ANNEX X.

PRIMARY ANALYSIS ON THE NUCLEAR ENERGY DEVELOPMENT SCENARIO BASED ON THE U-PU MULTI-RECYCLING IN CHINA

X-1. BACKGROUND

China, the largest developing country in the world, it needs to continually increase energy production for steady economic growth. From the very beginning, the Chinese government has paid much attention to energy supply and keeps the energy self-support ratio higher than 90%. The problem is that the structure of the energy supply is not good; coal occupies 80% of the primary energy. The total energy consumption is about 3.2 billion-ton coal in recent years. This induces two main issues, one of which is the supply unsustainability because coal reserves are limited, and the other problem is greenhouse effect caused by CO_2 emissions. In order to solve these issues, clean and renewable energy development is encouraged, including hydro power, solar energy, wind power, nuclear power, etc. The total capacity of clean energy will rise to about 15% of the primary energy [X-1]. Nuclear energy is a safe, mature and economical energy type with almost zero carbon emissions, so the Chinese government considers nuclear energy an important part of the energy structure for the future.

The Chinese government has consistently adhered to an approach of safely and efficiently developing nuclear power. To ensure safety after the Fukushima nuclear accident, 76 improvement projects were proposed for operating nuclear power plants (NPPs) and 26 projects were proposed for NPPs under construction. Seventy nine of the projects have been finished with a total investment of about 659 million RMB Yuan by 2013. For the approval of new NPPs higher requirements are put forward which demand them to meet higher safety standards. In order to improve the level of safety of the nuclear industry, the government released two programs, one of which is “Nuclear power development middle-long time plan” [X-2], and the other is “Nuclear safety development middle-long time plan” [X-3].

Unit 1 of the Yangjiang NPP in Province Guangdong was put in operation at March 25, 2014. So far, the total number of of NPP units in commercial operation is 18 in China mainland, their installed capacity 15.92 GW(e). In the first quarter of 2014, the mainland total generating electricity power was 1.27194 trillion kWh, and total nuclear power was 25.984 billion kWh, accounting for 2.04 percent of the total electric generation [X-4]. Presently, 28 pressurized water reactor (PWR) units are under construction and more about to start the construction. The new approval of nuclear power projects may start in 2014. Some studies show that the total nuclear capacity may be higher than 70 GW(e) till 2020, and may be increased to 400 GW(e) in 2050.

With the rapid development of nuclear power in China, limited available natural uranium resources will be one of the constraints of nuclear power development in the future [X-5, X-6]. In order to solve the problem, on the one hand China has increased the country's uranium exploration to increase the production. On the other hand, China is also actively exploring the international uranium market. It is an effort to get natural uranium resources through a variety of ways to meet the needs of nuclear power development. At the same time, based on the nuclear fuel breeding capacity of fast reactors (FR), China needs to implement the FR and related closed nuclear fuel cycle (CNFC) strategy to ensure the sustainable large-scale nuclear development. In this Annex, Chinese FR development strategy is introduced, and 4 cases of nuclear power scenarios of PWR-FR matching development with CNFC are presented and analyzed preliminarily to assess the potential of nuclear power development.

X-2. FAST REACTOR DEVELOPMENT STRATEGY IN CHINA

A three-step strategy is adopted to develop FR technology in China. The first step is to develop an experimental FR, which has been realized. The China Experimental Fast Reactor (CEFR) has been put into operation in 2011. A demonstration FR is the second step; the power capacity is about 600 MW(e), and the third step is to develop commercial FRs of 1000~1200 MW(e) [X-7].

Chinese research on FR was started initially from the middle of 1960s' and was mainly focused on the neutron physics, thermal hydraulics, fuel, materials, sodium technologies, safety etc. After 20 years, China mastered most of the basic knowledge about FR. From 1986, China started to study the design principles in order to design an experimental reactor. Before the end of 1995, the project named CEFR had been defined.

CEFR is a sodium cooled 65 MW(th) experimental FR using mixed oxide fuel (MOX). In order to gain more experience for the development of demonstration FR, CEFR adopts pool type design with electricity generation function. Main systems and parameters are very close to large FR. Table X-1 gives the main parameters of CEFR and Fig. X-1 shows the main heat transfer system.

TABLE X-1. MAIN PARAMETERS OF CEFR

Parameter	Unit	Value
Thermal power	MW	65
Electric power, net	MW	20
Reactor core		
Height	cm	45
Diameter equivalent	cm	60
Fuel		MOX (first loading is UO_2)
Linear power max.	W/cm	430
Neutron flux	$n/cm^2 \cdot s$	3.7×10^{15}
Fuel bum-up	MWday/t	60000
Inlet/outlet temp. of the core	℃	360/530
Diameter of main vessel (outside)	m	8.01
Design life	years	30
Primary circuit		
Number of loops		2
Mass of sodium	t	260
Flow rate, total	t/h	1328.4
Number of IHX per loop		2
Secondary circuit		
Number of loops		2
Quantity of sodium	t	48.2
Flow rate	t/h	986.4
Tertiary circuit		
Steam temperature	℃	480
Steam pressure	MPa	14
Flow rate	t/h	96.2

The demonstration FR of China is named CFR 600, with its design being very similar to CEFR using sodium coolant, pool type, Na-Na-HO_2 three loops, etc. CFR 600's thermal power is about 1500 MW, the electric capacity is about 600 MW, and the design life of NPP is about 60 years. It can be designed with two core types, as breeder or as burner, and the breeding ratio of the breeder type CFR 600 is about 1.2. The main design features CFR 600 correspond to the provisions of the fourth-generation nuclear technology, including sustainable development, security and reliability. The safety indicators include the core

damage frequency (CDF) less than 10^{-6} per reactor-year and the probability of a large-scale release of radioactivity less than 10^{-8} per reactor-year. The schematic diagram of CFR 600 is given in Fig. X-2.

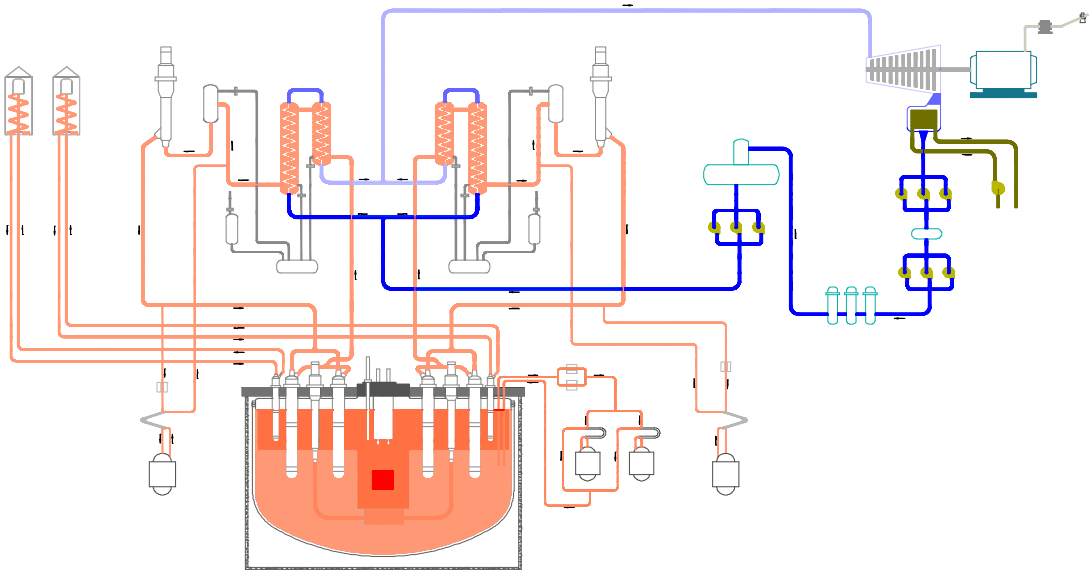

FIG. X-1. Main heat transfer system of CEFR.

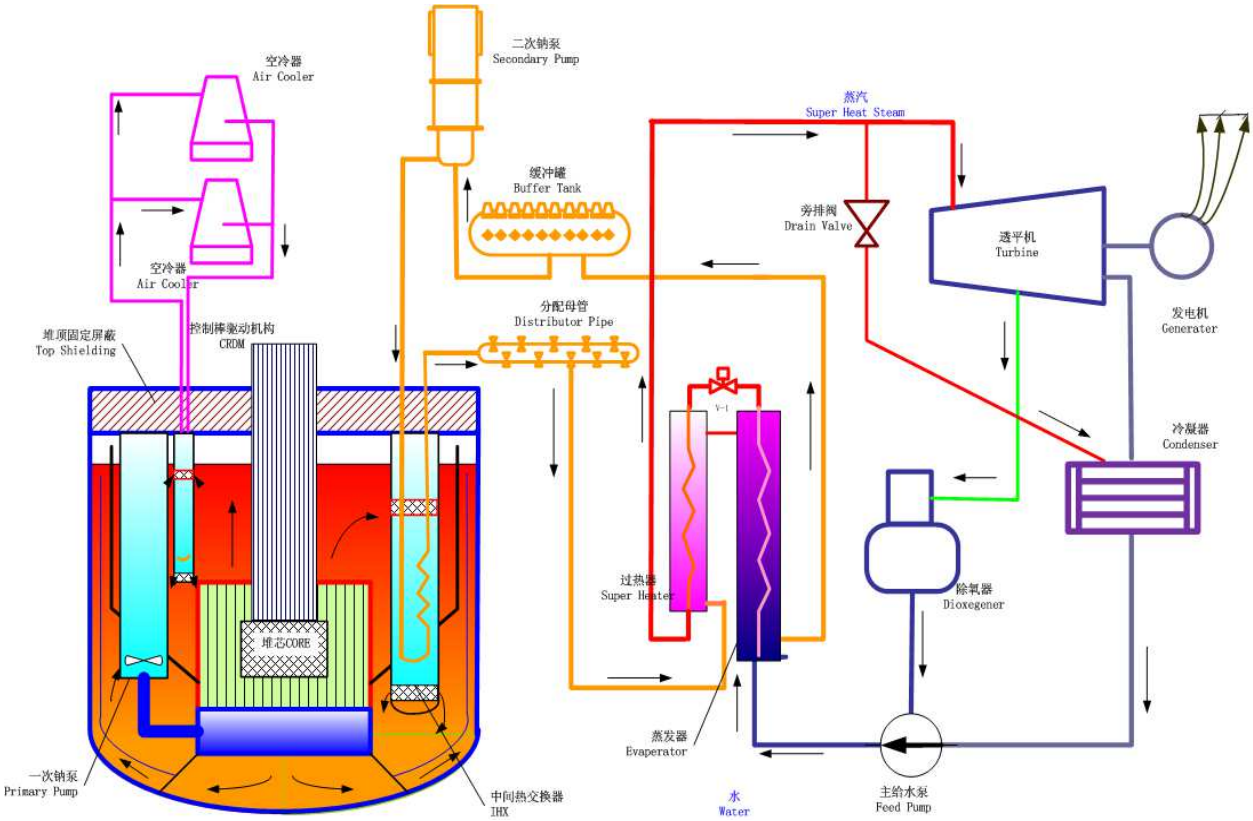

FIG. X-2. The schematic diagram of CFR 600.

The CFR 600 design has been launched in August 2012. The conceptual design was completed in 2013, with the preliminary design to be completed in 2015. Meanwhile, the

research work has been carried out some key equipment and technology. After the CFR 600, a larger-scale sodium-cooled FR is planned to be developed. The continuity of the FR technology in China is shown in Table X-2.

TABLE X-2. THE THREE-STEP DEVELOPMENT OF FR TECHNOLOGY IN CHINA

	CEFR	CFR	CDFBR
Electric power	20 MW	600 MW	1000~1200 MW
Coolant	Na		
Primary loop type	pool		
Fuel type	UO_2 / MOX	MOX / Metal	Metal
Cladding material	Cr-Ni SS	Cr-Ni SS / ODS	Cr-Ni SS / ODS
Core outlet temperature	530℃	550~500℃	500℃
Fuel linear power	430 W/cm	480 / 450 W/cm	450 W/cm
Fuel burn-up	60~100 MWday / kg	100~120 MWday / kg	120-150 MWday / kg
Fuel operation	straight pull manipulator with double plug		
Spent fuel storage	one cycle storage in the core and spent fuel storage water pool		
Engineered Safety Features	Active shutdown system Passive residual heat removal	Active shutdown system Passive shutdown system Passive residual heat removal	

It is necessary to mention fuel cycle because the fuel of FR is made from the spent fuel of PWR. China adopts a close fuel cycle approach to sustain the development of fission energy. Closed nuclear fuel cycle (CNFC) system is as shown in Fig. X-3. The industrial system of mining, refining, enrichment, UO_2 fuel fabrication and PWR power plants has been established. For reprocessing, a pilot reprocessing plant with the capacity of 50-80 ton/year has been put into operation, and an industrial-size reprocessing plant has been defined. There are two main options for FR fuel in China, which are MOX and U-Pu-Zr alloy. A laboratory size MOX fuel production line is under construction and an industrial MOX fuel plant is under discussion. Some research on metal fuel has been accomplished and more research will be carried out in the future.

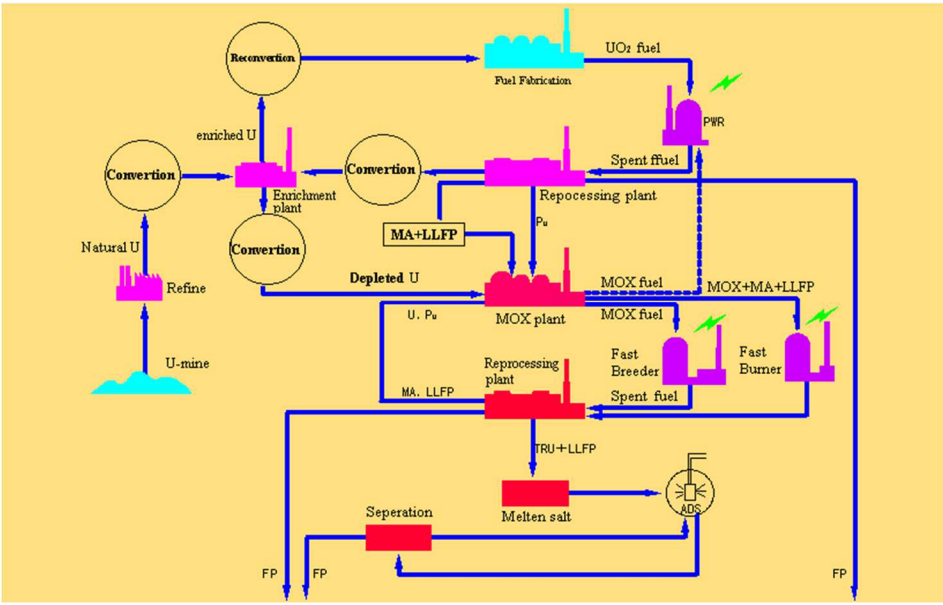

FIG. X-3. Fuel cycle in China.

X-3. PWR-FR MATCHING DEVELOPMENT SCENARIO ANALYSIS

X-3.1. Assumptions for scenario studies

Some research results show that China's population will increase up to 1.43 billion in 2050. The primary energy consumption will be increased to 3.5 t SCE[1]/year/person [X-8]. The total energy consumption will be 5 billion t SCE. The total electricity capacity will be 2.5 billion kW. If the scale of the 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 would be about 400 GW(e).

In order to accomplish the goal of nuclear power development, FR must be developed. There are two types of FR development scenarios. In the first type, there's sufficient uranium resource. The main task of fast reactors is to transmute minor actinides (MA) of PWR spent fuel. In the second type, there's not sufficient uranium resource. The main task of FR is to breed and to increase the capacity of nuclear power. This article focuses on the studies done for the second type scenarios. Through using the nuclear energy dynamic analysis code DESAE 2.2 [X-9], as provided by IAEA, some cases of FR and PWR matching development scenarios were analyzed under different constraints.

The CFR 1000 is selected as the FR model in this study. CFR1000 is an innovative FR concept of China, which is a pool-type sodium-cooled FR of 1000 MW(e). The core load is about 4.2 tons of plutonium, and this parameter may be slightly different when core is loaded with different fuel types. It uses 1/3 refuelling scheme, and the refuelling cycle is 330 effective full power days (EFPD). Using MOX fuel, the breeding ratio (BR) of CFR 1000 is designed for 1.2, and the BR is about 1.5 when metal fuel is used. The PWR model selected is the advanced M310 representing the Daya Bay NPP. The plant life of all NPPs with different reactors (PWR or FR) is 60 years. The fission material recycle times of PWR spent fuel and FR MOX spent fuel are both years, including the time of intermediate storage, reprocessing and fuel fabrication. This cycle time is 4 years when FRs use metal fuel. It is assumed there is sufficient reprocessing capacity to handle the spent fuel of every type reactor, and the handling ability of one reprocessing plant is assumed to be 1000 tons of heavy metal (HM) per year. The mass flow of this nuclear energy system with CNFC is shown in Fig. X-4.

X-3.2. Primary scenario analysis

This Annex primarily analyzes 4 cases according to the different supply of natural uranium resource and the different development plan of PWR and FR. The list of cases is shown in Table X-3. Cases I and II assume that the PWR NPPs develop more quickly than in Cases III and IV, and Cases III and IV roughly base on the national development plan; they have different PWR capacity because of the different uranium resource supply.

[1] SCE is standard coal equivalent.

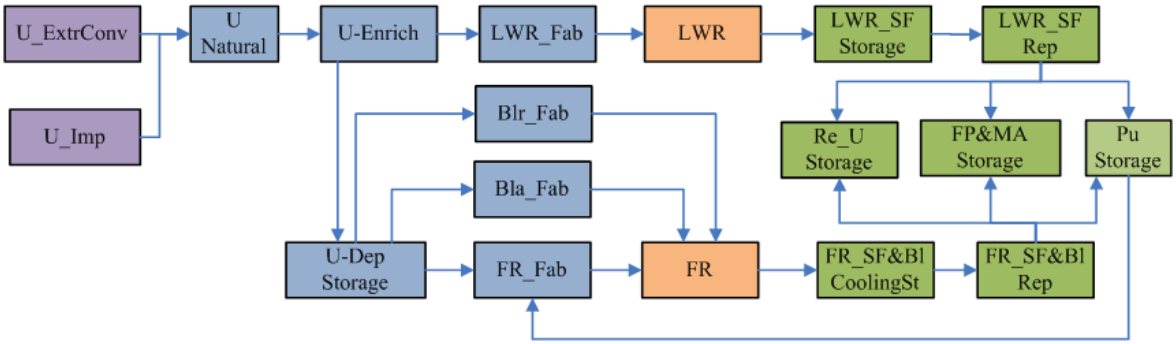

FIG. X-4. Mass flow of assumed scenario.

TABLE X-3. 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 200GW(e) in 2030	to 200GW(e) in 2030	to 40GW(e) in 2020; to 70 GW(e) in 2030; to 90 GW(e) in 2040; to 200 GW(e) in 2050	to 40GW(e) in 2020; to 70 GW(e) in 2030; to 90 GW(e) in 2040; to 100 GW(e) in 2050

X-3.2.1. Case I

Case I considers that the total availability of natural uranium is expected to be 2 million tons which should be the fuel consumption amount of PWRs with about 200 GW(e) in NPPs' life. PWR development is assumed to develop the maximum capacity supported by natural uranium resources. FR NPP with MOX fuel, named FR(MOX), are assumed to commercially operate in 2018, and the scale of their increase is one reactor unit per year in the initial stage (from 2018 to 2020), then the development scale would depend on the cumulative amount of plutonium which is obtained from the reprocessing plants of PWR and FR. The FRs with MOX fuel will no longer be developed after 2030, and the FR with metal fuel, which will be named FR(Metal), will develop instead as fast as possible. The calculated results are shown in the following Fig. X-5 to Fig. X-9.

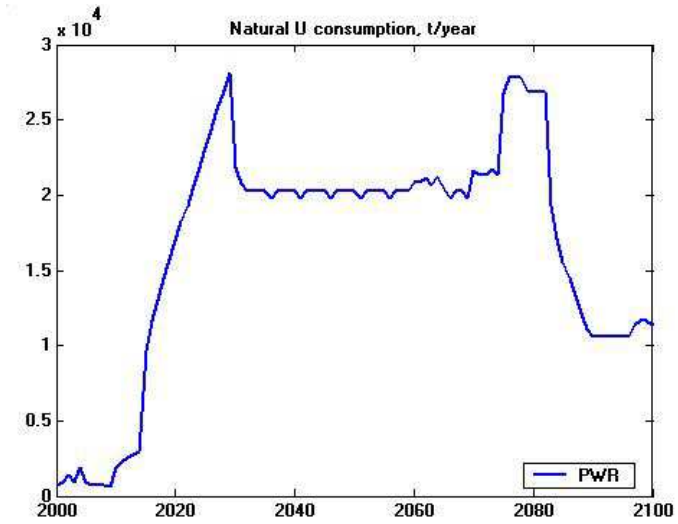

FIG. X-5. Annual consumption of natural uranium in Case I.

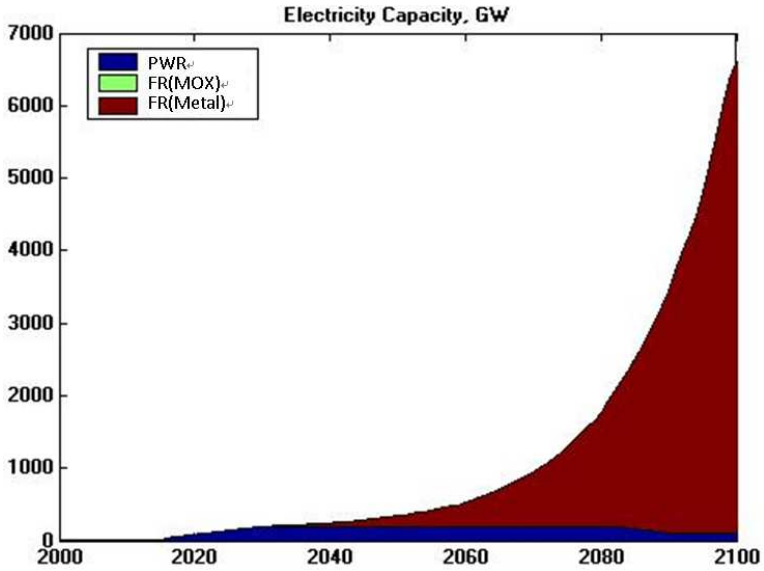

FIG. X-6. Total installed capacity development scale in Case I.

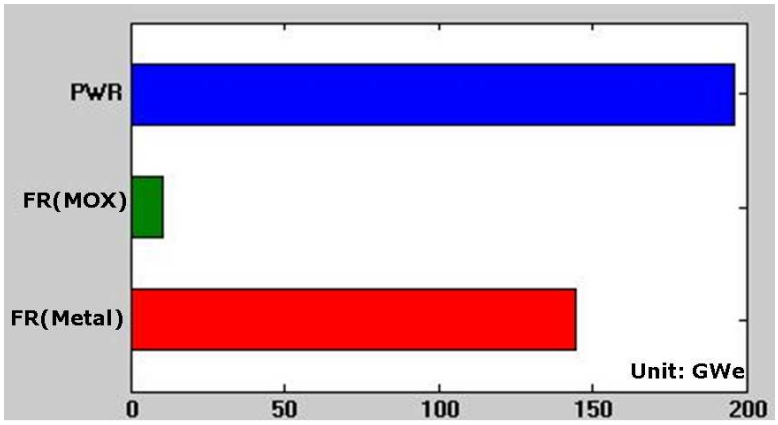

FIG. X-7. Nuclear power scale by each NPP type in Case I in 2050.

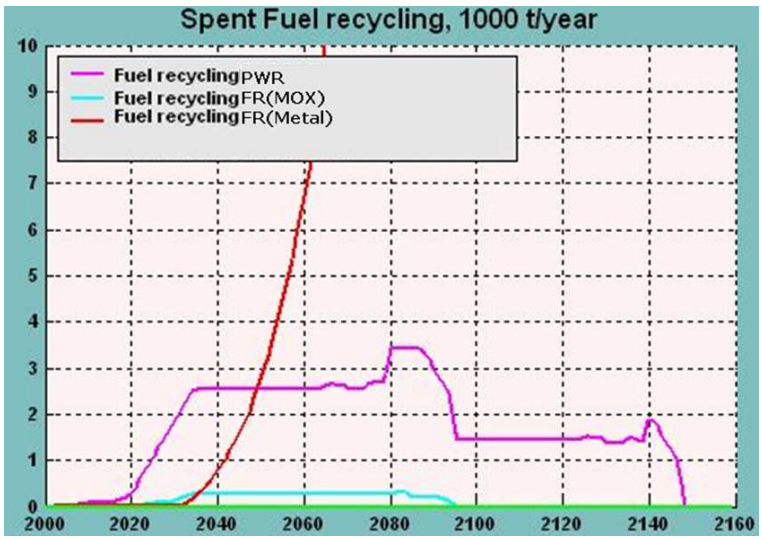

FIG. X-8. Reprocessing demand in Case I.

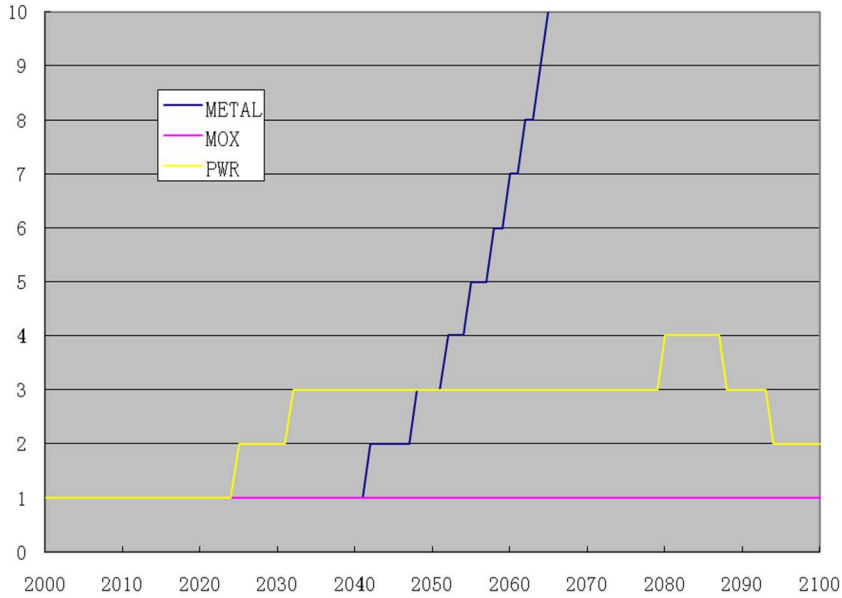

FIG. X-9. Reprocessing plant construction demand in Case I.

In Case I, the total consumption of natural uranium is 2.01 million tons, and the development scale of PWR peaks 200 GW(e) in 2030. In 2050, the total installed capacity of nuclear power is 360 GW(e), which includes PWR with 200 GW(e), FR(MOX) with 10 GW(e) and FR(Metal) with 150GW(e). The PWR spent fuel reprocessing amount is about 2,300 tons, the corresponding FR(MOX) spent fuel amount is 250 tons and the FR(Metal) spent fuel amount is 2700 tons.

X-3.2.2. Case II

In Case II, the available natural uranium and the PWR development plan are the same as in Case I. FR(MOX) is assumed to start from 2018, and the scale increase is one reactor unit per year from 2018 to 2020, then the FR will develop as fast as possible, just depending on the cumulative amount of plutonium which is obtained from the reprocessing plant of PWR and FR spent fuel. The difference with Case I is that FR(Metal) will not be developed in this case. The calculated results are shown in Fig. X-10 to Fig. X-14.

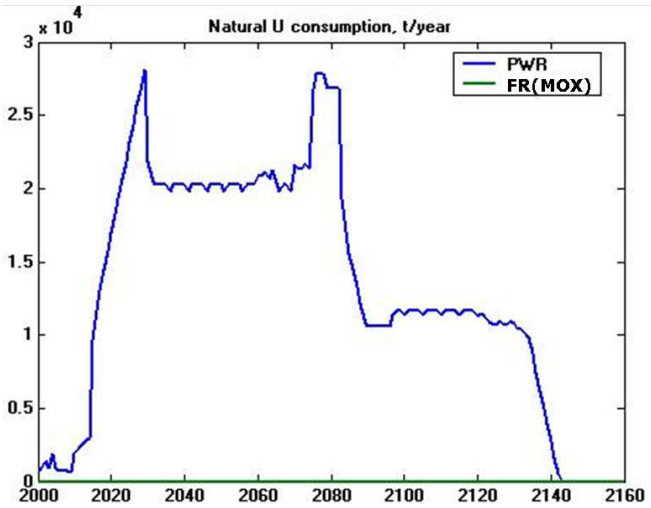

FIG. X-10. Annual consumption of natural uranium in Case II.

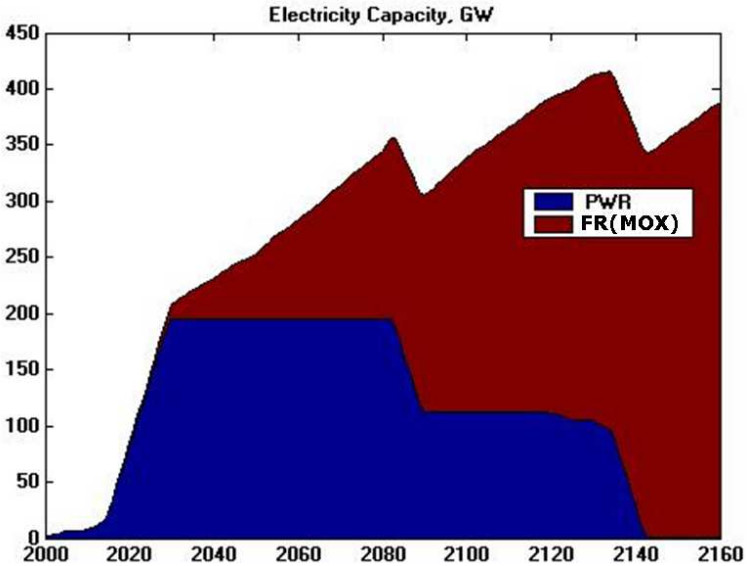

FIG. X-11. Total installed capacit5y development scale in Case II.

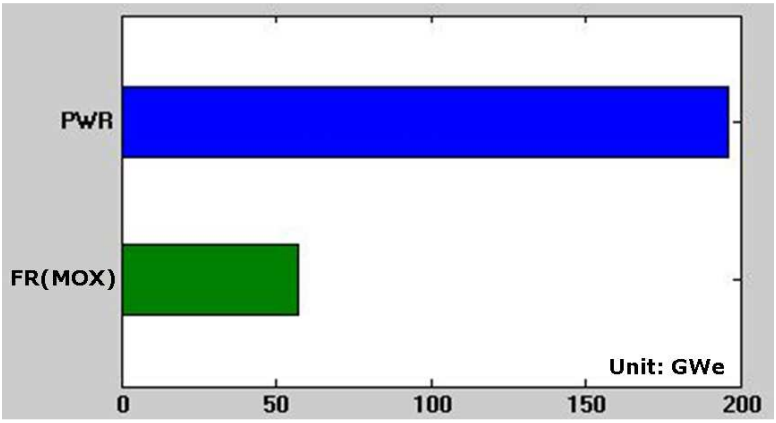

FIG. X-12. Nuclear power scale by each NPP type in Case II in 2050.

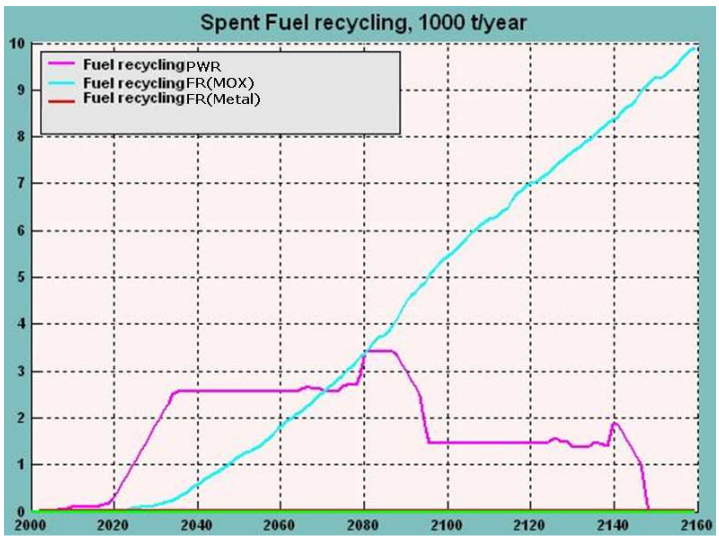

FIG. X-13. Reprocessing demand in Case II.

FIG. X-14. Reprocessing plant construction demand in 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 257 GW(e), which includes PWR with 200 GW(e) and FR(MOX) with 57GW(e). The PWR spent fuel reprocessing amount is about 2300 tons, the corresponding FR(MOX) spent fuel amount is 1100 tons.

X-3.2.3. Case III

The available natural uranium resource in Case III is also the same as in Cases I and Case II. FR development plan is same as in Case I. FR(MOX) is assumed to start from 2018, and FR(Metal) to start from 2030. The difference is that the development scale for PWR increases to 40 GW(e) in 2020, to 70 GW(e) in 2030, to 90 GW(e) in 2040 and to 200 GW(e) in 2050. The calculated results are shown in Fig. X-15 to Fig. X-19.

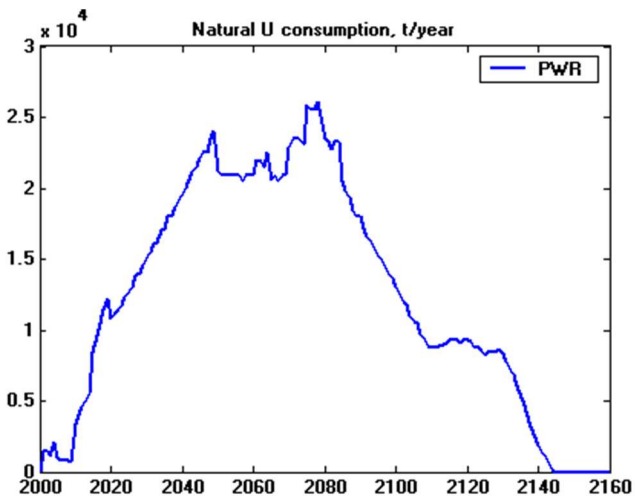

FIG. X-15. Annual consumption of natural uranium in Case III.

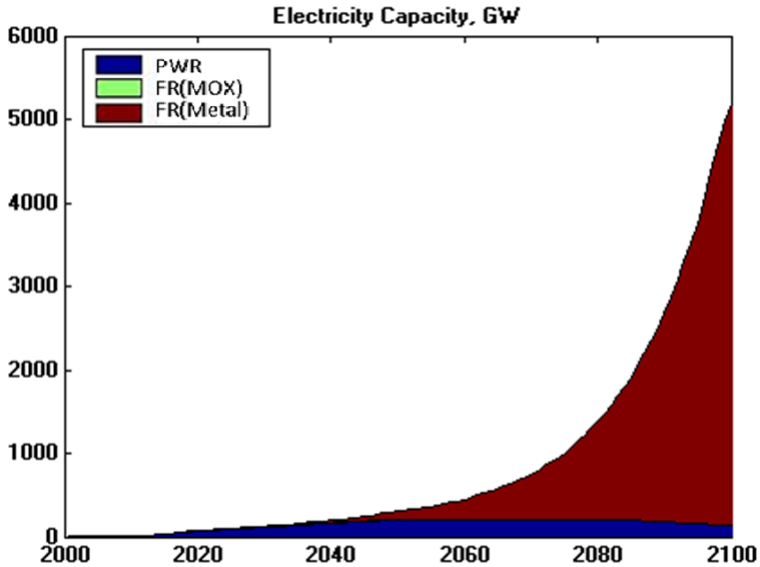

FIG. X-16. Total installed capacity development scale in Case III.

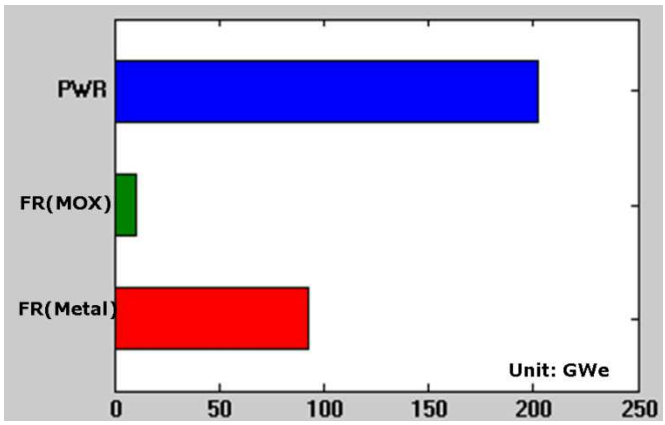

FIG. X-17. Nuclear power scale by each NPP type in Case III in 2015.

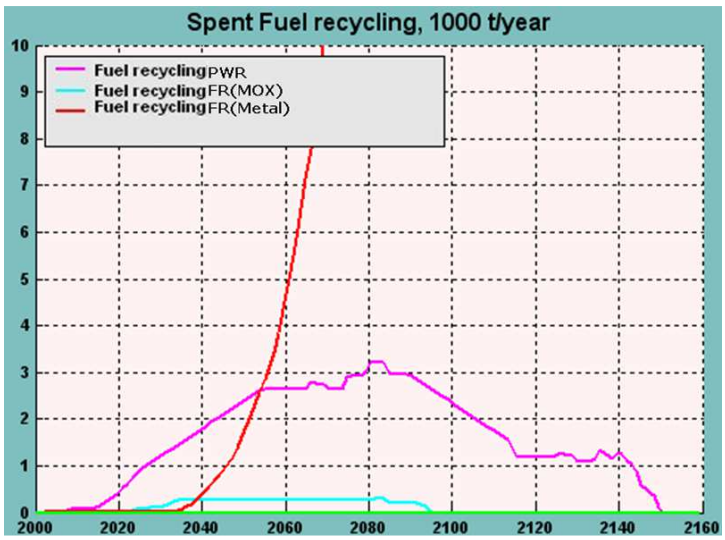

FIG X-18. Reprocessing demand in Case III.

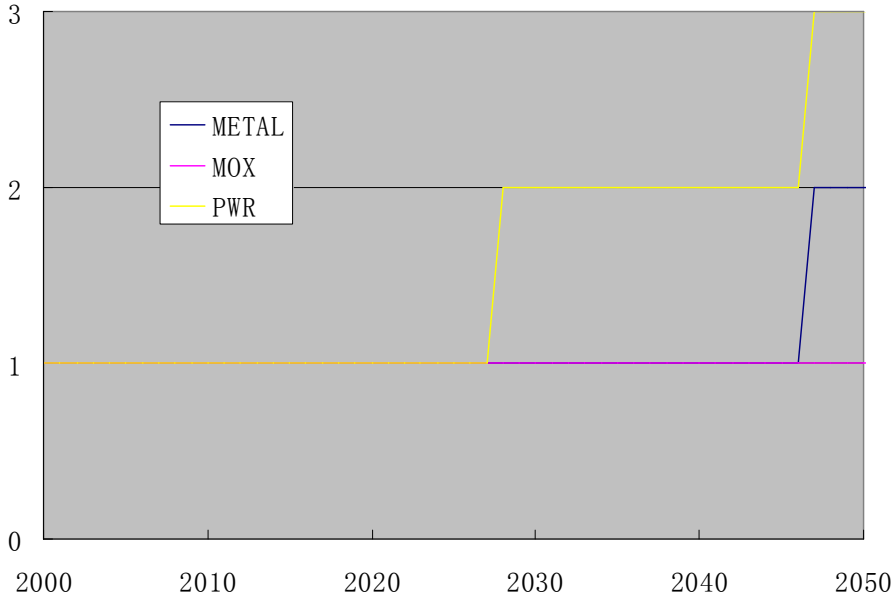

FIG. X-19. Reprocessing plant construction demand in Case III.

In Case III, the total consumption of natural uranium is 1.98 million tons, and the development scale of PWR peaks 200 GW(e) in 2050. In 2050, the total installed capacity of nuclear power is 303 GW(e), which includes PWR with 200GW(e), FR(MOX) with 10 GW(e) and FR(Metal) with 93GW(e). The PWR spent fuel reprocessing amount is about 2200 tons, the corresponding FR(MOX) spent fuel amount is 250 tons and the FR(Metal) spent fuel amount is 1700 tons.

X-3.2.4. Case IV

Case IV is very similar to Case III, and the difference is that the available natural uranium resources are just 1 million tons. The calculated results are shown in Fig. X-20 to Fig. X-24.

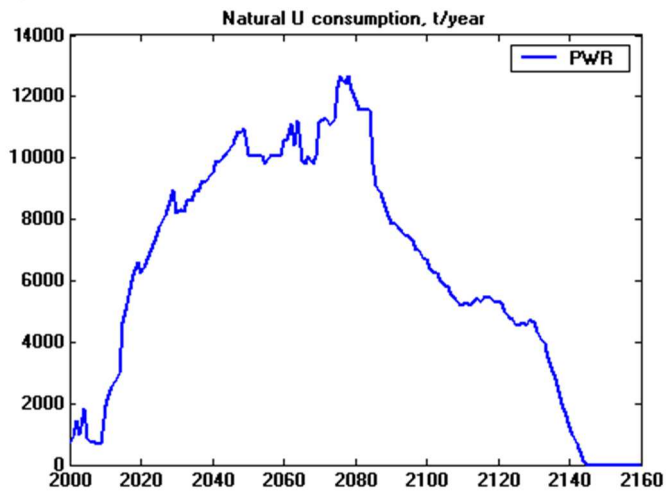

FIG. X-20. Annual consumption of natural uranium in Case IV.

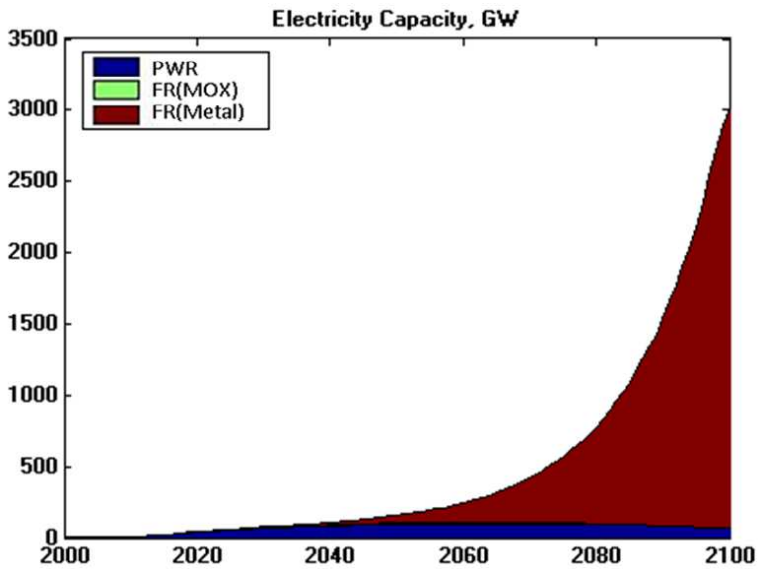

FIG. X-21. Total installed capacity development scale in Case IV.

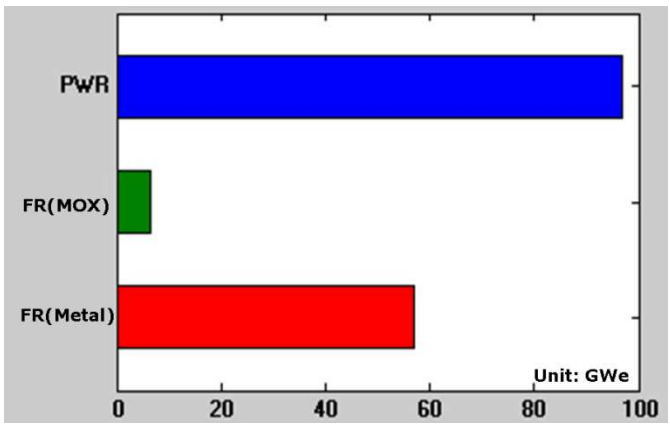

FIG. X-22. Nuclear power scale by each NPP type in Case IV in 2050.

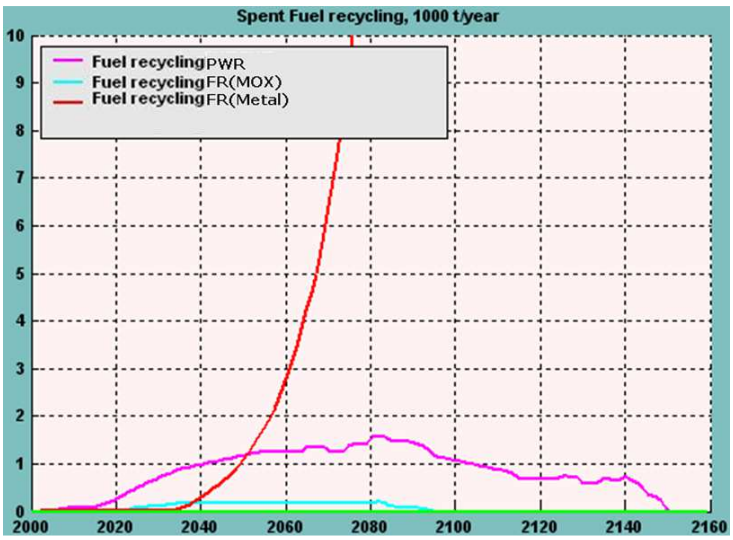

FIG. X-23. Reprocessing demand in Case IV.

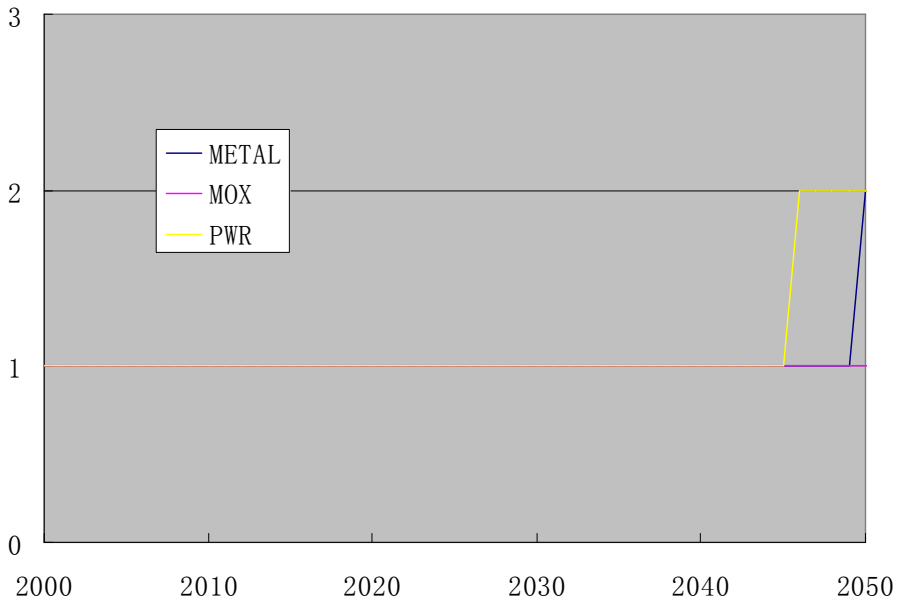

FIG. X-24. Reprocessing plant construction demand in Case IV.

In Case III, the total consumption of natural uranium is 1.01 million tons, and the development scale of PWR peaks 100 GW(e) in 2050. In 2050, the total installed capacity of nuclear power is 163 GW(e), which includes PWR with 100 GW(e), FR(MOX) with 6 GW(e) and FR(Metal) with 57 GW(e). The PWR spent fuel reprocessing amount is about 1100 tons, and the corresponding FR(MOX) spent fuel amount is 150 tons and the FR(Metal) spent fuel amount is 1000 tons.

When the four cases are compared, Case I is the closest to the ideal scale of the nuclear power, about 400 GW(e).

X-4. CONCLUSION

China devotes herself to the peaceful use of nuclear to meet the growing energy demand. Proper amount of nuclear power plants could provide clean energy with low risk.

This is very important for ensuring everyone to enjoy the outcomes of modern industrial civilization with as little damage to the environment as possible.

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-lived 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 fast reactor will provide enough clean power to people for a long term in the future.

Matching development of FRs and PWRs in China is very important for the nuclear energy large-scale sustainable development. But, to achieve faster development of the nuclear power capacity, it is necessary to have enough natural uranium 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 on metal fuelled FR with large breeding ratios (BR) and advanced reprocessing technology aimed at shortening the reprocessing time can be accelerated to increase the installed capacity.

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

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