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Research on Technological Direction and Development Roadmap of Nuclear Energy

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Abstract: This study focused on nuclear energy technology development with respect to thermal neutron, fast neutron, and Generation IV reactors, and on controlled nuclear fusion science and technology. Subject investigation, discussion, and systematically integrated methods were used in different stages of the research. This paper presents the current status, safety, technological direction, and development roadmap of China's nuclear energy. The study also suggests measures that should be taken. First, in the short-term, China should promote its independent advanced pressurized water reactor to enlarge the scale of its nuclear energy program in a safe and efficient manner. Second, China should accelerate research and development of Generation IV nuclear energy systems to address the problems of nuclear fuel breeding, the transmutation of transuranics, and long-life fission products. China also needs to actively develop small modular reactors to expand the application range of nuclear energy in the mid-term. Third, China should continue to explore fusion energy in the long-term. It is expected that by 2030 there will be 1.5×10^8 kW of nuclear reactors in operation and another 5×10^7 kW in construction, and there will be a harmonious development of pressurized water reactors and fast neutron reactors in 2050. The development of China's nuclear energy also faces certain challenges, such as insufficiencies at both the front and back ends of the nuclear industry chain, divergence in the research and development power with respect to core technology, and a lack of cooperation between state-owned companies (where extensive competition currently exists). It is anticipated that China will construct a State Nuclear Energy Lab involving the integration of existing resources with the aim of maximizing resources to promote the healthy and rapid development of the nuclear energy industry.

Keywords: nuclear energy; thermal neutron reactor; Generation IV nuclear system; controlled nuclear fusion; development roadmap

1 Introduction

Nuclear energy is a low-carbon strategic energy that is safe and clean, with a high energy density. Although the Fukushima nuclear accident in 2011 postponed the pace of nuclear energy development globally, its effect is now gradually weakening. The development of nuclear energy in China plays an important role in guaranteeing energy security and attaining green and low-carbon development in the country, and its use is necessary to drive the equipment manufacturing industry to a higher level and build an "upgraded version" of China's economy. Nuclear power construction worldwide is improving rapidly, and nuclear power export has become a national strategy. This paper summarizes the main content and conclusions of the study "Research on Technological Directions and Development Roadmap of Nuclear Energy". In addition, it highlights the key scientific and technological directions of nuclear energy in China and also provides a development roadmap.

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2 Developmental status of nuclear energy technology

2.1 Development of pressurized water reactors for nuclear power: the predominant global choice

There are currently 450 nuclear power units in operation in the world with a total installed capacity of 394 GW. Of these, 294 units are pressurized water reactors (PWRs), and 45 of the 55 units currently under construction are PWRs [1]. In China, 36 of the current 38 commercial nuclear power units are PWRs and 17 of the 19 nuclear power units currently under construction are PWRs. It is thus evident that PWRs will dominate the industry for a considerable number of years to come.

2.2 Continuously improved performance from existing reactors

From 1980 to 2016, the global nuclear power capacity factor increased from 60% to 80.5%. Approximately one third of all current units operate at capacity factors over 90%. The capacity factors of old units are almost equal to those of new units, and there are no significant age-related variations [2]. However, China's nuclear power capacity factor decreased from 86.32% in 2014 to 81.14% in 2017 [3], mainly due to the insufficient nuclear power consumption capacities of Liaoning and Fujian provinces. In addition, China's nuclear power industry is facing pressure to participate in peak regulations.

2.3 Life extension of old units became urgent

At present, approximately 300 nuclear power units globally have been in operation for more than 30 years, and approximately 100 of these have been in operation for more than 40 years [1]. The United States (US) began extending the life of old units in the 1990s, and after conducting life assessments, safety analyses, and systematic technical transformations, the performance of the equipment has significantly improved. As of 1 July 2017, 84 of the 99 operating units in the US had received a license extension to operate 60 years [4].

2.4 Worldwide nuclear power unit construction and Generation III reactors

There are 55 units under construction in 15 countries, including two units in Belarus and two units in the United Arab Emirates [1,5]. In addition, 42 countries are planning or considering the construction of nuclear power units; 26 of these countries do not currently have nuclear power [5]. The International Atomic Energy Agency (IAEA) predicts that by 2030, between 101 and 206 GW nuclear power units will have been built, and the world nuclear power will reach 345 GW–554 GW [6]. After the Fukushima accident, the international community proposed higher safety requirements for new nuclear power units, and Generation III reactors are expected to play a key role in this safety strategy. However, 16 of the 18 Generation III PWRs (A total of 8 AP1000, 6 AES, 2006, and 4 EPR) under construction in 2014 are currently delayed to varying degrees in their completion; therefore, the economics of the first several reactor projects are poor [7]. Conversely, China's HPR1000 demonstration projects at home and abroad are progressing smoothly.

2.5 Research and development (R&D) of small modular reactors (SMR)

Small modular reactors (SMRs) have certain advantages over large reactors, such as providing better inherent safety, lower upfront capital cost per unit, and more flexible power generation for a wider range of applications. The US government has been funding R&D of SMRs since the 1990s with the aim of replacing a large number of aging fossil fuel power units. Currently, there are at least 50 SMR designs in development for different applications. Three industrial demonstration SMRs are in the advanced stages of construction: in Argentina (CAREM, an integral PWR), in China (HTR-PM, a high temperature gas-cooled reactor), and in the Russian Federation (KLT40s, a floating power unit). Small modular PWRs that may be deployed in the near term include mPower, NuScale, and SMART.

China proposed the ACP100, CAP150, ACPR50S and other small PWR concepts, and ACP100 is the world's first small reactor to pass an IAEA safety review [8].

2.6 Accumulation of spent fuel results in an urgent demand for back-end capacity of the nuclear fuel cycle

By the end of 2016, the global amount of spent fuel in storage was approximately 2.73×10^5 t. This amount is accumulating at a rate of 7000 tons per year, and the pressure on spent fuel storage is thus increasing [9]. In addition, projects related to geological disposal of high-level radioactive waste are progressing at a slower pace than planned and many countries are facing public opposition. Only Finland, France, and Sweden have announced expected timelines for achieving technically feasible and socially acceptable deep geological repositories. Therefore, only a small quantity of waste from the reprocessing requires geological disposal. In China, the spent fuel storage capacity in some nuclear power plants is close to saturation, and the capacity of transportation and away-from-reactor storage is also limited; therefore, the demand for reprocessing and waste disposal is increasingly urgent.

2.7 Development of generation IV advanced nuclear energy systems

The Generation IV International Forum (GIF) was launched by the US in 2000 and it defined four goal areas in the advancement of nuclear energy development: sustainability (uranium resource utilization and waste management), safety and reliability, economic competitiveness, and proliferation resistance and physical protection. Generation IV reactors will play a key role in future sustainable development of nuclear energy. Following the Fukushima accident, the GIF placed more emphasis on inherent safety R&D in order to reach a higher safety level than current nuclear systems. GIF selected six systems that meet the above four requirements: sodium-cooled fast reactors (SFR), lead-cooled fast reactors (LFR), gas-cooled fast reactors (GFR), supercritical water-cooled reactors (SWCR), very high-temperature reactors (VHTR), and molten salt reactors (MSR). Traveling wave reactors (TWR) and accelerator-driven subcritical systems (ADS) are also able to meet the requirements of fourth generation reactors.

The above eight reactor systems are at different stages of development, as shown in Table 1. Among them, SFRs and VHTRs have better engineering experiences. VHTRs and TWRs are suitable for once-through fuel cycles, while the others are suitable for closed fuel cycles.

3 Safety of nuclear energy in China

The public is most concerned about nuclear power plant safety and radioactive waste management, and ensuring safety is at the core of nuclear energy development. Determining overall safety requires a comprehensive evaluation of risks and benefits. Under normal circumstances, the normalized radiation exposure dose to workers in the nuclear energy industry chain is only 1/10 of exposure in the coal industry, and the exposure to the public is only 1/50 of that of the coal lifecycle. The public's concerns about nuclear safety are mostly in response to the three severe historical nuclear accidents: Three Mile Island, Chernobyl, and Fukushima.

3.1 Guaranteed safety of nuclear power units in operation

More than 30 of the nuclear power units currently in operation in China are improved Generation II reactors, and the safety level of these is equal to or greater than most units in operation globally. In China, nuclear power plant (NPP) performance indicators in relation to the World Association of Nuclear Operators (WANO) are generally above those of the global average level. No level 2 or greater accidents have ever occurred, and the radioactive effluent dose level is far below the national standard. After the Fukushima nuclear accident, China immediately launched a nuclear power plant safety inspection and acted on feedback received from Fukushima by updating plants where necessary. After the safety review, and in accordance with nuclear energy safety and regulations, the ability of all units to cope with extreme natural disasters was improved, as were prevention and mitigation measures against the occurrence of severe accidents. Fukushima nuclear plant is located in the subduction zone of the Eurasian plate and the Pacific plate, and large earthquakes occur frequently in this area. The Fukushima reactors destroyed in the accident were old boiling water reactors that had a relatively low safety level. According to analyses by Chinese experts, an accident sequence similar to that occurring in Fukushima is unlikely to happen in China, regardless of the type of reactor, natural disaster occurrence conditions, or safety assurance measures.

3.2 PWRs that meet the highest international nuclear safety requirements

In accordance with the requirements of *China's 12th Five-Year Plan for Nuclear Safety and Radioactive Pollution Prevention and Control and Vision 2020*, all newly approved nuclear power units during the 13th Five-Year Plan period will be developed to practically eliminate the possibility of release of large quantities of radioactive materials. China's own brand HPR1000 and CAP1400 advanced PWRs have thorough measures for prevention and mitigation of severe accidents. In addition, they comprehensively implement the principle of defense in depth, and multiple physical barriers have been installed to achieve radioactive material containment. China's current HTGR and SFR

Table 1. Development status of Generation IV reactors.

Reactor	Main advantages	Development status
SFR	Closed fuel cycle	Performance phase; BN800 in operation China's SFR demonstration project in construction
LFR	SMR, flexible	Key technology research
GFR	Closed fuel cycle	Viability phase, tough challenges need to be overcome
VHTR	High temperature heat source	Performance phase; China's high temperature gas-cooled reactor (HTGR) demonstration project in construction
SWCR	Better safety and economics over PWR	Viability phase
MSR	Thorium utilization	Viability phase
ADS	Transmutation	Key technology research
TRW	High burnup, once-through	Key technology research

demonstration projects, and modular pressurized water reactors under development, have even higher inherent safety features.

3.3 Local manufacturing of nuclear power equipment

Since 2006, continuous advances have been made in the strategy to localize nuclear power and the ability to localize manufacturing of nuclear power equipment has dramatically improved. At present, the rate of localizing equipment for the improved Generation II nuclear power units is at 85%, and China has a batch manufacturing capacity of 8–10 units per year. By initiating major projects to construct large advanced PWR nuclear power plants, there have been breakthroughs in the development of key technologies for main pumps, key valves, and digital instrument control systems, which allows for future localization of manufacturing the components. The localization rate of the HPR1000 demonstration project will be no less than 85%, and it will be no less than 95% after batch construction. The localization rate of the CAP1400 demonstration project is also expected to reach 85%.

Nuclear power equipment manufacturing processes need to be continuously improved and normalized. Although nuclear power equipment has been fully developed in the past decade, the link between design and production is not yet adequate. Many manufacturing processes need to be continuously improved and normalized to further improve the equipment supply capacity and reduce costs.

In addition, the focus of R&D is too scattered. The three major nuclear groups are all developing new control systems, protection systems, core measurement systems, and related equipment, each of which has its own problems that require solving. Competition amongst developers is far greater than cooperation, which increases the cost of R&D and reduces the pace of improving national system equipment. Furthermore, there is no unified national technical appraisal platform. It is thus necessary to overcome institutional and organizational obstacles to accomplish an objective, scientific, and in-depth technical review.

3.4 Research on nuclear energy safety

The IAEA Fukushima accident report by the Director General states that a systemic approach to safety is needed that considers dynamic interactions between factors relating to individuals (knowledge, thoughts, decisions, actions), technical factors (technology, tools, equipment), and organizational factors (management system, organizational structure, governance, resources). Through conducting regular assessments, providing strict supervision, and fully understanding and applying the latest research conducted within China and abroad, it is possible to ensure that nuclear power plants meet the latest safety standards.

From a technical perspective, a major goal of nuclear power safety is to eliminate the release of large quantities of radioactive materials and to mitigate the need for off-site emergency response. To achieve this, it is necessary to continuously strengthen safety research related to reactors, including the following research areas: enhancing the inherent safety of reactors through innovative applications of advanced nuclear fuel technology and reactor technology to ensure there is a minimal risk of severe accidents occurring, studying the core melting mechanism and optimizing engineering measures and management guidelines for severe accident prevention and mitigation, strengthening research on the integrity of containment, focusing on residual risk protection measures to ensure that even in the event of an extremely severe accident, the release of radioactive materials is controlled and environmental safety is guaranteed, and enhancing nuclear emergency research and drills (as a last resort).

3.5 Advanced nuclear reactors and reprocessing for spent-fuel management and sustainable development

To enable the sustainable development of nuclear energy, it is necessary to solve problems related to the low utilization of uranium resources and the disposal of high-level radioactive waste. If a once-through fuel cycle is adopted, only about 0.6% of the uranium is utilized and it will be necessary to deep-dispose approximately 2 m^3/t uranium of high-level radioactive waste (HLW) for a nuclear power unit with 1 GW per year. With second generation reprocessing, which extracts uranium and plutonium from spent fuel and reuses it in a PWR, approximately 1% of the uranium is utilized, and the amount of HLW that requires deep geologically disposal is reduced to about 0.5 m^3/t uranium. In the near future, however, a combination of FR or ADS with third generation reprocessing technology will result in a uranium resource utilization rate of up to 60%. The amount of HLW that will need to be geologically disposed of will be less than 0.05 m^3/t uranium and the time for the HLW to decay to the radioactivity level of natural uranium will be less than 1000 years (instead of a few hundred thousand years). Through glass solidification, triple engineering barrier treatment, and deep geological burial, it can be ensured that the radioactive release of HLW is controllable, even under extreme conditions, and that the radioactive dose to the biosphere is lower than international standards by up to two to three orders of magnitude.

4 Developmental direction of nuclear energy technology

4.1 Major technical problems effecting nuclear energy development

4.1.1 Technical problems with large-scale development of thermal reactors

It is necessary for uranium exploration, mining, and metallurgy to be strengthened. According to the results of China's new round evaluation of uranium resource potentials, domestic natural uranium can only meet the 60-year demand of nearly 1×10^8 kW PWR nuclear power (without considering introduction of mixed oxide (MOX) fuel and a fast reactor). Uranium resource exploration in China is currently limited, and because it takes at least 15 years from ore exploration to providing a fuel product (with the long process of exploration, mining and milling, conversion, enrichment, and fuel manufacture), it is now necessary to enhance the development of uranium exploration, mining, and metallurgy to ensure the sustainable development of nuclear power in China.

In addition, the fuel assembly manufacturing capacity is insufficient. China's current fuel assembly capacity is 1400 t uranium per year. Assuming that 30 t uranium per year is required for a 1-GW PWR, the total fuel demand will be approximately 1800 t uranium per year by 2020 and the supply and demand gap will reach 400 t uranium per year.

The safety and economics of Generation III advanced PWRs need to be optimally balanced. At present, development of Generation III advanced PWRs under construction in China and abroad, such as the AP1000 and EPR, has been delayed to different degrees. The poor economic analysis provided with the demonstration project caused public concern about the economic viability of nuclear power. This has been a major issue in the large-scale promotion of Generation III nuclear power, and further systematic research work is urgently required.

In the large-scale development of nuclear energy, it is also necessary to upgrade technologies associated with operation and maintenance within the nuclear facilities. When there are a large number of old units, it is necessary to fully upgrade the operation and maintenance technology, which requires transitioning the workforce from junior manual labor to a more senior technology worker. Accordingly, equipment reliability, and aging management and emergency response technology need to be updated as soon as possible.

Furthermore, the software ability of nuclear power needs to be improved. In recent years, China has achieved key breakthroughs in its independent development of software, and now has its own nuclear power design software. The United States and the European Union are developing a "numerical reactor" based on high-performance computing technology, which uses multi-physics and multi-scale coupling technology to build a virtual simulation environment that can predict reactor performance online. China needs to unite and concentrate its strengths to keep pace with the development of advanced countries in the new round of nuclear energy software R&D.

It is also urgently necessary to increase the reprocessing capacity and develop away-from-reactor storage technology to reduce the challenges of reactor pool storage and spent fuel reprocessing. The HLW needs to be disposed of as quickly as possible.

4.1.2 Technical problems in the development of fast reactors and Generation IV reactors

(1) Breeding of fission fuel

Although uranium resource support is not a problem in the near future, China still faces the risk of a long-term insufficient supply (with the large-scale development of nuclear power). In principle, however, the fast reactors will use 60% of the uranium resource, and they are therefore expected to become the new millennial energy source. The breeding ratio of SFR is very high, and a short fuel-doubling time can be achieved with advanced pyro reprocessing and rapid metal fuel manufacturing technology, which is beneficial for expanding the scale of nuclear energy in a short period of time. However, relevant fundamental research needs to be conducted quickly.

(2) Partition and transmutation of transuranic elements (TRU)

TRU is a valuable nuclear fuel that needs to be separated from spent fuel or it becomes the main source of HLW. It is necessary to determine how best to treat TRU, as this is an important issue affecting public acceptance of nuclear energy. Separation of TRU from spent fuel is necessary for transmutation in an FR or ADS. It is thus necessary to develop advanced separation technology, waste conditioning technology, MA-containing assembly/target manufacturing technology, and accelerate the development of key equipment and materials. It is also necessary to develop a dedicated fast reactor or ADS system for transmutation.

(3) Extended application area of advanced nuclear energy

In addition to electricity generation, there is a huge potential for nuclear energy to provide a heat supply (urban heat supply, industrial process heating, sea water desalination) and nuclear powered propulsion. SMRs, such as modular PWRs, VHTRs, and LFRs, can play an important role in supplementing the development of nuclear energy.

(4) Generation IV reactor positioning and competition

There are six systems in addition to ADS and TWR that meet Generation IV criteria. They are all in different stages of development and each system uses several development concepts. As it is neither necessary nor possible for one country to develop all the Generation IV reactors, it is important to strengthen nuclear energy strategy research, which will clarify the unique advantages of each reactor type, degree of maturity, and associated scope of future development.

4.1.3 Technical problems relating to fusion science and technology

Magnetic controlled fusion (MCF) and inertial controlled fusion (ICF) are two main methods used in controlled fusion; they are both at different exploration stages and are currently far from meeting the requirements of fusion energy. The focus in the field of MCF is implementation of the international thermonuclear fusion experimental reactor (ITER) project, through which the physical and technical problems of the steady-state plasma burning processes will be solved, thereby fully demonstrating the scientific and engineering feasibility of developing and using fusion energy. In the field of ICF, Z-Pinch has more potential to become a competitive fusion-fission hybrid energy source. However, the first priority is to promote fusion ignition physics research.

The key technology required to achieve massive fusion reactions for MCF is heating, confinement (for fusion), and "maintaining" (a long-term or average long-term fusion reaction), while for ICF it is compression, ignition, and "high repetition frequency ignition." Future MCF devices must operate in long pulse or continuous modes in order to obtain net and stable fusion energy, while ICF needs to be operated in a high repetition frequency ignition mode, which presents considerable challenges.

Before fusion energy can be commercially applied, structural materials need to be developed that can withstand long-term, intense, high-energy, neutron irradiation. In addition, many engineering and technical challenges, such as the tritium self-sufficiency fuel cycle, need to be overcome. The development of fusion-fission hybrid reactors may promote the early application of fusion energy, however, its competitiveness in future energy sources must be comparable to Generation IV reactors and pure fusion reactors.

4.2 Development trends in nuclear energy science and technology

The PWR has been the workhorse in China's nuclear power development, and this will continue until 2030. The overall direction of current development is to maintain long-term safety and stability, and to maximize the effectiveness of using nuclear energy. Safety is the prerequisite for nuclear power development; however, providing an optimal balance between safety and economics is a realistic challenge in the development of Generation III reactors. The dry storage, transportation, and reprocessing of spent fuel and the disposal of high-level waste from PWRs needs to be considered and comprehensively conducted.

FR and Generation IV reactors will play a leading role in the next stage of nuclear energy development. It is expected that some mature Generation IV reactors will be introduced to the market around 2030 and their implementation will then gradually expand. SFR is currently the most mature Generation IV reactor technology, and it is close to commercialization. The major global nuclear power countries are focusing on the development of reactors with SFR after PWR. However, it is first necessary for demonstration projects to prove that SFR is safe and economically viable. The fuel cycle, which includes the reprocessing of PWR spent fuel, manufacturing FR fuel assembly, and reprocessing of FR spent fuel, is key to the large-scale and rapid development of FR.

If breakthroughs in unconventional uranium development are made, such as uranium extraction from seawater, the demand for FR to supply energy will decrease, while the demand for the transmutation of TRU and long-lived fission products (LLFP) will increase. Even if the main function of FR shifts from breeding to transmutation, and the scale of development decreases accordingly, it is still necessary to develop FRs and the related fuel cycle. Since the establishment of a fast reactor fuel cycle will take decades, relevant research should be conducted as soon as possible to strengthen the technical reserve. China is the world leader in HTGR and will facilitate the development of VHTR and play an important role in extending the application range of nuclear energy. Other Generation IV reactor technologies are still in the early stages of R&D. Since there are both advantages (in principle) and engineering challenges that need attention, research focusing on basic common problems should be conducted first.

Fusion energy is an ideal strategic future energy source. Tokamak research is the leading research entity in the field of MCF. In addition, China has officially participated in the construction and research of the ITER project and is independently designing and developing the China Fusion Engineering Test Reactor (CFETR). In the field of ICF, Z-pinch has greater potential, and is likely to become a competitive fusion-fission hybrid energy source. Although no shortcuts have been found in the application of fusion energy, it is still necessary to keep track of new ideas, new technologies, and new methods in international fusion energy research.

5 Developmental roadmap of nuclear energy technology

The near-term goal of China's nuclear energy development is to optimize Generation III nuclear power technology. The medium- to long-term goal is to develop a Generation IV nuclear energy system with the focus on SFR, and also to actively develop SMR for use as a heat supply and for nuclear power propulsion, while the long-term goal is to develop nuclear fusion energy technology.

According to research results of this project, the following key technologies are expected to be realized by the associated years:

Innovation technology (by 2020): development of Generation III nuclear power products by local brands in China will drive the full development of the nuclear power industry chain, and construction of the small modular PWR demonstration project will begin.

Forward-looking technology (by 2030): there will be breakthroughs in nuclear safety technology, represented by accident-tolerant-fuels (ATF), which will lead to elimination of the release of large quantities of radioactive materials and the enhancement of nuclear power competitiveness. The PWR fuel cycle will be closed, and the nuclear power industry chain will have coordinated development. Some Generation IV reactors, such as SFRs, will enter the market. Key technologies in nuclear fuel breeding and HLW transmutation will make breakthroughs. SMRs (including small pressurized water reactors, high-temperature gas-cooled reactors, and lead-cooled fast reactors) will be actively explored to realize the multi-purpose utilization of nuclear energy.

Cutting-edge technology (by 2050): closed fuel cycle for FR will be achieved, PWRs and FRs will form a symbiotic system, and endeavors will be made to finish construction of the nuclear fusion demonstration project.

Fig. 1 shows the development roadmap of nuclear energy technology according to technical readiness of the three fields of PWRs, Generation IV reactors, and fusion technology.

6 Conclusions and suggestions

6.1 Main conclusions

After the Fukushima nuclear accident, countries such as the US and those in the European Union conducted stress tests on their nuclear power plants. China also arranged safety inspections and acted on feedback received from Fukushima by updating plants where necessary. The overall growing trend of nuclear power worldwide has not changed, and nuclear power is still a rational and realistic energy choice. According to an analysis by Chinese experts, an accident sequence similar to Fukushima is unlikely to occur in China, regardless of the reactor type, natural disaster occurrence conditions, or safety assurance measures. It is thus considered that the safety of nuclear power in China is guaranteed.

Nuclear energy is a low-carbon strategic energy that is safe, clean, and has a high energy density. The development of nuclear energy is essential for China to overcome the current bottleneck in resources and environmental impacts, ensure energy security, and achieve green and low carbon development. The share of nuclear power generation in China is only 3.94%, which is far below the international average of 10.7%. However, nuclear power development must be safe, efficient, and should occur on a large scale to become one of the pillars of national energy.

According to the Medium- and Long-Term Development Plan for Nuclear Power (2011–2020), China's nuclear power capacity will reach 5.8×10^7 kW in 2020, and another 3×10^7 kW will be in construction at that time. In addition, based on President Xi's commitment that non-fossil energy will account for 20% of the primary energy consumption in China in 2030, and in accordance with the domestic design, construction, and equipment supply capacity of nuclear power, it is expected that the nuclear power capacity will be 1.5×10^8 kW by this date and that another 5×10^7 kW will be under construction; therefore, the nuclear power share will be approximately 10% to 14% of total energy

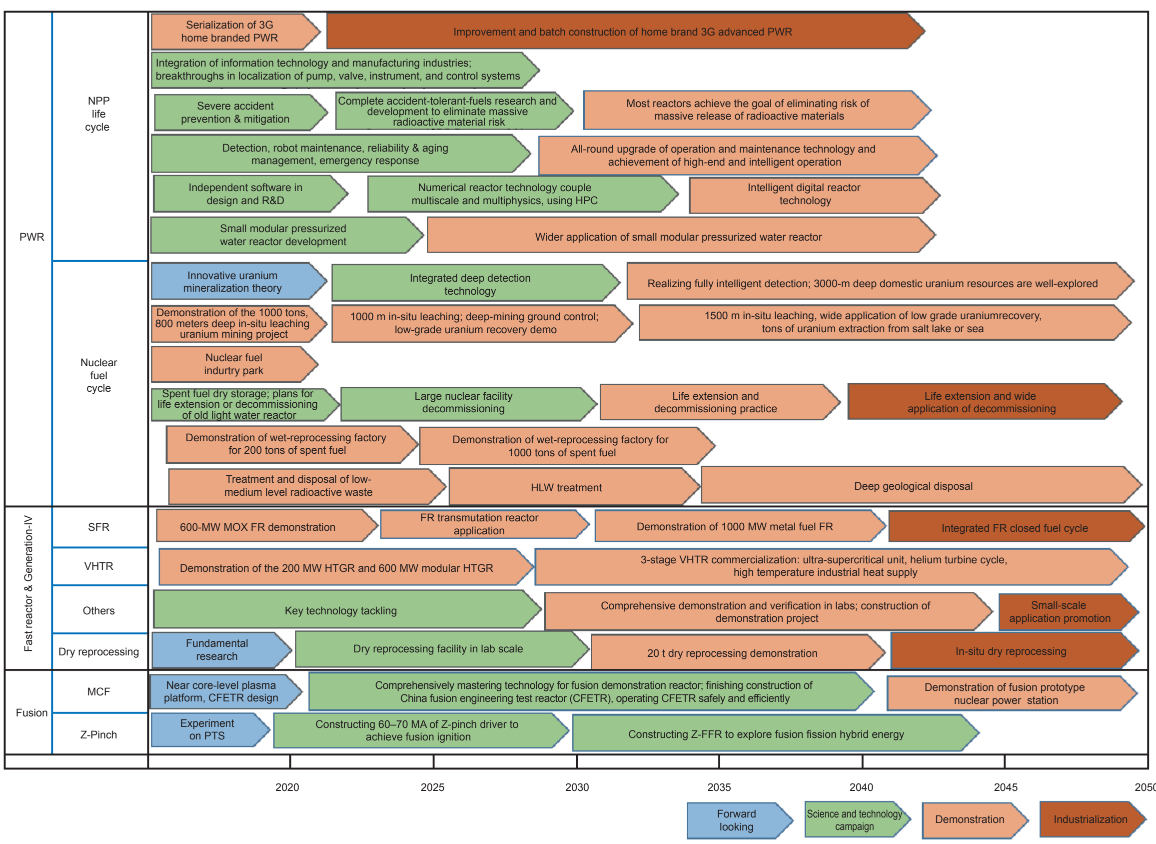

Fig. 1. Nuclear energy technology development roadmap.

provided at that time. It is also expected that FR and PWR will be developed together to form a symbiotic system from 2030 to 2050.

China's nuclear power development has had the advantage of being able to learn from international examples, and the safety level and operational performance of its operable units are now among the highest in the world. The brand local to China, Generation III PWR, represented by HPR1000 and CAP1400, can realize elimination of the release of large quantities of radioactive materials, and will be the workhorse of nuclear power development in the future. In the short-term, the supply of uranium resources will not form a fundamental constraint on the development of nuclear power in China.

Nuclear energy development still faces challenges relating to sustainability (uranium resource utilization and waste management), safety and reliability, economics, proliferation resistance, and physical protection. Generation IV reactors, particularly FRs, are being developed internationally; therefore, some of these problems are expected to be solved. The development direction of FR primarily depends on whether fuel breeding or TRU transmutation appears more favorable in the next few decades; there is currently large uncertainty in estimating the development scale of FR.

The development of fusion energy is very difficult and requires a long-term and sustained effort. It is hoped that a fusion demonstration reactor can be built by around 2050 and that fusion commercial reactors can subsequently be developed.

6.2 Suggestions for key technical development directions

6.2.1 Development of safe and efficient nuclear energy on a large-scale based on China's local brand Generation III PWR

The following developments are predicted to occur by approximately 2020: optimization of HPR and CAP local Chinese brand Generation III nuclear power technology, formation of serialization products, batch construction, promotion of technology upgrading, development of the nuclear power equipment industry, integration of nuclear fuel front-end production capacity through the nuclear fuel industry park project, promotion of seawater uranium extraction and uranium deep mining, realization of breakthrough key technologies for enabling construction of reprocessing demonstration project, and reprocessing commercial projects. Strengthening of R&D focused on spent fuel interim storage facilities and storage casks in-line with the pace of reprocessing, realization of disposal of low and intermediate level radioactive waste, life extension and development of decommissioning plans for PWRs, and active promotion of the geological disposal and transmutation of HLW to ensure public and ecological safety during the entire life cycle of nuclear energy are also expected.

By around 2030, it is expected that the R&D of ATF will be complete and that severe accident mechanisms and severe accident prevention and mitigation measures will be developed. Breakthroughs in nuclear safety technology are expected to be made and completely applied in both operable units and future-built units, with the aim of completely eliminating the release of large quantities of radioactive material. In addition, the extraction of uranium from seawater will occur on an industrial scale to support the large development of nuclear energy, a commercial-scale reprocessing capacity will be formed, the nuclear fuel cycle of PWR will be closed, and a geological disposal repository will be established.

6.2.2 Acceleration of R&D on Generation IV nuclear energy systems to solve nuclear fuel breeding and HLW transmutation

It is suggested that China should focus on SFR, which has the highest technological maturity at present. In this respect, China is encouraged to realize an SFR demonstration as soon as possible, improve SFR economics and promote industrialization, close the FR fuel cycle with pyro processing, and strive to achieve the harmonious development of PWR and FR by 2050. In addition, the development of dedicated FR or ADS systems for transmutation will be required when necessary, and fuel development of TWR should be closely tracked.

6.2.3 Development of SMRs and exploration of the wider application of nuclear energy

SMRs, such as modular PWRs, HTGRs, and LFRs, have improved inherent safety and provide unique advantages such as the cogeneration of heat and electricity and the ability to provide a heat supply (urban heat supply, industrial process heating, and seawater desalination). In addition, research into floating nuclear power and exploring ocean resources should be conducted.

6.2.4 Exploring fusion energy

It is suggested that China should deepen its involvement in the ITER international cooperation plan, comprehensively master fusion test reactor technology, actively promote R&D of key CFETR mainframe components, and begin timely overall construction of CFETR. It is also suggested that z-pinch should achieve ignition as soon as possible, and development of the inertial confinement fusion fission hybrid reactor driven by Z-pinch should be explored. In addition, tracking of the new fusion concept should be strengthened.

6.3 Problems and policy recommendations

The nuclear power industry chain consists of front-end (uranium exploration, milling and mining, metallurgy, conversion, uranium enrichment, fuel assembly manufacture), middle (reactor construction and operation, nuclear power equipment manufacturing), and back-end (spent fuel storage, transportation, reprocessing, radioactive waste treatment and disposal, and NPP decommissioning). Construction through decommissioning of a nuclear power plant takes approximately 100 years, but radioactive waste disposal takes longer and needs advanced planning. Historically, China's nuclear power development has focused more on the middle than the front- and back-end stages. However, with the rapid development of nuclear power, the insufficiencies of the front and back-ends of the business will cause an increasing amount of problems.

There are several cutting-edge technologies being developed in the nuclear energy field, such as seawater uranium extraction, FR, thorium-uranium recycling, fusion energy, and fusion-fission hybrid energy, that may have far-reaching effects on future energy structure. These technologies have the theoretical potential of providing a global energy supply for more than a thousand years, and each of them are at different levels of developmental maturity and have different technical directions. However, the focus of Chinese domestic research is currently too scattered and requires convergence to enable knowledge to be gathered and methods to be determined for tackling key common problems.

In response to the above problems, it is recommended that China further strengthens its top-level design, overall coordination, and system layout on nuclear energy development, establishes and improves nuclear energy science and technology innovation systems, enhances common fundamental research, particularly with respect to nuclear power equipment materials, radiation-resistant nuclear fuel, and structural materials, and establishes coordinated development of nuclear power industry chains that include both the front- and back-ends. It is also recommended that China relies on existing nuclear-related scientific research institutions and enterprises, integrates its domestic strengths, establishes a nuclear energy national laboratory, concentrates on promoting the healthy and rapid development of the nuclear energy industry, and promotes the transformation of energy to one that is green and low-carbon.

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