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China's Nuclear Power Strategic Emerging Industries 12th Five-Year Foster Outcomes and Long-Term Development Prospects

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Abstract: Nuclear power industry is an important component of the new energy industry, which is one of China's strategic emerging industries, and the development of nuclear power meets with the strategy of green low-carbon energy in China. According to the route that the scientific and technological breakthroughs lead to product upgrades and increase the production capacity and industrial development, this paper systematically analyzes the nuclear technology and its development outcomes during the l2th Five-Year Plan period, focusing on the development trend of China's nuclear power industry after the Fukushima accident, and the significant features of HPRl000—the advanced nuclear power technology; puts forward the development trends during the 13th Five-Year Plan period or even longer, including developing fuel closed-cycle system based on the fast reactor and the development of fusion technology to achieve "three-step" strategy and exploring the multipurpose utilization of nuclear energy through small module reactor technology to achieve the goal of large-scale and sustainable nuclear power industry development , and eventually to play a greater role in promoting China's economic stability, sustainable growth, energy and industrial structure optimization and upgrading.

Keywords: nuclear power technology industry; strategic emerging industries; HPR1000; fuel closed-cycle system; "three-step" strategy

1. Introduction

Nuclear science and technology is an extremely important achievement in science and technology field in the 20th Century. The peaceful usage of nuclear energy with nuclear power as the main symbol has played a significant role in securing power supply, promoting economic development, responding to climate changes, and benefiting individual lives.

The nuclear power technology industry is an important component of the new energy industry in China's strategic emerging industries. *The 12th Five-Year National Strategic Emerging Industry Development Plan* proposed to accelerate development of new energy with a mature technology and strong market competitiveness in China, such as nuclear power and other energy, and clarified the direction of industrial development and the main task [1]. The nuclear power technology industry covers the complete life cycle of nuclear power plants, which includes the construction, operation, and decommissioning, and involves an entire industry chain of nuclear power and related stakeholders. It focuses on establishing a sustainable development of nuclear fuel cycle system.

This study provides a comprehensive discussion on the main areas of development in the nuclear power technology industry during the 12th Five-Year Plan period, and summarizes the technological and industrial achievements in various fields through the cultivation of strategic emerging industries, including the safe & robust operation of nuclear power plants, self-reliant Generation III nuclear power technology, advanced nuclear power technology characterized by the Generation IV nuclear power technology, mining & milling, conversion & condensation, fabrication of nuclear fuel, and spent fuel reprocessing. This paper highlights the development of the industry over the 13th

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Five-Year Plan period and beyond to realize the scalable and sustainable development of nuclear power technology and to provide a reference for the development of the nuclear technology industry.

2. Nuclear power is a green and low-carbon energy with the characteristics of strategic emerging industries

Nuclear security is an important component of the national security system. The nuclear technology industry is a significant cornerstone of national defense construction. Nuclear power is an energy source with characteristics of cleanliness, low carbon, stability, and high energy density. It is a crucial non-fossil energy source that contributes to increase the supply of energy sources and is also an important mean to govern pollution (haze) and meet growing energy demands. Uranium resources are characterized by high energy density, small volume, and low proportion of fuel costs in power generation, so they constitute a strategic choice to solve the paradox of the reverse distribution of energy supply and demand in China, and they present a special strategic advantage in energy security. Additionally, as nuclear power has equal carbon emissions with that of wind power during its life cycle, so it plays an important role in the transformation of the low carbon industry in China and is a significant strategy to deal with the climate change. Conversely, nuclear power does not release harmful gases and other pollutants into the atmosphere during the production process, thus it is an important measure to build an ecological civilization. Nuclear power is a high-tech intensive industry, and it is an important pillar of the energy technology and a significant symbol of national scientific and technological strength. The development of nuclear power plays a very important role in improving the fabrication, material, and processing level of several industries such as material, metallurgy, chemical, machinery, electronics, and instrument technology industries, and it also helps to promote the transformation of Chinese industry from a labor-intensive industry to technology intensive industry.

It is estimated that the installed capacity of nuclear power in operation will reach 5.8×10^7 kW, and its production and operation output will be approximately 200 billion yuan in 2020. Furthermore, the installed capacity of nuclear power in construction is projected to reach 3×10^7 kW, and the total output will be approximately 400 billion yuan [2].

3. The development status of nuclear power technology industry in China

More than 60 years ago, the CPC Central Committee made a strategic decision to develop the atomic energy industry in China and established a complete nuclear research and nuclear industry system. After nearly 30 years of development, China's nuclear power industry is currently evolving. There are 26 operating nuclear power units with a total installed capacity of 24.42 GW that ranks fifth in the world. There are 24 nuclear power units in construction with a total installed capacity of 26.25 GW that accounts for 36% of the total installed capacity and ranks first in the world.

In 2015, the national cumulative generating capacity reached 5.618×10^{12} kW·h, and the accumulated generating capacity of nuclear power reached 1.689×10^{11} kW·h accounting for 3.01% of the cumulative national power generation. When compared with coal-fired power generation, the use of nuclear power reduced the burning of standard coal by 5.373×10^7 t, carbon dioxide emissions by 1.407×10^8 t, sulfur dioxide emissions by 4.568×10^5 t, and nitrogen oxide emissions by 3.977×10^5 t. Each nuclear power plant strictly controlled the operational risks and continued to maintain safe and stable operation records. There were no operational incidents of level 2 or above according to the international nuclear event classification (INES). In accordance with national environmental protection regulations and environmental radiation monitoring standards, the emissions of nuclear power plants and nuclear fuel cycle facilities are considerably lower than the national standard limits. The operation of nuclear facilities does not impact operational staff, the public, or the environment [3].

The continuous transformation and upgrading of nuclear industry facilitates a successful transformation from "import, digestion, and absorption" to "re-innovation". In the 12th Five-Year Plan period, China developed "HPR1000" with independent intellectual property rights and Generation III million-kilowatt scale nuclear power technology which had been exported, and fulfilled the "going global" strategy of nuclear power. Moreover, China also actively participated in international competitions. China's experimental fast reactor with fourth generation characteristics had achieved full power operation; the high temperature gas-cooled reactor was being constructed. All the fore-mentioned achievements indicate that China has entered the first tier of countries with advanced nuclear power. Additionally, aerospace nuclear power has achieved periodical results, and marine nuclear power has realized further innovation and upgrading. Furthermore, nuclear medicine, nuclear agriculture, and other fields of nuclear applications are also constantly enriched and extended.

4. The cultivation and development of nuclear power technology industry in the 12th Five-Year Plan period

4.1. China's nuclear industry has entered a stage of rational development following the Fukushima nuclear accident in Japan

A nuclear accident occurred in Fukushima in Japan on March 11, 2011. The root cause of the accident was the extreme external natural disasters including a super strong earthquake and the resulting tsunami. These disasters made the nuclear power plant (boiling water reactor type) lose all power sources, and made the reactor residual heat cannot be exported, which resulting in core melting, hydrogen explosion, and the release of a large amount of radioactive substances. Following the accident, the State Council decided to suspend the approval of nuclear power projects including the projects for which preliminary work was completed and to perform safety inspections with respect to nuclear power plants in service and in construction. The results indicated that the risks of nuclear facilities in China were controllable and that the security was guaranteed [4]. Nuclear power in China uses pressurized water reactor technology. Hence, given the reactor type, conditions including natural disasters and safety measures, it is impossible that nuclear accidents, such as Chernobyl and Fukushima, will happen in China.

The National Nuclear Security Agency also released *the General Technical Requirements for the Improvement of Nuclear Power Plants after the Fukushima Nuclear Accident* [5], and it also proposed improved requirements for flood control capacities of nuclear power plants, emergency water supplies and related equipment, mobile power supplies, and response abilities with respect to extreme external natural disasters. The proposed requirements were consistent with the safety requirements and action plan proposed by the international nuclear community to summarize the lessons learned from the Fukushima nuclear accident. It also reflected the design safety standards requirements provided by the latest version of International Atomic Energy Agency (IAEA). These measures were fully implemented in currently operational as well as under construction nuclear power plants in China.

The National Nuclear Security Agency released the *12th Five-Year Plan and the 2020 Vision of Nuclear Safety and Radioactive Pollution Prevention and Control* [6], which proposed that the design of new nuclear power plants constructed during the 13th Five-Year Plan period should practically eliminating the risks of large-scale radioactive material releases. The National Nuclear Safety Agency also attached considerable importance to the nuclear safety legislation that came into effect prior to the Fukushima nuclear accident. Additionally, the *Nuclear Safety Law* will be reviewed and adopted by the Standing Committee of the National People’s Congress in the future.

4.2. Independent innovation to achieve a comprehensive breakthrough in nuclear Industrial Science and technology

4.2.1. The introduction of advanced pressurized water reactor based nuclear power technology with independent intellectual property rights

The self-developed “HPR1000” and “CAP1400” of China represent a series of pressurized water reactor models that use the advanced third-generation nuclear power technology involving severe accident prevention and mitigation measures. These models have comprehensively implemented the principle of defense in depth and set up multi-channel solid security barriers to achieve the inclusion of radioactive materials. Specifically, the main technical features of “HPR1000” include “177 sets of fuel assembly core”, “multiple redundant security system”, and “the significant feature of active and passive safety design philosophy”, Additionally, it also adopts the world’s highest safety requirements and the latest technical standards which meet the standards of the International Atomic Energy Agency and the third-generation technical standards of United States and Europe. It completely utilizes approximately 30 years of China’s accumulated valuable experience, technology, and talent advantage in the design, construction, and operation of nuclear power plants. Furthermore, it ensures the optimal use of the advantages presented by advanced nuclear power technology including the passive pressurized water reactor (AP1000) and the European pressurized water reactor (EPR). It fully accounts for the experience gained (both domestic and overseas) after the Fukushima nuclear accident and fully implements the nuclear safety regulatory requirements. Additionally, it completely relies on the mature technology of the nuclear power equipment manufacturing industry in China and adopts proven mature technology to realize an integrated innovation. Specifically, large-scale test verifications were performed with respect to key independent innovation technologies such as passive systems, core, and main equipment. These test activities involved several years and included subsequent crucial tests related to passive system design and core and main equipment. These tests included a verification test of cavity injection and cooling system (CIS), a verification test of passive residual heat removal system of secondary side (PRS), a verification test of a passive containment heat removal system (PCS), a reactor hydraulics comprehensive test, a reactor side flow test, a reactor cavity cross mixing test, a seismic test of control rod drive line (CRDL), a flow induced vibration test, and a steam generator verification test.

4.2.1.1. Overall technical features

There were 177 sets of a 12-feet fuel assembly of the reactor. The use of an advanced fuel assembly increased the number of core fuel assemblies from 157 to 177. The reactor reduced average power density and simultaneously improved core rated power. It also enhanced the core thermal margin by more than 15%, and this not only increased the power generation capacity of nuclear power plants, but also improved the safety margin of nuclear power operation. The implementation of the specific project *Design and Manufacture Technology of Pressurized Water Reactor Fuel Element* of CNNC enabled three types of radiation test components to be installed into the reactor over a period of three years, which produced the “Chinese core” of “HPR1000”.

The redundant safety system comprehensively and thoroughly implemented the design principle of nuclear safety defense in depth and the reliability design principle. It innovatively used the "safety design concept of active and passive combination" in conjunction with a combination of active and passive safety measures. The active safety system was highly efficient and was verified by the project. The passive safety system could effectively deal with the loss of power. By complementing the active safety system, the passive safety system could ensure technical maturity and security. The design involved maintaining the integrity of the containment and a high likelihood of achieving the safety goal. Completed prevention and mitigation measures were adopted in response to a serious accident sequence that was defined by probability theory and the determination method. These measures were adopted to reduce core damage frequency (CDF) $<1.0\times10^{-6}$ per reactor year and to decrease the large release frequency (LRF) $<1.0\times10^{-7}$ per reactor year, and to realize the practical elimination of the risk of large-scale radioactive material release in the design.

Furthermore, the site safety margins were sufficient to prevent earthquake disasters. Specifically, the basic earthquake acceleration of "HPR1000" reached 0.3*g*, and seismic safety was fully guaranteed. A double containment design was adopted wherein the outer shell design used reinforced pre-stressed concrete such that the contained nuclear fuel and key equipment could effectively resist the impact of large commercial aircrafts and other possible external projectiles and explosions. The design also involved the superposition of the fortification measures in response to the small probability of external events. Thus, site selection and evaluation of the above-mentioned factors ensured a high safety margin and high security of the nuclear power plant design.

4.2.1.2. Measures to improve economic and advanced characters of nuclear power plants

The application of leak before break (LBB) technology, advanced digital instrument control system technology, and design optimization technology of the waste system enabled waste minimization, radiation protection design optimization, and fire protection design. "HPR1000" represented a continuous improvement and development based on existing nuclear power technology. The first reactor construction localization rate was not below 85%. Additionally, the localization rate of the equipment was not below 95% after the batch construction. The key equipment supply relied on the localization capacity formed by the existing nuclear power unit such that the domestic demonstration project cost of "HPR1000" could possess a competitive advantage compared with the Generation III of nuclear power units in current global construction.

4.2.2. The development of advanced nuclear power technology with the fourth generation features

4.2.2.1. The present situation and trends of fast reactor technology development

A fast reactor is a nuclear power plant which can produce electric converted by heat from fission chain reaction induced by a fast neutron.

The operation of fast reactors not only consumes fissile materials but also produces new fissile materials. Furthermore, the production exceeds consumption, and this achieves the proliferation of fissile material. The development of fast reactors breeds nuclear fuel, improves the utilization of uranium resources, as well as transmutes the long life and high radioactive waste to reduce the amount of the nuclear waste.

The China experimental fast reactor project (CEFR) independently completed preliminary design, construction design, and more than 50 verification tests. It was based on Sino-Russian technical design cooperation and design consultation. In July 2011, CEFR achieved 40% power grid-connected power generation. The experimental fast reactor was a sodium cooled fast reactor, which used liquid sodium as a coolant. Hence, the main loop design was maintained in normal pressure, where the safety was good, and the pool provided the fastest initial heat sink for a serious incident of the reactor core. The use of passive residual heat removal had a strong ability to deal with an accident. Additionally, the chemical property of sodium was active， and this could provide good radiation tolerance ability with respect to the accident. The intrinsic safety characteristics of the sodium cooled fast reactor were conducive in meeting fourth generation requirements such that the realization of the core damage frequency was less than 10^{-6} per reactor year and accidents did not necessitate external emergencies.

4.2.2.2. Development status and trend of a high temperature gas-cooled reactor

The early gas-cooled reactor and improved gas-cooled reactor had solid technical foundations and provided the basis for developing a high temperature gas-cooled reactor. A high temperature gas-cooled reactor possessed inherent safety characteristics that eliminated the possibilities of catastrophic nuclear accidents in terms of technical aspects. Simultaneously, there were major breakthroughs in scientific research and engineering validation work. China began to carry out the scientific research and engineering construction of commercial-scale modular high temperature gas-cooled reactor nuclear power plant demonstration project on the basis of the experimental reactor. In December, 2012, pouring the first tank of concrete after the State Council approval, demonstration projects of fuel elements, key systems and equipment of the scientific research and engineering verification work had made a series of major breakthrough results.

4.2.3. Development status and trend of China's spent fuel reprocessing industry

The reprocessing of spent fuel is a key link of the back end of a nuclear fuel cycle, and it provides charging for a fast reactor and greatly improves the utilization of uranium resources. Separated minor actinides and fission products are consumed by burning and transmutation in a fast reactor, and this is conducive in the treatment and disposal of nuclear wastes to achieve waste minimization and ensure green environmental protection and the sustainable development of nuclear energy.

In 2007, China decided to include the R&D technology projects of large-scale spent fuel reprocessing plants as part of the main national R&D projects to ensure the sustainable development of the reprocessing industry that was integral to the development of nuclear power. This involved carrying out extensive investigations on reprocessing technology, key equipment and materials, nuclear and radiation safety technology and design technology, and other aspects, constructing a series of research and development platforms to fully grasp core technology with independent intellectual property rights, as well as enhancing independent design abilities and the abilities to build advanced commercial spent fuel reprocessing plants. Currently, China has built up the state-level reprocessing test facilities of nuclear fuels and is actively promoting the construction of reprocessing engineering technology research center, a nuclear critical laboratory, and other relatively concentrated and completed engineering R&D facilities. China is also striving to improve the ability of independent innovation. Furthermore, China will actively implement advanced technology, key equipment, and design, safety, and other technological breakthroughs related to large-scale reprocessing plants.

4.3. Technological breakthroughs promoting product upgrades and production capacity

"HPR1000" constitutes a self-developed Generation III pressurized water reactor nuclear power technology. The demonstration project was successfully launched in units 5 and 6 in Fuqing. This marked the achievement of a nuclear power technology representing the transformation from introduction, digestion, and absorption to independent innovation. It realized small batch construction and represented a main model of large-scale development through the construction of units 3 and 4 in Fangchenggang and the foreign projects. Specifically, "HPR1000" successfully passed the Generic Reactor Safety Review (GRSR) of IAEA. This indicated that "HPR1000" was mature and reliable in terms of safety and design aspects, it met the safety requirements of the latest design of IAEA advanced nuclear power technology, and it involved mature and reliable creative design based on mature technology and detailed experimental verification. Thus, "HPR1000" obtained international certification to participate in international competitions.

The nuclear fuel industry achieved technological upgrading. Moreover, the integration of uranium purification and transformation projects was completed and operated, and the fuel enrichment achieved a transformation to the centrifugal process, thereby self-developed fuel elements were equipped with the industrialization conditions. The supply system of natural uranium was guaranteed. The nuclear fuel capacity of all sectors steadily increased, the uranium purification and transformation project has been built, and the enrichment and the capacity of the PWR fuel assembly possessed the necessary scale.

Natural uranium mining and milling theory achieve a breakthrough, changing from the hard rock mining in the south to the large base construction of in-situ leachable sandstone in the north. The uranium resources exploration capacity has been improved, and new uranium resource reserve have been identified. The large base construction of the north has begun to take shape, and the natural uranium safeguard system has been continuously improved on the basis of domestic uranium production capacity and active use and control of international market resources.

In order to meet the demand of the large-scale development of China's nuclear power, it is necessary to speed up the establishment of the spent fuel reprocessing production capacity at a corresponding scale. In 2010, China's first spent fuel reprocessing plant self-constructed successfully completed commissioning, indicating that China had mastered the spent fuel reprocessing technology of nuclear power plants.

5. Long-term development prospects of emerging nuclear energy strategic industries

According to China's *Long Term Development Plan of Nuclear Power (2011–2020)* [7], installed capacity in operation will reach 5.8×10^7 kW and installed capacity in construction will reach 3×10^7 kW by 2020. Simultaneously, a joint statement issued by China in response to climate change states that, by 2030, the proportion of non-fossil energy consumption in primary energy will be up to 20%, and that the installed capacity of nuclear power will be expected to reach 1.5×10^8 kW in 2030.

It is projected that in 2020, the spent fuel accumulation in China's nuclear power plants and the amount of spent fuels discharged annually from the nuclear power plants will increase along with the total installed capacity of the nuclear power plants. Currently, the storage capacity of spent fuel in China is close to saturation in varying degrees. Additionally, the rapid growth of nuclear power capacity is accompanied by a growing demand for the storage and processing of spent fuel.

5.1. China needs to develop an advanced nuclear fuel closed cycle based on the application of a fast reactor [8]

China decided to "insist on the closed cycle of nuclear fuel" policy and formulated the "three-step" strategy of the "pressurized water reactor, fast reactor, fusion reactor" to solve problems of restricting the optimization of uranium resources and the minimization of radioactive wastes in the development of nuclear power in China. China also adhered to the "safe and efficient development of nuclear power" policy. The second step strategy involved ensuring the sustainable development of nuclear power.

Hence, China considered the coordinated development of reprocessing of PWR, fast reactors, and spent fuel, and performed research and demonstration projects including the construction of fast reactors and reprocessing engineering to achieve the efficient use of nuclear fission resources.

At present, China has entered the second stage of designing and building its own demonstration fast reactor project based on the design, construction, and commissioning experience with respect to experimental fast reactors. This involves building a nuclear fuel cycle technology demonstration project. The industrial scale reprocessing capacity will be initially formed after the completion of the project.

In order to construct a sustainably developed reprocessing industry that can adapt to the development of nuclear power, China is actively striving to make technological breakthroughs in aspects including advanced technology, key equipment, and design and safety related to large-scale reprocessing plants. Furthermore, China is actively promoting international cooperation in the construction of large-scale commercial reprocessing plants. With respect to the development of nuclear power and the construction of reprocessing abilities, China will actively improve storage technology systems for spent fuel and perform dry storage technology research. This can form a certain scale of offsite storage capacity for spent fuel and ensure sustainable, stable, and safe operations of nuclear power plants. China will continue to carry out the research and design work of production line technology and tests for mixed oxide (MOX) fuel element of industrial scale fast reactor based on the research and development of a fuel element production and test line of uranium plutonium MOX, and will establish a MOX fuel production line that is adapted to the demonstration fast reactor to realize the closed cycle of nuclear fuel and to ultimately realize green, low-carbon, and sustainable development of nuclear energy.

5.2. Actively focusing on fusion research to achieve the "three-step" strategy

Given the abundance of fusion fuel reserves, fusion fuel energy is almost ten million times larger than that of fossil fuels. Additionally, the operation of fusion reactors is more safe and clean than that of fossil fuel sources, and fusion is considered as the ultimate human energy solution in terms of future (after 2050) energy needs.

There are two ways to realize the fusion reaction, namely magnetic confinement and inertial confinement. Currently, considerable progresses (including gains and losses) have been achieved worldwide in the field of magnetic confinement fusion. An International Thermonuclear Experimental Reactor (ITER), which is under construction, will achieve a power amplification factor that exceeds 10 and realize a steady operation. The ITER will demonstrate the feasibility of the fusion energy reactor physics and key engineering technology. It is expected that a demonstration reactor will be built in 20–40 years. Despite significant progresses in laser ignition engineering technology, research is yet to achieve a single ignition. Thus, physical theory and experimental studies are required to develop a fusion energy reactor. China's considerable momentum in the fore-mentioned areas indicates significant potential.

Fusion-fission hybrid reactors can be developed after successfully developing a fusion reactor. Specifically, Z-pinch shooting can provide fusion neutrons that can be developed into a fusion-fission hybrid reactor with multiple functions.

5.3. Realizing modular small reactor technology to explore the multipurpose utilization of nuclear energy

Currently, most nuclear power is used for power generation and only less than 1% of the power is applied in a non-electric field. Hence, the development and application of other potential markets will greatly affect the development of nuclear energy. Small quantities of nuclear heating, cooling, and sea water desalination are performed worldwide with individuals exploring the high temperature utilization of nuclear energy, the development of high temperature processes of nuclear power heating in the thermal recovery of heavy oil, coal liquefaction, metallurgy and other fields, the hydrogen produced by high temperature pyrolysis of water, and the applications of hydrogen energy and fuel cells. Thus, hydrogen has considerable development prospects as a secondary clean energy source and a means of transport energy.

Multipurpose reactors are mainly small reactors. In addition to the early research reactors and nuclear power plants, hundreds of small reactors that were used for the propulsion system of ships were also built. In recent years, given the saturation of the power generation capacity of industrialized countries, small reactors can better adapt to the power load demands of these countries. In terms of the applicability of the site, small reactors can be built in remote areas far away from the main power grid. Additionally, small reactors used for combined heat and power can be built inland or near cities. Small reactors can supply power for small and medium power grids, polar islands, and remote mountainous areas. Furthermore, they can also provide power and heating for cities, industrial parks, and petrochemical enterprises, and provide power for icebreakers and marine vessels. Hence, the advantages of small reactors include low overall costs, short construction cycles, and lower financial and management risks.

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