Annals of Nuclear Energy 111 (2018) 635–643

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Fuel cycles optimization of nuclear power industry in China

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ARTICLE INFO

Article history:
Received 11 July 2017
Received in revised form 24 September 2017
Accepted 28 September 2017
Available online 7 October 2017

Keywords:
Nuclear power industry
Fuel cycle
Optimization
Natural uranium
Spent fuel
Cost

ABSTRACT

With the rapid rise of installed nuclear power in China, meeting the increasing demands on natural uranium and rationally treating the vast spent fuel are essential issues for the sustainable development of Chinese nuclear power industry. This paper discusses four most potential nuclear fuel cycle modes in China and analyzes the natural uranium requirements under these different fuel cycle modes first based on three development patterns (low-, medium-, and high-speed) of installed nuclear power capacity. Then, an optimization model including natural uranium requirements, spent fuel final disposal amounts and total cost of electricity generation is constructed and optimization problem under two scenarios of reprocessing capacity are solved and results discussed. The annual and cumulative natural uranium requirements under these two scenarios are also calculated. Finally some conclusions are put forward based on the analyses.

1. Introduction

Continually growth of energy demand with the development of economy, the shortage of fossil fuels supply and the limits on greenhouse gas emissions will greatly speed up the nuclear power industry's development in China in the coming next decades (National Development and Reform Commission, 2007; China Academy of Engineering, 2011). At the same time as effected by the Fukushima accident, China's nuclear power development is slower than expected in recent years. According to some plans and research reports, it is reasonable to present three scenarios for nuclear power development in China to 2050 (see Table 1).

It can be seen from Table 1 that nuclear power will step into a rapid development period in the future in China. To promote the sustainable development of nuclear power, the sustainable supply and use of nuclear fuel, as well as the treatment of spent fuel, are very important issues for the nuclear power industry. However, the actual state of China's uranium resources is not ideal. Uranium ores have been predominantly low-grade, with 0.05%–0.3% grade ore accounting for the highest percentage. At the same time, the reserves were mainly small- and medium-sized (accounting for more than 60% of the total reserves) (China Academy of Engineering, 2011). Enhancing the uranium use efficiency is an important issue for the nuclear power industry in China. Uranium resources use efficiency is closely related to the modes of nuclear fuel cycle, so the development of nuclear fuel cycle modes have a vital role for the sustainable development of nuclear power industry.

Some studies on the development of nuclear fuel cycle modes have been carried out. Kunsch and Teghem (1987) carried out the optimization analysis of nuclear fuel cycle modes by using multi-objective stochastic linear programming application, conforming to the four standards of production cost, resource supply, balance of business and provide employment as the goals. Kim et al. (1999) compared the six kinds of fuel cycle [pressurised water reactor(recycling uranium, Pu), pressurised water reactor (mixed oxide)-pressurised heavy water reactor(recycling uranium), pressurised heavy water reactor(Pu-U), pressurised heavy water reactor(direct use of spent PWR fuel in CANDU reactors), pressurised water reactor and pressurised heavy water reactor (once through)] by Goal Programming Method and Analytic Hierarchy Process (AHP), considering the four quantifiable factors: the fuel demand, the total depreciation cost, cost sensitivity and the environmental impact, the conclusion is the adoption of pressurised water reactor(mixed oxide)-pressurised heavy water reactor(recycling uranium) is the optimization scheme. Liu et al. (2006) forecasted the natural uranium resources demand and spent fuel generation for PWR in China till 2035, and discussed the effects of spent fuel reprocessing and plutonium separating to reduce the natural uranium demand and waste accumulation of China's nuclear power industry in the future. Bernard (2007) proved mixed

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https://doi.org/10.1016/j.anucene.2017.09.049
0306-4549/

Table 1
Installed nuclear power capacity in China to 2050 (unit: GWe).

Year	2020			2030			2050		
Capacity	Low 40	Medium 58	High 70	Low 83.8	Medium 150	High 200	Low 250	Medium 325	High 400

Sources: 1. China Academy of Engineering (2011); 2. National Development and Reform Commission (2007); 3. OECD Nuclear Energy Agency and International Atomic Energy Agency (2014); 4. Nuclear Energy Agency and International Energy Agency (2015).

oxide (MOX) fuel and uranium oxide (UOX) fuel are very similar by the French thermal reactor operating experience, the use of MOX can reduce almost equivalent amount of UOX. Cao et al. (2013) given China's nuclear power installed capacity in 2050 in accordance with the three different growth speed (300 GW, 400 GW, 500 GW) according to the present situation of China's nuclear power development and long-term development plan, and forecasted natural uranium resources demand, the amount of spent fuel, plutonium and minor actinides (MA) under these three schemes by 2050, and pointed out that advanced nuclear fuel cycle mode and spent fuel reprocessing plant construction can effectively reduce the accumulation of spent fuel quantity. Worrall (2013) analyzed the utilization of used nuclear fuel in a potential future US fuel cycle scenario. Ma et al. (2013) calculated the natural uranium demand and spent fuel accumulated quantity under "once through" fuel cycle mode and closed fuel cycle mode by using the dynamic analysis program of DESAE-2, the results showed that the closed fuel cycle mode has certain advantages in the saving of uranium resources and reducing the amount of spent fuel disposition compared with the "once through" fuel cycle mode. Yolanda Moratilla Soria et al. (2015) analyzed the impact of the taxes on used nuclear fuel on the fuel cycle economics in Spain. Zhang et al. (2016) carried out the uranium demand and economic analysis of different nuclear fuel cycles (the once-through cycle route and the partial recycling in PWR route) in China. Park (2017) assessed the spent nuclear fuel amounts to be managed based on disposal option in Republic of Korea. Yoon et al. (2017) used an integrated multicriteria decision-making approach for evaluating nuclear fuel cycle systems for long-term sustainability on the basis of an equilibrium model.

However, few studies have been carried out on fuel cycles modes optimization in China's nuclear power industry. This paper will give four most potential nuclear fuel cycle modes and analyze the natural uranium requirements under these different fuel cycle modes first. Then an optimization model including natural uranium requirements, final spent fuel disposal amounts and total cost of electricity generation will be constructed and optimization problem will be solved and results discussed. Finally some conclusions will be put forwarded based on the analyses.

2. Natural uranium requirements under different nuclear fuel cycle modes in China

2.1. Nuclear fuel cycle modes

Pressurised water reactor (PWR) and pressurized heavy water reactor (PHWR) are the two types of reactors used in China now. Sodium fast reactors are expected to be put into use in the 2030s in China. So four most potential nuclear fuel cycle modes of China's nuclear power industry in the future are mainly discussed here (see Fig. 1).

(1) PWR and no recycling of spent fuel [PWR-OT (Once Through)]
(2) PHWR and recycling uranium (RU) used in PHWR (PHWR-RU)
(3) PWR and mixed oxide (MOX) used in PWR (PWR-MOX)
(4) Sodium fast reactor (SFR) and MOX used in SFR (SFR-MOX)

2.2. Scenario analysis

Natural uranium requirements under different nuclear fuel cycle modes till the year 2050 will be analyzed.

2.2.1. Scenario I: The newly-built reactors are all PWRs and no recycling of spent fuel (PWR-OT)

The reactors in operation now in China are two PHWRs and the installed capacity is 1456 MW, the other reactors are all PWRs. If the newly-built reactors are all PWRs in China till the year 2050, then natural uranium requirements under this condition will be as the following

$$M_{NU} = a_1 \times IC_{PWR} + a_2 \times IC_{PHWR} \quad (1)$$

where M_{NU} is annual natural uranium requirements, t/a; a_1 and a_2 are natural uranium requirements per power rating of PWR and PHWR, t/MW; IC_{PWR} and IC_{PHWR} are installed capacity of PWR and PHWR, MW.

The values of a_1 and a_2 are 0.1935 and 0.1321 t/MW (see Table S1 in Supplementary Information) respectively (Yue et al., 2017). Then annual and cumulative natural uranium requirements can be obtained according to Eq. (1) and Table 1 (the installed capacity of PWR is assumed to be in a linear increase in each time period, the same circumstances are also occurred in the other scenarios), which are depicted in Fig. 1a and Fig. 1b. The three curves are corresponding to the low-, medium- and high-speed development of installed nuclear power capacity in Table 1.

Annual natural uranium requirements under scenario I are 48,286, 62,798 and 77,311 tons respectively in 2050 for low-, medium- and high-speed development schemes of China's installed nuclear power capacity. And cumulative natural uranium requirements under scenario I will reach 727,657, 1,155,534 and 1,561,933 tons in 2050 respectively.

2.2.2. Scenario II: The ratio of installed capacity between PWR: PHWR = 1:0.221 and recycling uranium used in PHWR since the year 2025 (PHWR-RU)

A spent fuel industrial reprocessing plant will be in operation in the year 2025 in China (China Academy of Engineering, 2011; Hu et al., 2012; World Nuclear Association, 2015) and recycling uranium is assumed to be used in PHWR since the year 2025 (World Nuclear Association, 2014). The average U-235 content in spent fuel of PWR is about 0.80% (Hu et al., 2012). Then spent fuel generation of 1 MW PWR can support 0.221 MW PHWR (see Table S1 in Supplementary Information). Assuming the ratio of installed capacity between PWR and PHWR is 1:0.221, then natural uranium requirements under this condition will be as the following

$$\begin{cases} M_{NU} = a_1 \times IC_{PWR} + a_2 \times IC_{PHWR} & (2015\text{–}2024) \\ M_{NU} = a_1 \times IC_{PWR} & (2025\text{–}2050) \end{cases} \quad (2)$$

Then annual and cumulative natural uranium requirements can be obtained according to Eq. (2) and Table 1, which are depicted in Fig. 2a and Fig. 2b.