Primary Analysis on The Nuclear Energy Development Scenario base on the U-Pu Multicycling with PWR, FR and CNFC in China

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Abstract. As one of the largest developing country, China needs reliable energy supply. At the same time, China should improve the energy structure and reduce carbon dioxide emissions. Nuclear and renewable energy is the main solution to these problems. According to some studies, nuclear power capacity will increase to 400GWe in 2050. Due to limitations of uranium resources, we must consider the development of fast reactor (FR) and closed nuclear fuel cycle. Development Strategy of China's FR is three-step model "Experimental Reactor - Demonstration Reactor - Commercial Reactor". The construction of the China Experimental Fast Reactor (CEFR) has completed, and has obtained the necessary experience on FR. The design of the demonstration FR CFR-600 is ongoing, which is 600MWe power. After this step, the commercial FR with more large power will be constructed. Based on the development of nuclear energy and the constraints of uranium resource in China，this article presents and analyses some cases of nuclear power scenarios of PWR-FR matching development with closed nuclear fuel cycle (CNFC) including some indicators such as the matching capacity, the uranium resource consumption, reprocessing capabilities etc.

Key Words: Nuclear Energy Development Scenario, Fast Reactor, Closed Nuclear Fuel Cycle

1. Introduction

As China seeks the rapid development of nuclear power, limited natural uranium resources will be one of its constraints [1][2]. To address the problem, China has increased the country's uranium exploration and is actively exploring the international uranium market. At the same time, China seeks to implement a strategy for developing fast reactors (FRs) and related closed nuclear fuel cycle (CNFC) infrastructure to ensure the sustainability of its large-scale nuclear power development.

A three-step strategy has been adopted to develop FR and CNFC technology in China. The first step, which has already been realized, is to develop an experimental FR. The China Experimental Fast Reactor (CEFR), a sodium cooled 65MWt experimental FR, has been operating since 2011. The second step is to develop a demonstration FR with a 600MW power capacity, while the third step is to develop commercial FRs with the capacity of 1000~1200 MW [3]. China has also decided to adopt a closed fuel cycle approach to sustain the development of fission energy.

The objective of this analysis is to primarily evaluate the synergistic collaborative scenarios of fuel cycle infrastructure development. China expects to enable a significant growth of FR capacity through a FR-centered scenario with reprocessing of PWR fuel.

2. Objective and problem formulation

In order to accomplish the goal of nuclear power development, FR technology must be developed. There are two types of FR development scenarios. In the first type, there are sufficient uranium resources and the main task of FRs is to transmute minor actinides (MA) of PWR spent fuel. In the second type, there are not sufficient uranium resources, and the main task of FRs is to breed and increase the capacity of nuclear power. This report focuses on the second development scenario.

The mass flow of this nuclear energy system in a CNFC is shown in FIG. . This report presents and analyzes the nuclear power scenarios in which the PWR-FR is developed for CNFC, based on the FR-centered scenario in order to preliminarily assess the potential of nuclear power development.

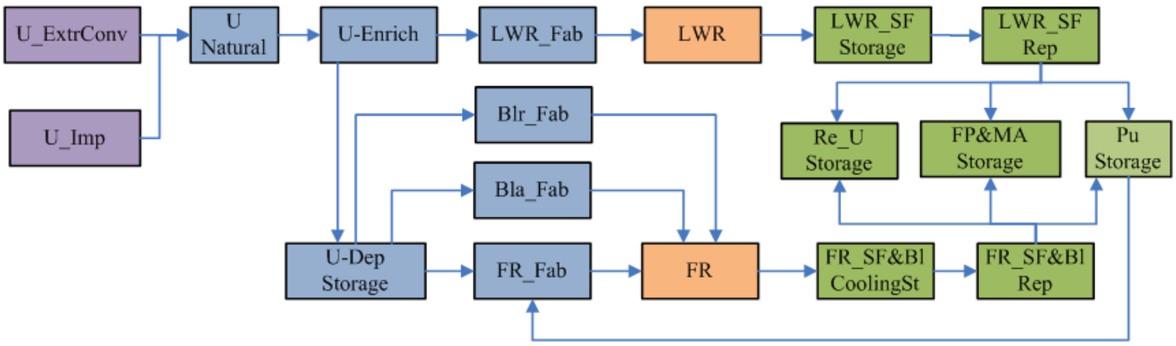

FIG. 1. Mass flow of FR centered scenario.

3. Assumptions, methods, codes and input data used

Research has shown that the population of China will increase to 1.43 billion by 2050. Primary energy consumption will be increased to 3.5 tSCE/year/person[4]. Total energy consumption will be 5 billion tSCE. The total electricity capacity will be 2.5 billion kW. If the scale of Chinese nuclear power increases to 16% of total electricity capacity in 2050, which is the factor of the world average level at present, the capacity of nuclear power will be about 400GWe.

This report is focused on a nuclear power development scenario in which there are not sufficient uranium resources available. In order to accomplish the goal of nuclear power development under this scenario, FRs must be developed. Cases of FR and PWR matching development scenarios were analysed under different constraints using the nuclear energy dynamic analysis code DESAE [5] provided by the IAEA.

The CFR1000 is selected as the FR model in this study. CFR1000 is a Chinese designed innovative FR concept which is a pool-type sodium-cooled FR with 1000MWe. The core loads about 4.2 tons of plutonium but can also support different fuel types. It operates on a 1/3 refuelling scheme, with a refuelling cycle of 330 effective full power days (EFPDs). Using MOX fuel, the breeding ratio (BR) of CFR1000 is designed for 1.2, and the BR is about 1.5 when using metal fuel. These two FR are separately called FR(MOX) and FR(Metal). The PWR model is selected from advanced M310 based on the Daya Bay NPP. The planned operational lifespan for all NPPs (PWR or FR) is 60 years. The recycling time for PWR spent fuel and FR MOX spent fuel are both two years, which includes the time of intermediate storage, reprocessing and fuel fabrication. The time for this cycle is four years when FRs use metal fuel. These estimates assume there is sufficient capacity to reprocess the spent fuel of every type reactor and handle 1000 tons heavy metal (HM) per year.

The four cases are analyzed primarily according to the different supply of natural uranium resources and the development plans for PWR and FR. The list of cases is shown byTABLE 1. Case I and II assumed that the PWR NPPs develop more quickly than in Cases III and IV. Cases III and IV are roughly based on the national development plan; different PWR capacities correspond to the different uranium resource supplies.

TABLE 1: The 4 cases of China scenario in this study

	Case I	**Case II**	**Case III**	**Case IV**
Uranium resource, million tons	2.0	2.0	2.0	1.0
Matching Strategy	PWR-FR(MOX)-FR(Metal)	PWR-FR(MOX)	PWR-FR(MOX)-FR(Metal)	PWR-FR(MOX)-FR(Metal)
PWR Development Goals	To 200GWe in 2030	To 200GWe in 2030	To 40GWe in 2020, to 70 GWe in 2030, to 90 GWe in 2040, to 200 GWe in 2050	To 40GWe in 2020, to 70 GWe in 2030, to 90 GWe in 2040, to 100 GWe in 2050

4. Summary presentation and analysis of the results

4.1. Case I

Case I considers that the total availability of natural uranium is expected to be 2 million tons, which should be the amount of fuel consumption for PWRs in the range of 200GWe over the course of their operating life. PWRs are expected to develop according to the maximum capacity supported by natural uranium resources. FR NPPs with MOX fuel, named FR(MOX), are assumed to achieve commercial operatation by 2018; the scale increases by one reactor unit per year in the initial stage (2018 to 2020), and then depends on the cumulative amount of plutonium which is obtained from reprocessing of PWR and FR spent fuel. The FRs with MOX fuel will no longer be developed after 2030.FRs with metal fuel, named FR(Metal), will be deployed instead as quickly as possible. The calculated results are shown in FIG. to FIG. .

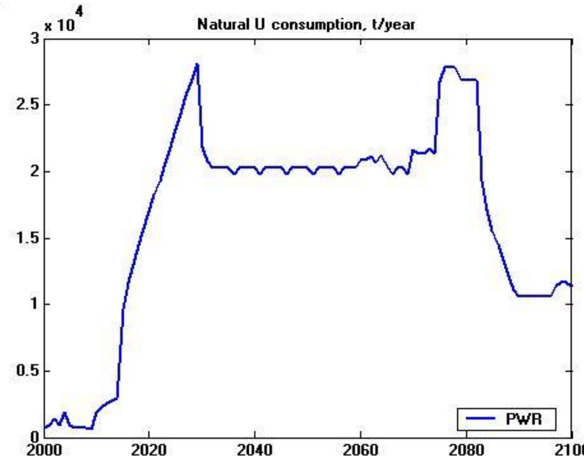

FIG. 2. Annual consumption of natural uranium of Case I.

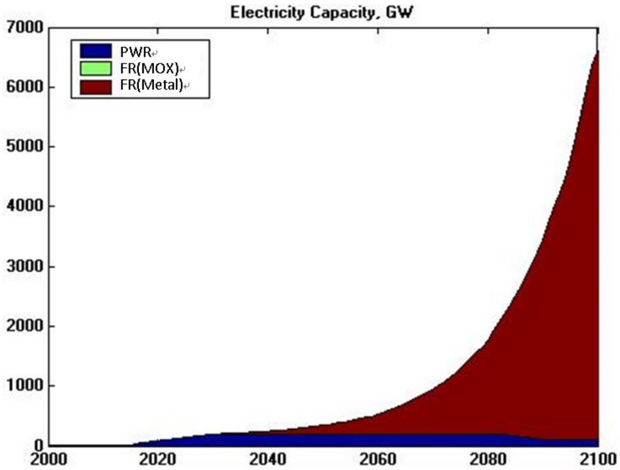

FIG. 3. Total development scale of installed capacity of Case I.

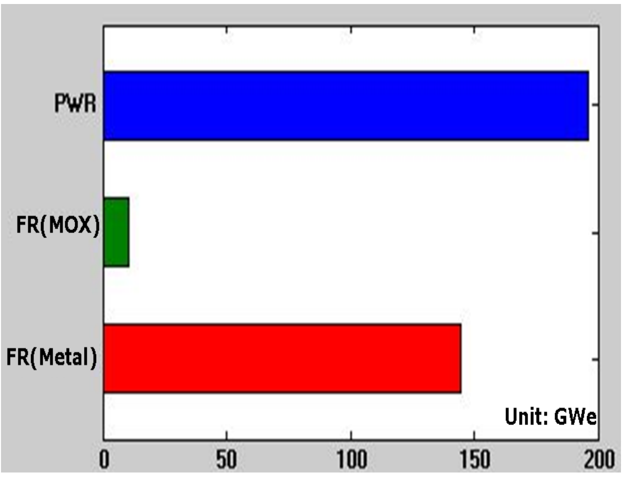

FIG. 4. Nuclear power scale of every type NPP in 2050 of Case I.

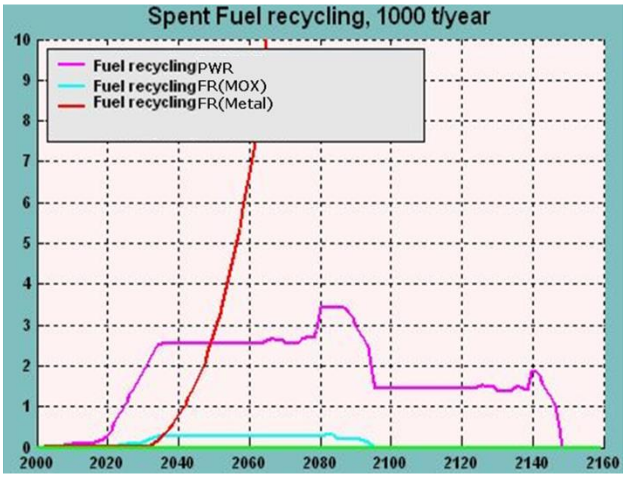

FIG. 5. Reprocessing demand of Case I.

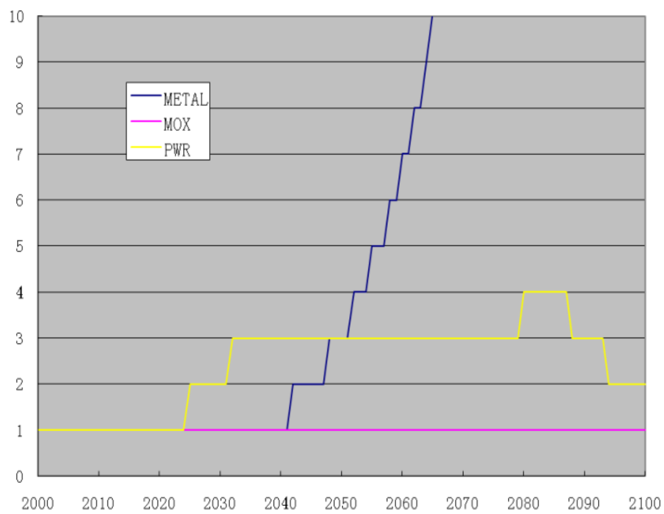

FIG. 6. Reprocessing plant construction demand of Case I.

In Case I, the total consumption of natural uranium is 2.01 million tons, and the development scale of PWR peaks at 200GWe in 2030. In 2050, the total installed capacity of nuclear power is 360GWe, which includes 200GWe from PWRs, 10GWe from FR(MOX), and 150GWe from FR(Metal). 2,300 tons of PWR spent fuel are reprocessed, along with 300 tons FR(MOX) spent fuel and 2700 tons FR(Metal) spent fuel by 2050.

4.2. Case II

In Case II, uranium resouces and the PWR development plan are same as Case I. FR(MOX) is assumed to start operating from 2018, and the scale increase one reactor unit per year from 2018 to 2020; then FRs will develop as quickly as possible, according to the cumulative amount of plutonium obtained from reprocessing PWR and FR spent fuel. The difference in comparison to Case I is an assumption that FR(Metal) will not be developed. The calculated results are shown as follows FIG.   to FIG. .

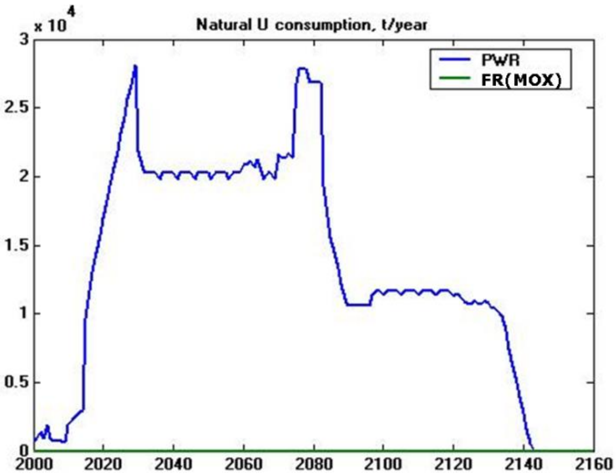

FIG. 7. Annual consumption of natural uranium of Case II.

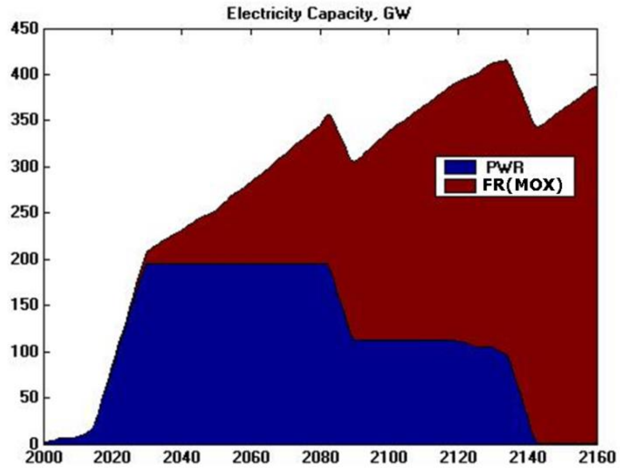

FIG. 8. Total development scale of installed capacity of Case II.

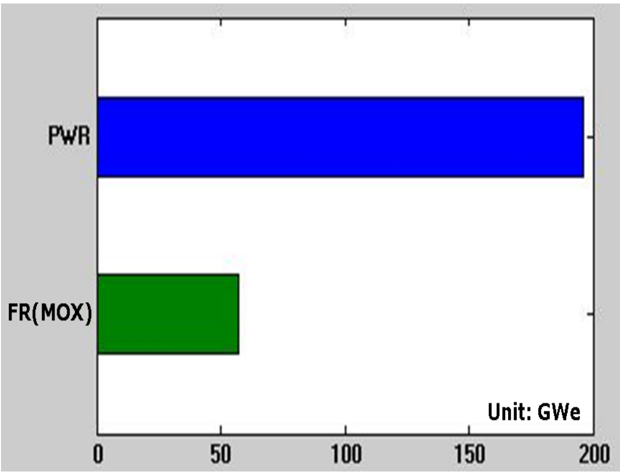

FIG. 9. Nuclear power scale of every type NPP in 2050 of Case II.

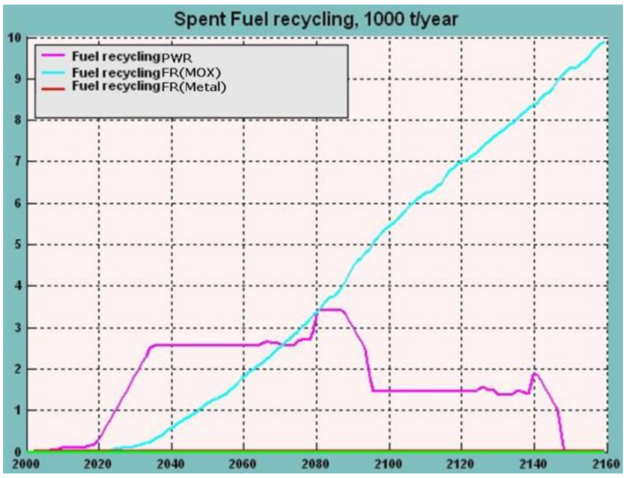

FIG. 10. Reprocessing demand of Case II.

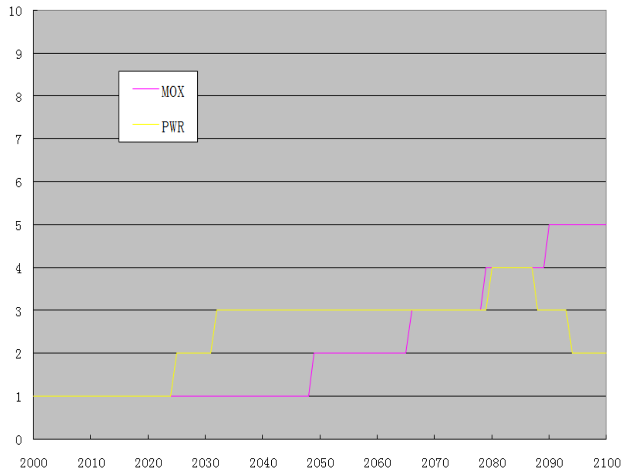

FIG. 11. Reprocessing plant construction demand of Case II.

In Case II, the total consumption of natural uranium is also 2.01 million tons. In 2050, the total installed capacity of nuclear power is 257GWe, which include 200GWe from PWR and 57GWe from FR(MOX). 2,300 tons of PWR spent fuel are reprocessed, with corresponding 1100 tons of FR(MOX) spent fuel by 2050.

4.3. Case III

This case also assumes the availability of natural uranium resources and the same FR development plan as in Case I. FR(MOX) is assumed to start from 2018, and FR(Metal) is planned for 2030. The difference is that the development scale for PWR increases to 40GWe by 2020, to 70GWe by 2030, to 90GWe by 2040, and to 200GWe by 2050. The calculated results are shown as follows FIG. to FIG. .

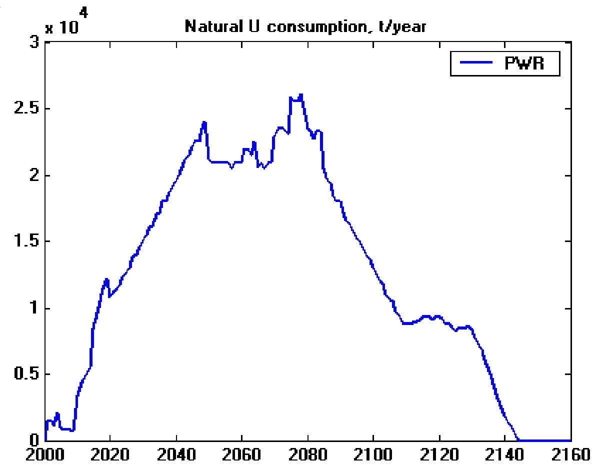

FIG. 12. Annual consumption of natural uranium of Case III.

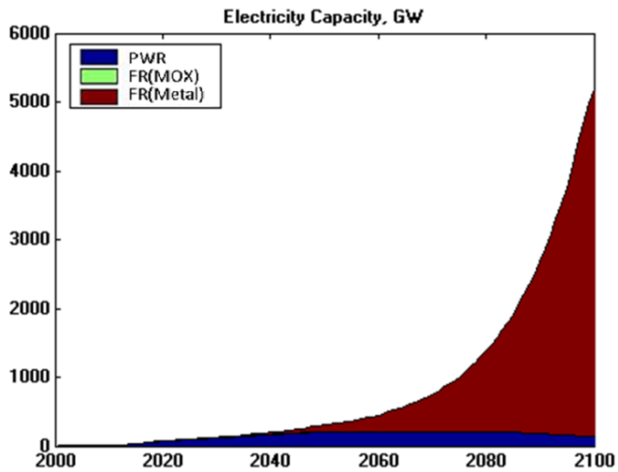

FIG. 13. Total development scale of installed capacity of Case III.

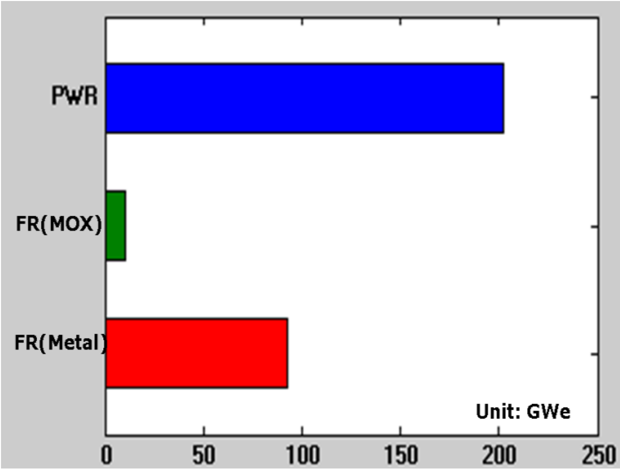

FIG. 14. Nuclear power scale of every type NPP in 2050 of Case III.

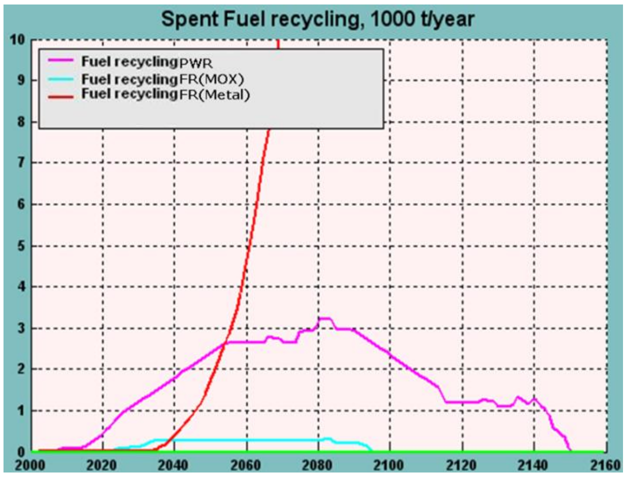

FIG. 15. Reprocessing demand of Case III.

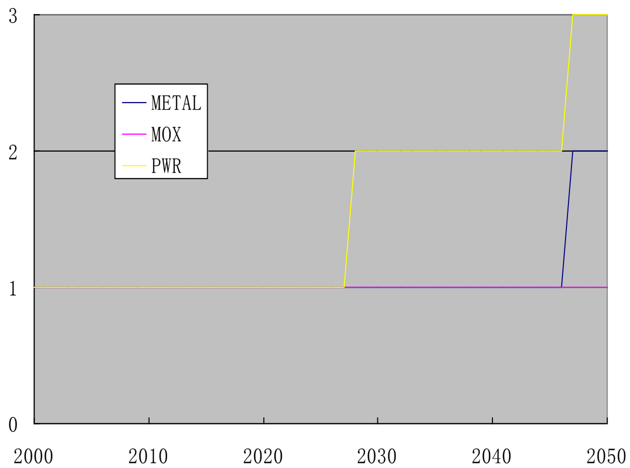

FIG. 16. Reprocessing plant construction demand of Case III.

In Case III, the total consumption of natural uranium is 1.98 million tons, and the development scale of PWRs peaks at 200GWe in 2050. In 2050, the total installed capacity of nuclear power is 303GWe, which includes 200GWe from PWR, 10GWe from FR(MOX), and 93GWe from FR(Metal). About 2,200 tons of PWR spent fuel are reprocessed, with corresponding 300 tons FR(MOX) spent fuel and 1700 tons FR(Metal) spent fuel by 2050.

4.4. Case IV

Case IV is very similar to Case III except only 1 million tons of natural uranium resources are available. The calculated results are shown as follows FIG. to FIG. .

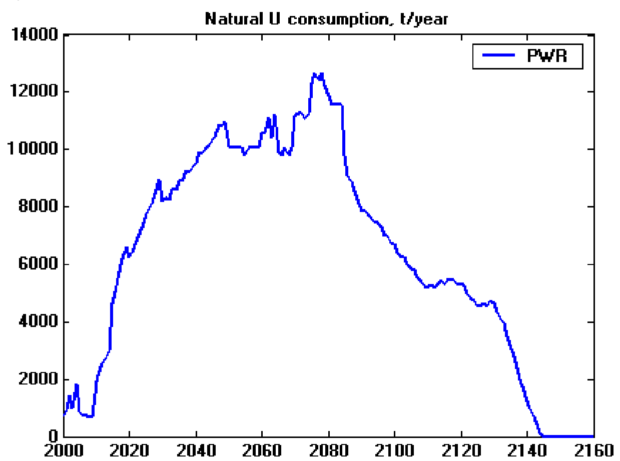

FIG. 17. Annual consumption of natural uranium of Case IV.

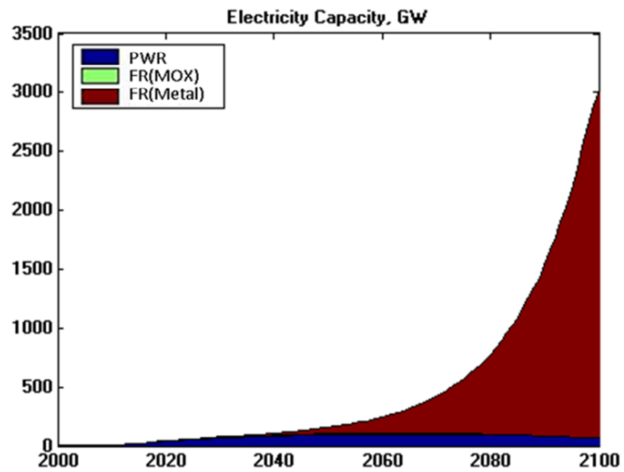

FIG. 18. Total development scale of installed capacity of Case IV.

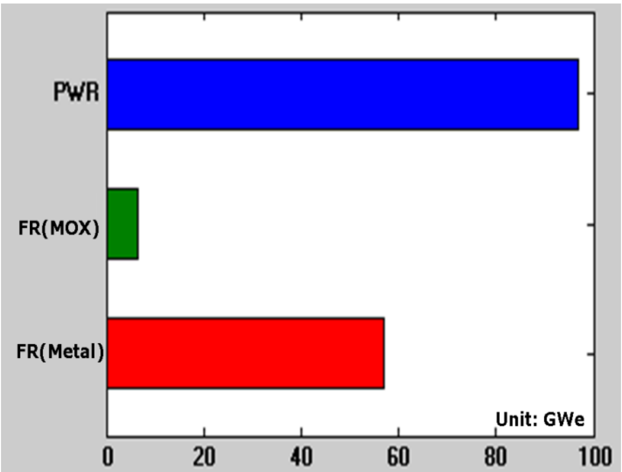

FIG. 19. Nuclear power scale of every type NPP in 2050 of Case IV.

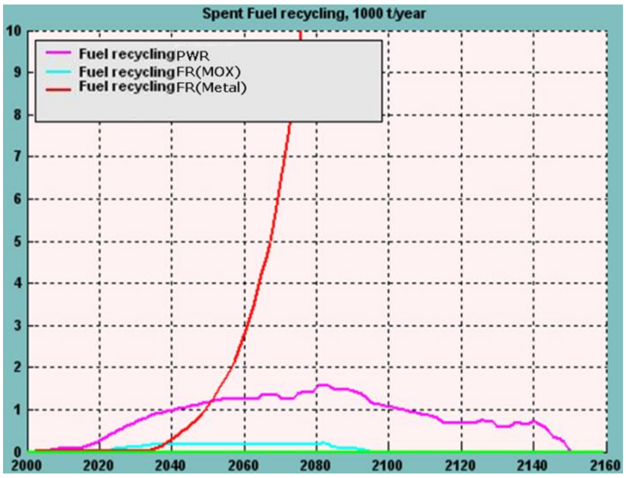

FIG. 20. Reprocessing demand of Case IV.

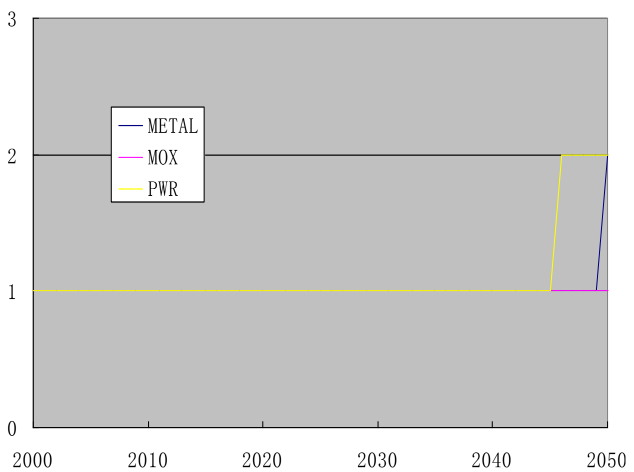

FIG. 21. Reprocessing plant construction demand of Case IV.

In Case IV, the total consumption of natural uranium is 1.01 million tons, and the development scale of PWRs peaks at 100GWe in 2050. In 2050, the total installed capacity of nuclear power is 163GWe, which include 100GWe from PWR, 6GWe from FR(MOX), and

57GWe from FR(Metal). About 1,100 tons of PWR spent fuel are reprocessed, with a corresponding 200 tons of FR(MOX) spent fuel and 1,000 tons of FR(Metal) spent fuel by 2050.

Comparing the four cases, Case I is closest to the ideal scale of the nuclear power (about 400GWe).

5. Conclusions

China is devoted to the peaceful use of nuclear energy to meet growing energy demand. The proper amount of NPPs can provide clean energy with low risk, which is essential to ensure that modern industrial civilization can be enjoyed with as little damage as possible to the environment.

The fast reactor is a promising technology to ensure the sustainable development of nuclear energy which can produce new fuel from depleted uranium and burn the long-life radioactive waste at the same time. Sodium-cooled fast reactor technology is one of the six recommended Generation IV technologies with inherent safety features. It is expected that the fast reactor will provide people with sufficient clean power for the long term future.

Development of FRs and PWRs in China is very important for the large-scale sustainable development of nuclear energy. To achieve faster development of the nuclear power capacity, it is necessary to have sufficient natural uranium resources to support the large-scale development of PWR NPPs, and as the result, to accumulate enough plutonium from spent fuel reprocessing to load fast reactor cores, which is a prerequisite for the rapid development of FRs. The large-scale development of FRs requires sufficient reprocessing capacity. On the other hand, R&D of metal fuel FR with big BR and advanced reprocessing technology can shorten the time needed for reprocessing and increase the installed capacity.

China researches and develops nuclear energy technology independently to increase the nuclear power share, but also requires cooperating with the international community on uranium resources and fast reactor and reprocessing technology.

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