and concepts. This kind of studies provides answers to different aspects of transition scenarios, such as the period of time needed to reach equilibrium, the number and date of introduction of facilities in the fuel cycle, the amount of stored material, and the nuclear waste. Moreover, these studies can be improved with economics analyses, also required to evaluate the viability of a fuel cycle strategy.

In this work the transition from the existing LWR fleet to strategies with advanced reactors is analyzed, including Generation III+ reactors in a European framework, involving a number of European Union countries according to the choice performed in PATEROS (González-Romero et al., 2007). The analysis of these fuel cycle scenarios has been performed following the recommendations specified in reference documents provided by the CP-ESFR EU project (Bianchi et al., 2009) and ARCAS EU project (Klaasen et al., 2012).

These nuclear fuel cycle scenarios have been evaluated using TR_EVOL (Álvarez-Velarde et al., 2010), a module developed by CIEMAT to improve the capabilities of its burn-up simulation system,

---

* Corresponding author. Tel.: +34 913466731; fax: +34 913466576.
E-mail address: francisco.alvarez@ciemat.es (F. Álvarez-Velarde).

http://dx.doi.org/10.1016/j.anucene.2014.03.015
0306-4549/

EVOLCODE 2.0 (Álvarez-Velarde et al., 2007). TR_EVOL has been designed to study different short-, medium- and long-term options for the introduction of various types of nuclear reactors and for the usage of associated nuclear material, giving due consideration to the isotopic composition of the material in any stage of the fuel cycle: essentially uranium, plutonium, minor actinides and fission products. Moreover, the application of its economic module can give additional and relevant information to study the fuel cycle in a global context.

2. Objectives

The main goal of this work is to analyze – in economic and resources terms – the impact of the implementation of different representative scenarios for a European nuclear fleet with a constant demand of energy. This objective requires the estimation of:

- Natural uranium and plutonium needs.
- Quantity of fast reactors (FR) and accelerator-driven subcritical systems (ADS) facilities to reach the equilibrium of minor actinides (MA) content in the fleet.
- The MA evolution for transmutation scenarios.
- The Levelized Cost of Electricity (LCOE) for each scenario and by reactor type.
- Impact in the LCOE of its main components.

3. Main hypotheses and input data

3.1. Hypotheses for the fuel cycle processes

The scenarios assessed here are formed by five reactor types that are named depending on the technology and the fuel type used:

- *LWR_UOX*: For light water reactors (LWR Gen II, pressurized water reactor – PWR – or boiling water reactor – BWR-type) with UO_2 fuel.
- *LWR_MOX*: For LWR (Gen II, PWR or BWR) with MOX fuel.
- *LWR_GENIII*: For LWR (Gen III+) with 100% of UO_2.
- *SFR (T-SFR)*: For sodium-cooled FR with MOX fuel (with transmutation capability for 2.5% of MA homogeneously distributed in the fuel). The average amount of Pu in the MOX fuel is close to 15%, but it depends on the isotopic composition of the fabrication streams.
- *ADS*: For ADS with inert matrix fuel (45% Pu and 55% MA).

The simulation characteristics of the reactors are summarized in Table 1 and have been obtained from Refs. (Bianchi et al., 2009; Klaasen et al., 2012).

Note that in this table, the ADS Pu conversion ratio accounts for Pu occurrence after Am capture and Cm decay.

The composition of the initial legacy of spent fuel (SF) in the fleet comes from 7 EU nuclear countries, assumed associated for back-end fuel management purposes. The accumulated actinide mass until year 2010 is provided from EU CP-ESFR project, as well as from the previous PATEROS project (González-Romero et al., 2007). This document estimates that the total amount of plutonium in year 2010 is 386.6 t. In addition, 126.7 t are released from one country in year 2022 (phase out assumption in that country) and added to the initial legacy.

Table 1
General parameters for each reactor type.

	LWR_UOX	LWR_MOX	LWR_GENIII	SFR	ADS
Plant thermal power (MWth)	2965	2965	4400	3600	400
Plant thermal efficiency (%)	34	34	34	40	32
Plant electrical power (MWe)	1008	1008	1496	1440	128
Plan capacity factor (%)	80	80	85	80	75
Fuel burn-up (GWd/tHM)	50	45	55	99	150
Lifetime (yr)	40	40	60	60	60
Conversion ratio (Pu)	0.42	0.66	0.48	1.08	1.00

Regarding the UO_2 fuel enrichment, no maximum limit in the SWUs plants capacity has been considered here. The tails assay for ^{235}U enrichment is 0.25% until 2020 and 0.20% after this year. Moreover, the time required for fuel fabrication is 1 year for any type of fuel. No restriction in fabrication capacity has been considered in this work.

Three reprocessing plants are considered in these scenarios depending on the fuel types (LWR fuel, SFR fuel and ADS fuel). The minimum cooling time for the irradiated fuels before reprocessing is 5 years. Reprocessing period lasts 1 year. A reprocessing loss rate for Pu, U and MA of 0.1 (wt%) has been considered. For the fabrication stage, no loss rate has been taken into account in this exercise, in coherence with CP-ESFR reference scenario.

According to NEA/OECD (2010) the total amount of uranium at world level rises to 16.8 million t, ignoring the uranium resources in phosphates and seawater. Although this value is not directly used in this work, it is a reference to be respected at world scale.

3.2. Hypotheses for the fuel cycle costs

The LCOE can be defined as a sum of four components, averaged in a period of time:

- *Investment cost*: It includes the overnight cost and financial costs (financial costs are additionally split in interest during construction, where a large disbursement takes place, and interest for the financing).
- *Fuel cost*: In this study, this contribution represents the front-end cost, including structural fuel assembly and required reprocessing in case of MOX and advanced fuel fabrication.
- *Operation and Maintenance (O&M)*: Annual cost for the plant, which depends on the installed capacity.
- *Decommissioning, Dismantling and waste Disposal (DDD)*: In addition to reactor plant dismantling, the fuel waste final management associated to the back-end fuel costs is included here; i.e., repository costs.

All costs, excluding those ones for DDD, are summarized in Table 2 where the Best Case (BC) unit costs for each item, taken from the ARCAS project, are shown. Plant and reprocessing technologies have different readiness levels; therefore a cost uncertainty band with low and upper values is provided around the Best Case values. Uncertainties are taken from bibliography NEA/OECD (2006), and they were duly adjusted regarding inflation and currency conversion.

Concerning MOX and advanced fuel costs, there are two contributions: (i) the assembly costs (simply named 'fabrication' in the table) and (ii) a mixed reprocessed material compound cost in terms of new fabricated fuel. This compound price is obtained after assumptions of fixed unitary cost of spent fuel reprocessing, which implicitly include the investment, O&M and decommissioning costs of fabrication and reprocessing facilities. In Table 2 assembly, unitary reprocessing and compound costs are shown but not the total final cost (i.e., addition of assembly and compound fabricated fuel costs).

Current LWR_UOX and LWR_MOX plants are working since the 1970s and 1980s, while our analysis starts in year 2010. Hence, we assumed them to be paid off at the beginning of the scenarios and therefore it is considered that generation costs for this type of plants will only include fuel, O&M and DDD costs, excluding all their investment cost.

For the DDD cost, an average value of 15% of the reactor overnight cost has been applied as Decommissioning and Dismantling