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Technical Note

Sustainability issues of plutonium recycling in light water reactors: Code evaluations up to 2050

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ABSTRACT

Plutonium recycling in light water reactors is a viable and mature technology capable of improving several indicators of great importance in the evaluation of the sustainability of nuclear energy development in the near- and long-term such as the shortage of natural uranium resources, the increase of spent fuel inventories and the proliferation risks of high-level radioactive waste. This paper, after a brief review of the status of plutonium recycling, presents the results of a scenario analysis carried out in the hypothesis that the share of nuclear fleet loaded with mixed uranium–plutonium oxide fuel (MOX) is kept constant up to the middle of the century. Beside mentioned indicators, the paper discusses the needs for complex and costly fuel cycle infrastructures required for the reprocessing of spent nuclear fuel and the fabrication of MOX. Assuming that the deployment of fast reactors occurs beyond the middle of the century, the article focuses on the comparison of an open fuel cycle strategy with a closed fuel cycle strategy where plutonium is recycled.

Presented calculations, according to moderate and high projections of nuclear energy development, confirm that plutonium recycling, although deployed to a limited extent, could be beneficial in reducing the stockpiles of nuclear spent fuel and in reducing the risks of proliferation due to the amount of fissile plutonium in the system. The improvement found in the consumption of natural uranium resources was limited promoting to this purpose the deployment of next-generation fast reactors. If a moderate development of nuclear energy is confirmed, the current capacity for reprocessing and MOX fuel fabrication could be sufficient to cope with the foreseen demand, on the contrary, significant investments could be necessary in case of steep increase of installed nuclear energy. Calculations were performed by means of the DESAE code (Dynamic Energy System – Atomic Energy), a tool developed within the IAEA INPRO project.

1. Introduction

The concept of sustainable development addresses the capability to meet present needs without compromising the ability of future generations to meet their own needs. Energy is fundamental to improve living standards and to support societal development. The use of fossil energy sources, accounting for about 80% of the global primary energy needs, leads to phenomena of increasing concern like urban air pollution, regional acidification and human-induced climate change (IAEA, 2005). The capability of nuclear energy to tackle greenhouse gas emissions (GHG) at a competitive cost is recognized as a fundamental driver for its future development (IAEA, 2011a). Nuclear energy faces drawbacks such as the management of radioactive waste and their proliferation risks. Safety is a crucial factor for the development of nuclear business as confirmed by the Fukushima-Daiichi accident that raised new questions in the public opinion forcing the decision to phase-out or to abandon any plan to enter nuclear business. Nevertheless, main reasons that have been promoting the so-called nuclear renaissance seen in the last decade are still valid as confirmed in the projections where, even though to a smaller extent, an increase in the deployment of nuclear energy is confirmed.

Plutonium recycling has proven to be a mature technology capable, addressing the public acceptance of nuclear energy, of safely managing spent fuel, but, beside this, improvements in other

Abbreviations: ALWR, advanced light water reactor; CFC, closed fuel cycle; DESAE, Dynamic Energy System – Atomic Energy; GHG, greenhouse gases; HM, heavy metal; HWR, heavy water reactor; IAEA, International Atomic Energy Agency; INFCIS, Integrated Nuclear Fuel Cycle Information Systems; INPRO, International Project on Innovative Nuclear Reactors and Fuel Cycles; LWR, light water reactor; MOX, mixed oxide fuel; NPP, nuclear power plant; OECD/NEA, Organization for Economic Co-operation and Development/Nuclear Energy Agency; OFC, open fuel cycle; PRIS, Power Reactor Information System; SNF, spent nuclear fuel.

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relevant aspects are to be highlighted (Haas and Hamilton, 2007; IAEA, 2003):

- Efficient use of natural uranium resources.
- Concentration of spent fuel volumes to feed Generation IV reactors (about eight spent light water fuel assemblies are necessary for the fabrication of a single MOX fuel assembly).
- Proliferation resistance with a reduction by about 30% of loaded fissile plutonium and an isotopic composition of discharged plutonium less attractive for non-peaceful use.

In this paper, the impact of plutonium recycling is investigated addressing, together with already mentioned indicators, the infrastructural needs, an important issue when assessing the sustainability of nuclear energy (Piera, 2010). The adopted curves of development account for the early evaluations of the effect of the Fukushima-Daiichi accident. DESAE 2.2 is the code used for the investigations presented in this paper (Andrianova et al., 2009; Tsibulskiy et al., 2006).

2. Status of plutonium recycling in light water reactors

The Power Reactor Information System (PRIS) reports that at present 437 nuclear power plants are in operation with a total net installed capacity of about 372 GWe, 1 nuclear power reactor is in long term shutdown and 64 under construction (PRIS, 2012). Pressurized light water reactors and boiling water reactors account for about 88.2% of the total capacity with, respectively, 272 and 84 units. The share of pressurized heavy water technology is 6.7% with 49 units. Gas-cooled, light water-cooled graphite-moderated, and fast breeder power plant technologies cover the residual fraction of nuclear fleet. At the end of 2000, national safety authorities had approved the use of MOX for 40 light water plants (36 pressurized and 4 boiling) in France (20), Germany (11), Belgium (2), Switzerland (3), and Japan (4) (Dyck, 2011). The USA with the Duke Power Catawba plant plays an important role in the recycling of weapon-grade plutonium in light water reactors (Maldonado et al., 2010). As a consequence of the Fukushima-Daiichi accident some countries announced the decision to phase out from nuclear business in the next two decades (Belgium, Germany and Switzerland) or to abandon any plan to reintroduce nuclear energy in the near-term (Italy); nevertheless several countries confirmed their nuclear option revising the projected rate of development (NEA, 2012). The Fukushima-Daiichi accident caused the decision to shut down two plants loaded with MOX fuel, see Table 1 (Chiguer, 2011; Provost, 2011). Plutonium recycling is carried out in 10.1% of the total installed nuclear capacity through the use of MOX fuel with typical values of reactor core inventory of the order of one third; see Table 2 (PRIS, 2012).

Table 1
NPPs loaded with MOX fuel.

Nuclear power plant	Country	Type	Net capacity (MWe/unit)
Doel-3	Belgium	PWR	1006
Tihange-2	Belgium	PWR	1008
Chinon-B-1, -2, -3, -4	France	PWR	905
Dampierre-1, -2, -3, -4	France	PWR	890
Gravelines-1, -2, -3, -4, -6	France	PWR	910
Blayais-1, -2	France	PWR	910
St. Laurent-B1, -B2	France	PWR	915
Tricastin-1, -2, -3, -4	France	PWR	915
Emsland	Germany	PWR	1329
Brokdorf	Germany	PWR	1410
Grafenrheinfeld	Germany	PWR	1275
Grohnde	Germany	PWR	1360
Gundremmingen-B, -C	Germany	BWR	1286
Isar-2	Germany	PWR	1410
Neckarwestheim-2	Germany	PWR	1310
Philippsburg-2	Germany	PWR	1402
Unterweser[a]	Germany	PWR	1345
Fukushima-Daiichi-3[a]	Japan	BWR	760
Genkai-3	Japan	PWR	1127
Ikata-3	Japan	PWR	846
Takahama-3	Japan	PWR	830
Beznau-1, -2	Switzerland	PWR	365
Goesgen	Switzerland	PWR	970

[a] Permanent shut down as a consequence of the Fukushima-Daiichi accident.

In 2004 the total inventory of spent nuclear fuel was close to $2.68 \cdot e^{+05}$ t_{HM} reaching in 2011 a value of $3.41 \cdot e^{+05}$ t_{HM} with an increase by about $0.11 \cdot e^{+05}$ t_{HM} per year (Dyck, 2011; IAEA, 2008). Nearly 30% of this inventory was reprocessed with a global installed capacity capable of treating up to 4100 t_{HM} of spent fuel yearly (INFCIS, 2012).

3. General assumptions and adopted MOX projections

Main assumptions in presented results are as follows:

- Scenarios extend from 1960 up to 2050.
- SNF is at first delivered to the interim storage nearby power plants for cooling hence either to the final repository or to the reprocessing plant for the recycling of plutonium.
- Plutonium recovered from the reprocessing of spent UOX is recycled in advanced light water reactors with cores full-loaded with MOX fuel.
- In the closed fuel cycle strategy, minor actinides and fission products created under irradiation are stored in the final repository.
- Identified and undiscovered uranium resources: 15.804 million tonnes (NEA, 2010).[1]
- Total reprocessing capacity (1990–2010): 1800 t_{HM}/yr.
- Total reprocessing capacity (beyond 2010): 4100 t_{HM}/yr (INFCIS, 2012).
- Fabrication capacity for MOX fuel: 440 t_{HM}/yr.[2]
- Tails assay of natural uranium enrichment: 0.3%.
- Load factor in operating plants: 0.8.

The curves of electrical generating capacity, after a common historical part (1960–2010), depict different trends of nuclear development; the first one represents a moderate increase in electricity generation from nuclear, in the second a high rate of deployment is considered. The Fukushima-Daiichi accident had an impact on the projections of the IAEA with a decrease of 5–13%; see Table 3 (IAEA, 2010, 2011b; PRIS, 2012). Other international organizations published similar results (NEA, 2012).

The decrease in the projections due to the Fukushima-Daiichi accident is shown in Fig. 1 (colored areas).

Presented analysis deals with two strategies for the management of spent fuel: open fuel cycle (OFC) and closed fuel cycle (CFC) by assuming moderate and high projections of nuclear energy development. In the OFC, spent fuel is piled-up in a long-term storage after cooling at the interim storages nearby NPPs. In this strategy, the installed heavy water plants account for 6.7% of the total capacity. The deployment of advanced light water reactors takes place beyond 2010; see Fig. 2. In the CFC scenario, the SNF of light water reactors supplies, through reprocessing, the plutonium required by advanced light water reactors loaded with

[1] Total identified uranium resources (reasonable assured and inferred): 5.404 million tonnes in the <USD 130/kg U category; total undiscovered uranium resources: 10.4 million tonnes (NEA, 2010).

[2] MOX fabrication plants considered: United Kingdom – SMP Sellafield (15 t_{HM}/yr), Belgium – FBFC International (100 t_{HM}/yr), France – Melox (195 t_{HM}/yr), Japan – Rokkasho (J-MOX, 130 t_{HM}/yr to be operated in 2016), (INFCIS, 2012).