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A Preliminary Study of a Sustainable Energy System for China Based on Fast Reactors

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Abstract: Nuclear energy is an important resource that can optimize energy structures and reduce carbon emissions. In the short-term, the development of nuclear energy in China will still be dominated by pressured water reactors (PWRs), but long-term utilization of PWRs will result in issues such as a shortage of uranium resources and radioactive waste disposal. Previous studies have found that closed fuel cycles based on fast reactors can breed nuclear fuel through multiple cycles while burning the minor actinides (MA) that are produced in over six PWRs, and with the same capacity. Considering a three-stage strategy of experimental reactor, demonstration reactor, commercial reactor for fast reactors, and because nuclear power development in China has been relatively slow, a roadmap is suggested here for the development of fast reactors that can breed nuclear fuels until 2050 and that can burn MA beyond 2050.
Keywords: fast breeder reactor; sustainable nuclear energy system; proliferation and transmutation

1 Introduction

1.1 The function of nuclear energy in China

As one of the world's most important energy resources, nuclear energy plays a key role in supporting the global electricity supply and in reducing carbon emissions. In 2016, the nuclear power capacity of China was approximately 2% of the total electricity capacity, generating just 3.56% of the country's total power, which is below the global average.

The efficient development of nuclear energy and support for the development of other renewable energy resources have become a basic national policy in China. Nuclear energy, which has a high energy output and is clean and low-carbon, can support the dual mission of ensuring energy security and alleviating environmental pressure.

According to the *China Energy Mid-term (2030, 2050) Development Strategy Research Consultation Program* report by the China Academy of Engineering, the installed capacity of nuclear power in China will reach 200 million kilowatts by 2030 and 400 million kilowatts by 2050. This will account for 16% of the total installed capacity; electricity generation from nuclear energy will account for 24% of the total electricity generation. Under these conditions, carbon emissions could be reduced by 2.98 billion tons per year.

1.2 Problems with nuclear energy development

Currently, most nuclear power plants in China are thermal neutron reactors based on pressured water reactors (PWRs). It can be expected that thermal neutron reactor technology will still be widely used in nuclear power generation globally by 2030 and beyond, and PWRs will still be the most widespread reactors. The demand for uranium is very high as a large amount is required to meet the average global installed capacity of nuclear power. If the capacity of PWRs in China reaches 200 GWe, and if this is maintained until units are decommissioned (typically after 60 years), the demand for natural uranium will be approximately 2 million tons during this period. The continued development of nuclear power in China will consume one-third of global

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uranium resources (Table 1) and a significant amount of depleted uranium will accumulate as a result [1].

A further issue is the need to dispose of highly radioactive waste. If the total capacity of PWRs reaches 200 GWe by 2050, and if this is sustained, over 200 000 tons of spent fuel will be generated in China this century, including 400 tons of minor actinides (MA). Even with a decay time of one thousand years, according to the radioactive toxicity of spent fuel, the risk involved can still reach 10^{12} Sv (Fig. 1) [1].

2 Sustainable nuclear system

Nuclear energy is not only an important means of optimizing China's current energy structure and reducing carbon emissions, it can also serve as a sustainable energy source for long-term use. However, the sustainability of nuclear energy is disputed. According to the International Atomic Energy Agency's (IAEA) International Project on Innovative Nuclear Reactor and Fuel Cycle (INPRO), the intention of an "advanced nuclear energy system", or an innovative nuclear energy system (INES), is to meet general sustainable goals including economics, the environment, waste management, security, non-proliferation, physical security, and infrastructure [2]. After more than ten years of research ranging from the GAINS program (Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactor Including a Closed Fuel Cycle) to the more recent nuclear energy regional cooperation program and the current nuclear energy development roadmap program, the proposed solution is to establish a coupled system using fast and thermal reactors.

Table 1. Global uranium resources in 2013.

Resource category	Reserves (10 000 tons)
Reasonably assumed resource	
<130 USD/kgU	369.89
<260 USD/kgU	458.72
Inferred resource	
<130 USD/kgU	220.40
<260 USD/kgU	304.80
Total	
<130 USD/kgU	590.29
<260 USD/kgU	763.52

Data from OECD/NEA's *Uranium resource Redbook 2013*.

The fourth-generation nuclear energy forum tends to adopt a narrow definition of sustainability goals, namely the high utilization of uranium resources and the management of radioactive waste [3]; this is the function of fast reactors in the nuclear energy system, i.e., proliferation and transmutation.

As well as the generation of nuclear power, the coupled closed fuel cycle system (using thermal and fast reactors) enables additional functions such as fuel manufacturing and post-processing. Fig. 2 shows a schematic diagram of the system. After mining, uranium is enriched to generate low-enriched uranium for use as fuel in PWRs. The spent fuel from PWRs then undergoes post-processing and industrial plutonium is extracted as fuel for fast reactors. Separated MA is mixed into the fast reactor fuel at the same time for transmutation. The fast reactor receives industrial plutonium and MA from the PWR as fuel, and the spent fuel from the fast reactor is reused after post-processing. Therefore, the plutonium in fast reactor fuel is proliferated and the MA content is decreased. Finally, after large quantities of uranium are consumed, the plutonium that has been proliferated in the fast reactor can serve as fuel for other reactors.

3 Proliferation and transmutation of fast reactors

The function of a fast reactor differs between the nuclear energy systems of different countries, and its core design is flex-

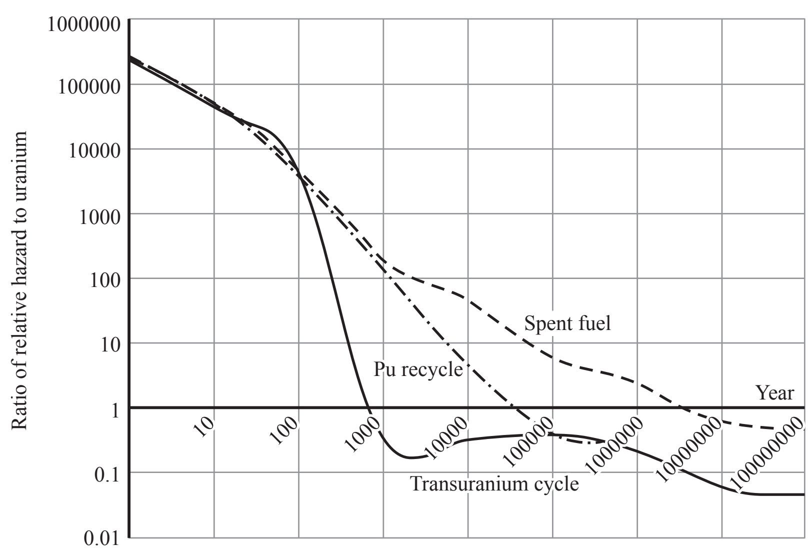


Fig. 1. Radioactive hazard of spent fuel.

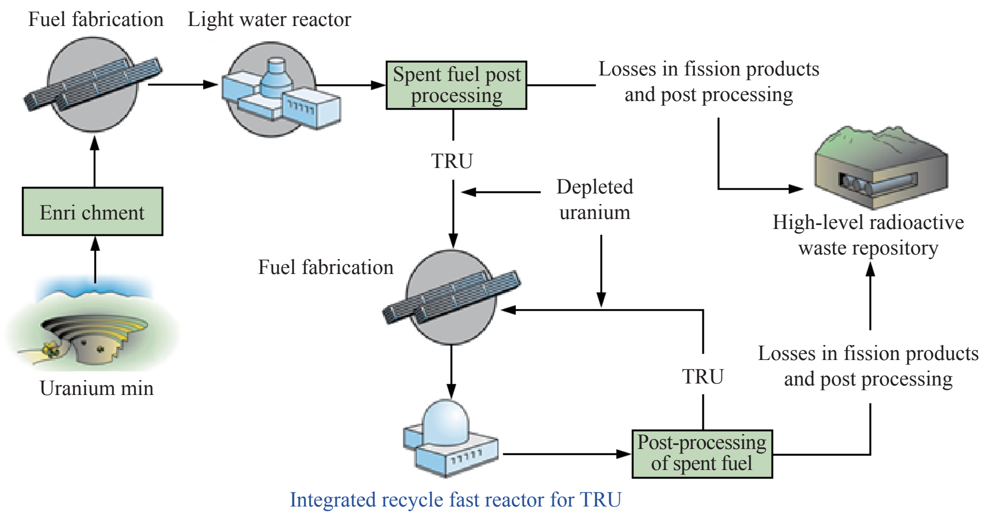


Fig. 2. Schematic diagram of the advanced nuclear energy system.

ible. According to the demand of the country, fast reactors can be designed as high-breeder, low-breeder, transmutation, or fast reactors with high proliferation and transmutation.

In counties that are developing nuclear energy, such as the United States, France, Russia, and Japan, PWRs have been developed on a large scale and have been operating for a long time. Commercial post-processing capabilities have been established and a large amount of industrial plutonium has been accumulated, which is sufficient to support transition from PWRs to fast reactors. At the same time, the demand for nuclear power is no longer growing. Therefore, these countries only require the proliferation ratio of fast reactors to slightly exceed 1.0 in order to maintain a long-term supply of nuclear energy and burning of MA.

In developing countries such as China, the scale of nuclear energy is still relatively small and there is little pressure from large amounts of spent fuel accumulated by PWRs. Therefore, the main intention for the development of fast reactors in China in recent years has been the continued proliferation of nuclear fuel and the rapid increase of installed capacity of nuclear power. High-breeder fast reactors and dry post-processing are the most suitable technical choices for nuclear energy in China owing to the specific conditions of the country.

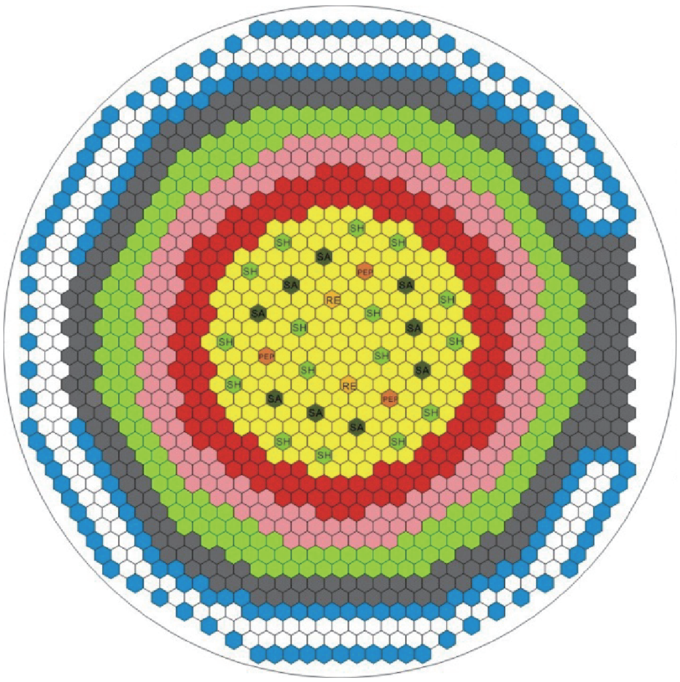
3.1 Proliferation

The proliferation ability of fast reactors is affected by many factors. One such factor is the proliferation ratio; the larger the power, the larger the proliferation ratio. For fast reactors with the same power, the more compact the reactor core structure is, the greater its efficiency becomes (i.e., less fuel is used to achieve the same proliferation). Another factor is the time delay of post-processing spent fuel. Discharged fuel contains a large amount of fissile materials that must be cooled for several years and then re-prepared into fuel before they can be reused. The spent fuel cooled by the fuel pool is an unused but occupied resource for the reactor. According to the “Study on Advanced Nuclear Fuel Cycle Technology Model” (2009AA050701) by the 863 Program, if the scale of the nuclear energy system is to be increased in the short-term, shortening the post-processing time delay will be more effective than simply increasing proliferation. Therefore, the spent fuel from the fast reactor cannot be removed from post-processing, but this is different from the spent fuel of widely used PWRs, from which the recovered plutonium cannot be recycled more than two or three times as its quality deteriorates to render it unusable. In contrast, the plutonium in fast reactors can be recycled indefinitely and the nuclear fuel proliferated by fast reactors is a viable, fissile plutonium.

For a CFR1000 commercial fast reactor core with a proliferation ratio of 1.2 (Fig. 3) [4], Table 2 shows that the isotope of plutonium in the fast reactor core tends to reach equilibrium after multiple cycles, and this is not dissimilar from the initial reactor core. The MA in the core (excessive MA in the spent fuel poses an engineering challenge to the fuel cycle) does not increase significantly as the number of cycles increases, as it does in PWRs. Therefore, the fuel cycle of a fast reactor can be indefinite. Theoretically, regardless of the fuel used in each cycle, the useful elements in the spent fuel will be eventually fissured in continuous cycles and the uranium resource can be fully utilized. However, the efficiency of each process in the fuel cycle cannot reach 100% owing to wastage at each stage of the process, and the utilization rate of uranium resources in fast reactors can exceed 60% under realistic conditions. As this technology develops, the utilization rate will increase.

3.2 Transmutation

Internationally, it is believed that a moderate-sized fast reac-



Symbol	Description	Number
	Fuel assembly in inner core	211
	Fuel assembly in middle core	156
	Fuel assembly in outer core	174
	Radial blanket assembly	210
	Steel shield assembly	232
	Boron shield assembly	177
	Spent fuel storage well	179
SH	Shim control rod	16
SA	Safety control rod	9
PER	Passive control rod	3
RE	Regulating control rod	2

Fig. 3. CFR1000 core arrangement.

Table 2. Fuel composition change in CFR1000. %

Number of cycles	Isotope composition of Pu					MA
	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	
1	4.06	62.54	21.93	7.03	4.44	1.50
2	5.70	64.05	21.95	4.19	4.11	1.49
3	6.57	64.72	22.05	3.02	3.64	1.49
4	6.99	64.84	22.08	2.68	3.40	1.48
5	7.20	64.99	22.18	2.53	3.10	1.48
10	7.34	65.43	22.48	2.47	2.28	1.47
15	7.36	65.57	22.56	2.48	2.03	1.47
20	7.37	65.63	22.55	2.48	1.96	1.47
23	7.38	65.65	22.55	2.48	1.94	1.47

tor is ideal for transmutation. A demonstration fast reactor for China is currently being designed with transmutation as one of its important applications alongside fuel proliferation. According to the international consensus, excessive MA in the core affects the Doppler, sodium vacuole, and other reactive feedbacks of a fast reactor. However, adding less than 5% MA has no impact on the safety of the reactor core. To assess the transmutation capability of a fast reactor core, Np and Am were separately added to its fuel. Table 3 shows the results of the physical core calculations. For a fast reactor core without any MA, approximately 10 kg of MA per GW·a are produced and for a fast reactor core with 5% MA, the burned MA exceeds 200 kg per GW·a. Therefore, one 600-MWe transmutation reactor could withstand an amount of MA produced by a PWR with six times the equivalent capacity.

In addition, the results in Table 3 show that with 5% MA, the effective delayed neutron fraction, Doppler reactivity coefficient, and sodium vacuole reactivity of the reactor core are not significantly worse than those with the pure uranium-plutonium core.

4 China's fast reactor development strategy

China is a post-nuclear power development country. Nuclear power development began approximately 20 years after it did in the West. Considering the national state of nuclear power development in China, the main goal for the development of fast reactors is to breed nuclear fuel until 2050 and to burn MA beyond 2050, i.e., "proliferation and then transmutation". Therefore, high-breeder fast reactors with metal fuel and dry post-processing technologies should be the goals of developing fast reactor technology in China.

The development of fast reactors in China follows three stag-

Table 3. MA changes in a 600-MWe fast breeder reactor (FBR). kg

Nuclide	MOX fuel	MOX fuel with 5% Np	MOX fuel with 5% Am
^{237}Np	3.20	−201*	
^{241}Am	−8.88*	/	−182*
^{243}Am	9.00	/	−25.6*
^{242}Cm	5.58	/	
^{244}Cm	1.19	/	
^{245}Cm	0.0792	/	
^{246}Cm	0.00242	/	

*Negative values indicate the amount of nuclide reduction; MOX represents mixed oxide.

es of "experimental, demonstration, and commercial reactors". Based on experience from the design, construction, and operation of the China experimental fast reactor (CEFR), a second phase of design and construction of a 600-MWe demonstration fast reactor (CDFR) has begun. International cooperation to bring in mature international fast reactor power plants has also begun. In a third stage, a large-scale, high-breeder fast reactor (CDFBR) will be developed. CFR600 is expected to be completed by 2023 and will be promoted according to the needs of China at that point in time. The reactor is designed to be economically competitive and, furthermore, 600-MWe fast reactors are more suitable for transmutation. At that time, based on the accumulation of MA in China, the reactor core will be converted so that it can burn MA from PWRs. The third step will involve developing a CDFBR with an electric power of 1000–1200 MWe. This will require economic justification. The use of metal fuel for on-site fuel cycles can be used to avoid off-site fuel transportation, strengthen centralized physical defenses, and prevent nuclear proliferation. It is estimated that the CDFBR will be in operation by 2035 and will be promoted following industrialization in China.

5 Contribution of fast reactors to nuclear energy in China

According to the estimation presented in the *Re-research on Nuclear Energy Development in China* by the Chinese Academy of Engineering, the installed nuclear power capacity in China will reach 200 million kW·h by 2030 and 300 million–400 million kW·h by 2050. According to China's predicted demand for 2 million tons of uranium, developing PWRs to reach a capacity of 200 GWe is more appropriate, and the deficiency needs to be supported by fast reactors and the proliferation of nuclear fuel (Fig. 4).

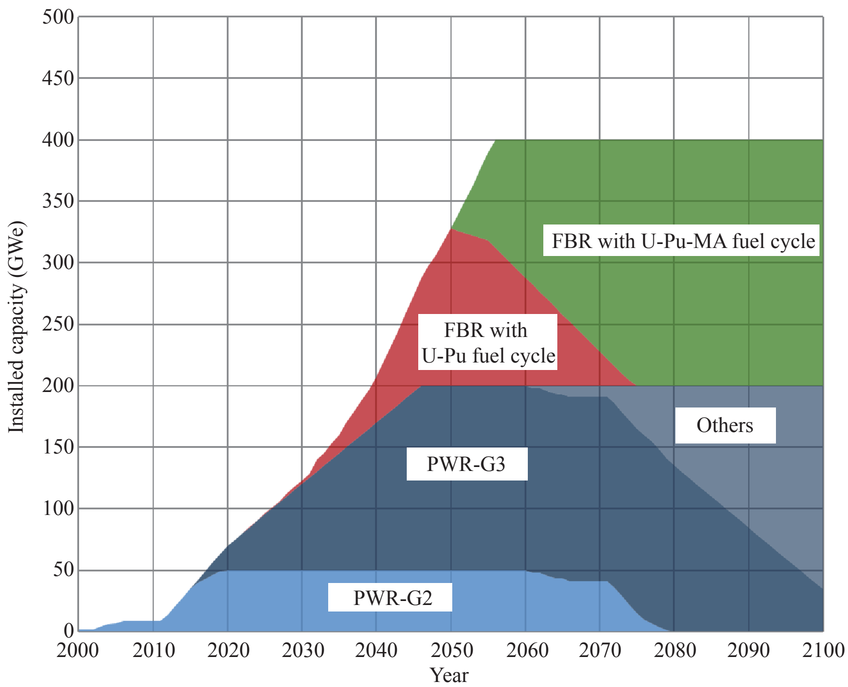


Fig. 4. A scenario for the assumed nuclear energy system in China.

Under the scenario in Fig. 4, the annual consumption of natural uranium will increase as the capacity of PWRs increases, reaching a peak of 35 000 tons per year by 2050. This will then gradually decrease with the decommissioning of PWRs after 2070. After a century of development, 2.1 million tons of natural uranium would be consumed and 1.85 million tons of depleted uranium tailings would be produced. This depleted uranium would provide sufficient raw material for fast reactor proliferation.

Fast reactors will begin to develop rapidly from 2032 with mixed oxide fuel used in the initial stages and MA added at later stages. Depending on the amount of industrial plutonium recovered from spent fuel from PWRs and its own proliferation, capacity could reach 130 GWe by 2050. The balance of MA in an innovative nuclear energy system (INES) is shown in Fig. 5, which projects that the MA extracted by post-processing could reach 100 tons by 2050. At this time, fast reactors with a U-Pu-MA cycle must be deployed. After the capacity of nuclear power plants reaches 400 GWe in 2055, there would be a large amount of plutonium in fast reactors that could provide fuel for other reactors.

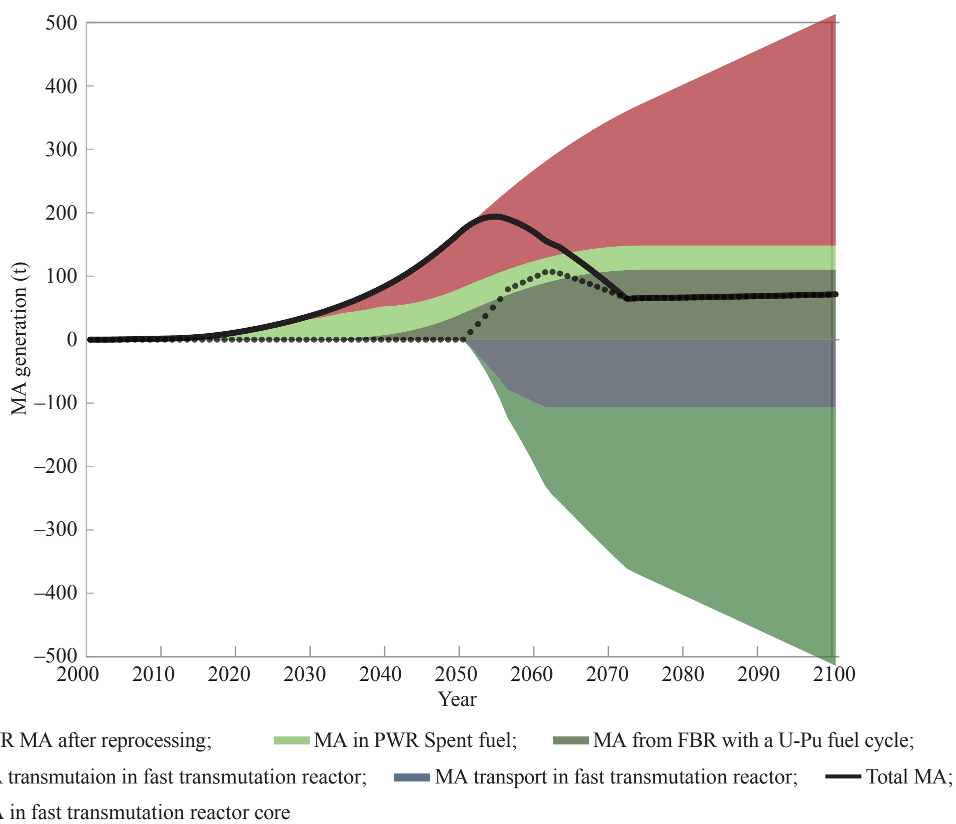


Fig. 5. Balance of MA in an INES.

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