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Overall Development Strategy of Materials Used for China's New-Generation Nuclear Power Plants

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Abstract: Materials and their manufacturing technology are the premise and foundation to support and guarantee the safe and stable operation of nuclear engineering. Among the 56 nuclear power plants in service or under construction, 52 nuclear power plants have adopted pressurized water reactors. Demonstration power plants are being built for a high temperature gas cooled reactor and sodium cold fast reactor, and other reactor types such as molten salt reactors, accelerator-driven subcritical (ADS) systems, and supercritical water reactors are still in the research stage. This paper summarizes and analyzes the challenges and problems in the course of researching and manufacturing materials used in China's new-generation nuclear power plants, as well as their engineering application, and further proposes strategic suggestions for the development of these materials, including establishing a national steering committee to guide their development; establishing a national research fund to specially support their development; creating an advanced and complete standards system for their development; constructing a national shared engineering-level radiation experimental device; and under the principle of independence, continuing international cooperation in the related field.
Keywords: new-generation nuclear power plants; pressurized water reactors (PWR); materials used for nuclear power plants; development strategy

1 Introduction

Nuclear power can be obtained by two types of nuclear reactions: fission and fusion. Currently, the technology for sustaining controlled nuclear fission reaction has been well developed and applied in nuclear power plants to provide a clean energy supply to human beings. However, nuclear fusion technology is still at an early stage of development. Therefore, in this paper, we discuss technologies associated with nuclear fission reaction.

2 State-of-the-art nuclear power technology in China

Nuclear power technology, representative of the core competitiveness of the country, is an advanced technology of strategic importance. It is also a strategic industry developed with close military–civilian integration. Since the founding of the People's Republic of China, the nuclear power industry in China has witnessed tremendous progress, from its initial struggle of self-reliance and hardship to the recent innovation-driven development. Under these efforts, China has formulated its own development path of "import, digest, absorb, innovate, and transcend" in the nuclear power industry featuring the characteristics of the country itself. Currently, China has already established an independent and complete nuclear industry system. In particular, a variety of discoveries and findings have been made in nuclear power technology. Entering the 21st century, China "imported" the world's

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leading Generation III pressurized water reactors (PWR), the AP1000 and EPR reactors, and “digested and absorbed” the associated nuclear power technology. On this basis, China designed its own large-scale world-leading advanced PWRs through independent innovation and R&D. These PWRs are named “Hualong One” and CAP1400. In particular, the construction of the domestic demonstration project for the construction of “Hualong One” has already begun. “Hualong One” has also been successfully exported to Pakistan, and construction of the first batch of reactors is currently progressing smoothly. The necessary conditions for initiating the demonstration project for the construction of the CAP1400 reactor have already been satisfied. The construction of the demonstration projects for the high-temperature gas-cooled reactor (HTGR) and sodium-cooled fast reactor are currently being actively promoted. In addition, the construction site of another demonstration project, the ADS molten salt reactor supported by the Chinese Academy of Sciences Priority Research Program, has also been finalized. Lastly, foundational research and engineering design of the supercritical water reactor and traveling wave reactor are currently being strengthened [1,2].

PWR is currently the most mature commercial nuclear power technology in the world. During the 1980s, the Chinese government selected PWR as the primary nuclear power technology for future development. At present, 52 out of 56 nuclear reactors in operation or under construction are PWRs. For a certain period of time in the future, the Generation III large-scale advanced PWR will be the primary nuclear reactor built in China. In March 2016, the National Development and Reform Commission (NDRC) and National Energy Administration (NEA) jointly released the *Energy Innovation Action Plan (2016–2030)* (hereinafter referred to as *Action Plan*). In the *Action Plan*, innovation in advanced nuclear energy technology is placed in a prominent position. It is clearly stated in the “Action Plan” that the next step is to prioritize the development of PWR in China; to improve the safety and economic value of the Generation II PWR already built and in operation; to import and digest the nuclear power technology associated with the Generation III PWR; to develop China’s own Generation III PWR technology with independent intellectual property rights represented by “Hualong One” and CAP1400; and to allow China to reach world-leading standards in Generation III nuclear power technology and achieve continuous development. In summary, with steady and highly efficient development, the nuclear power industry in China has become a global industry and engineering center in the field of nuclear power. Based on these achievements, China will continue to strengthen efforts to facilitate the construction of a global nuclear power technology center and innovative highland, allowing China to become a global science and technology giant in nuclear power in the near future.

3 State-of-the-art material development and challenges of nuclear power in China

New-generation nuclear power technology focuses on technologies related to electricity generation from nuclear power. These include the large-scale advanced PWRs, modular small-scale reactors, HTGRs, fast reactors, molten salt reactors, ADS systems, supercritical water reactors, and traveling wave reactors.

3.1 State-of-the-art material development of new-generation nuclear power in China

In the past decade, nuclear enterprises have devoted considerable efforts to material development for nuclear power in China, with particular support from the National Major Science and Technology Project on large-scale advanced PWRs and HTGRs, as well as special projects on fast reactors. These efforts have led to significant progress in the material technology for building the main facilities in the nuclear island of PWRs, HTGRs, and fast reactors. At present, the material issues for constructing the main facilities in the nuclear island of engineering reactors (mostly PWRs) have already been resolved. This has allowed China to achieve independent development and large-scale industrialization of nuclear power reactors. The establishment of a material technology industry chain connecting the main facilities in the nuclear island of these engineering reactors marks a significant improvement in the core competitiveness of the high-end equipment manufacturing industry in China.

The material technology for building the main facilities of the reactors at the research stage, such as the molten salt reactor, is still undergoing preliminary industrial testing or is at the stage of laboratory research and development. While China has already realized mass-production of nuclear fuel for PWRs locally, the self-reliant development of nuclear fuel and corresponding materials required for constructing all of the nuclear reactors (including PWRs) still cannot be realized. Systematic research on the materials and technology required for post-processing the fuel is still lacking.

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3.2 Main issues in the development of materials for new-generation nuclear power in China

3.2.1 Common issues in the development of materials for new-generation nuclear power

The transformation of China from a nuclear giant in terms of size to one in terms of strength is characterized by the development of self-reliant engineering nuclear power technology that can be deployed on a large scale. The key to realizing the engineering applications of nuclear power lies in the development of material technology. Currently, the top-level design and overall planning of material development for new-generation nuclear power are still lacking in China. In other words, there is still no strategic planning of material development for new-generation nuclear power at the national level. Such a deficiency will severely affect the independent, efficient, and ordered material development for nuclear power in China. Strategic planning of material development for new-generation nuclear power can establish a consensus and achieve global coordination in the efforts aimed at nuclear material development. Therefore, it is of strategic significance to realize complete self-reliance in the nuclear power industry in China and to open China up to the world.

Research activities on different types of nuclear reactors have been concurrently initiated in China at the same time, leading to the diffusion of research forces and resources related to nuclear power. At the same time, the initiation of research studies on multiple Generation IV reactors, and the rush into constructing demonstration projects while reactor technology has not yet fully matured will lead to a waste of the very limited nuclear engineering resources in China, as well as pose as a potential nuclear safety risk. To conduct research on nuclear engineering reactor technologies, considerable manpower and financial investments are required. Therefore, the amount of effort dedicated to different reactor technologies should be coordinated in the top-level design of the national nuclear power development plan. This will considerably improve the utilization efficiency of manpower and financial resources in the development of nuclear engineering in China.

Currently, radiation experiment facilities at the engineering level are seriously lacking in China. Such a deficiency restricts rapid development in various aspects, including the material of the nuclear island, nuclear fuel and cladding material, and additive manufacturing material.

In addition, there is still no systematic study on the post-processing of nuclear fuel. The facilities used in the nuclear island for the “Hualong One” and AP1000 PWR are constructed in alignment with the RCC-M and ASME standards. These standards introduce additional complexity and workload to material research, device manufacturing, and nuclear safety supervision.

3.2.2 Primary issues in the construction materials of engineering-level reactors

China has already achieved self-reliant industrialization of the structural materials used for constructing the main facilities in the nuclear island of Generation III PWRs. However, further efforts are still required to ensure stable product quality. The main body materials used in large-scale advanced PWRs are mainly the structural materials of the key facilities on the nuclear island and conventional island. These facilities include the reactor pressure vessel, steam generator, voltage regulator, core components, control rod driving mechanism, main pipeline, main pump, valves, turbine generator, and other equipment. The materials used in such equipment cover a wide range of categories and are characterized by their wide variety, small quantity, and extremely high performance requirements. These materials include carbon steel, low alloy steel, stainless steel, zirconium alloy, titanium aluminum alloy, nickel base alloy, and polymer insulating materials. Based on the material group, they can be divided into castings and forgings, plates, tubes, steel round bars, and welding consumables. The main body materials used in large-scale advanced PWR fall in three categories. The first category is materials for the extra-large one-piece alloy steel forging in complex shapes. Examples of materials include the SA508-3cl.1 extra-large forging for pressure vessels in reactors, SA508-3cl.2 extra-large forging for steam generators, and 3.5NiCrMoV extra-large forging for turbine rotors in the conventional island. These materials generally require suitable strength, excellent toughness at low temperatures, and good uniformity over the cross-section.

The main manufacturing processes include the following: (1) heat treatment technology for refining and stabilizing the structure as well as improving the toughness at low temperature; (2) steel ingot smelting control technology with high purity and high uniformity; and (3) forging technology of extra-large one-piece parts with complex shapes. The second category is materials for the large one-piece stainless steel forging in irregular shapes. Examples of materials include large 316LN austenitic stainless steel forging for the main pipeline, and large F6NM martensitic stainless steel ring forging for the compression spring. These materials require sufficient strength, excellent ductility, and high fracture toughness. In particular, these materials should exhibit a strong resistance to stress corrosion and fracture, high resistance to uniform corrosion, and good weldability. The manufacturing process of nuclear grade stainless steel large forging primarily involves accurate composition control and high-purity smelting control technology, anti-cracking control technology during forging, inner hole machining and bending control technology, and grain uniformity and uniform deformation control technology. The third category is materials for the precise nickel-based corrosion-resistant alloy for pipe fittings, such as the alloy 690 U-shaped heat transfer tube in the evaporator. These materials require good resistance to stress corrosion and fracture, good resistance to uniform corrosion, good machinability (bent tube, expansion tube, etc.), superior piping performance, and good weldability. The alloy 690 U-shaped tube is a masterpiece of pipe manufacturing. The manufacturing process involves highly uniform and ultra-pure smelting, hot extrusion molding quality control technology, cold processing technology and online degreasing control technology for ultra-long pipes with a thin wall and a small diameter, and Thermal Technology (TT) heat processing control technology. The main body materials used in large-scale advanced PWRs are subjected to harsh conditions such as high temperatures, high pressures, fluid erosion and corrosion, and even strong neutron irradiation during their service period. The materials for some equipment cannot be replaced during the entire 60-year life cycle of the PWRs. Therefore, extremely stringent requirements are imposed on the performance of the equipment materials. In addition to a superior toughness match, weldability, and cold processing properties, excellent resistance to radiation brittleness, excellent corrosion resistance and aging resistance, and excellent cross-section homogeneity are also demanded of some materials.

The structural materials used in the nuclear island of HTGRs can now be produced in China. Research on heat-resistant materials for future ultra-high temperature gas-cooled reactors has not been initiated yet. The application performance of heat transfer tubes used in evaporators and graphene-based materials still requires further research. The primary bottleneck for technological advancement in ultra-high temperature gas-cooled reactors are high-temperature metal structural materials. Currently, the helium exit temperature from the core of HTGR is around 750 ℃. In the future, this temperature will rise to 900 ℃ and to 1000 ℃ for ultra-high temperature gas-cooled reactors. Therefore, the corresponding components such as steam generators, metal components in the core, and helium–helium intermediate heat exchangers must satisfy the associated requirements for mechanical properties and physical properties at elevated temperatures. Nickel-based heat and corrosion-resistant alloys are preferred high-temperature metal structural materials used in HTGRs. However, systematic research on sustainably producing such materials locally has not yet been conducted. Nuclear graphite has also been investigated in China during the early stages of research on production reactors and HTR-10. However, the size, radiation performance, and radiation lifetime of these nuclear graphene samples failed to meet the requirements of current HTGR applications. At present, the nuclear graphite products used in the HTGR demonstration project HTR-PM are produced by Toyo Tanso Co., Ltd. in Japan. In recent years, progress has been made in the research of nuclear graphite. Several domestic enterprises, including Sinosteel Group New Materials (Zhejiang) Co., Ltd. and Fangda Group Co., Ltd., are now promoting the production of nuclear graphite locally in China.

For a long time, the sources of nuclear fuels and materials used in PWRs and fast reactors in China were imported from foreign countries. In recent years, significant progress has been made in the production of nuclear fuels for PWRs in China, and such self-sufficiency has been achieved for most of the nuclear fuels. Nevertheless, complete self-reliance has not yet been realized. While the nuclear fuel for HTGR can also be produced in China independently, the expansion of production capacity and improvement of fuel performance still require further investigation. These materials generally have a long development cycle and require repeated engineering validation under irradiation.

3.2.3 Primary issues in the construction materials of research-level reactors

The structural materials used in the nuclear island for molten salt reactors and ADS subcritical reactors have already been preliminarily finalized. Preliminary manufacturing of these materials at the engineering level has also started. However, systematic research is still required to understand the compatibility of these materials under an engineering environment. All of the components used in the molten salt reactor, such as the pressure vessel, loop pipe, and heat exchange pipes, must operate stably and effectively over a long time in an extreme environment with multiple adverse factors, including high temperatures, molten salt corrosion, and neutron irradiation. However, it is very difficult to find a single mature engineering material that satisfies all of the above conditions. Therefore, developing a suitable structural material is a prominent technical challenge in the development of molten salt reactors. Between the 1940s and the 1960s, Oak Ridge National Lab in the United States developed a nickel-based alloy for the Aircraft Nuclear Propulsion (ANP) program and the Molten Salt Reactor Experiment (MSRE). This alloy, known as the Hastelloy N alloy, is the only structural alloy in the world that has served in a

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molten salt reactor. The material selection for the nuclear island in supercritical water reactor and travelling wave reactor is still at a stage of laboratory testing. The engineering-level manufacturing of these materials have not yet started.

The solid and liquid fuels used in molten salt reactors are still under laboratory investigation. The fuels and cladding materials used in lead-cooled fast reactors, sodium-cooled faster reactors, supercritical water reactors, and traveling wave reactors are yet to be determined.

3.2.4 Policy issues in the material development for nuclear power

A high level of safety and reliability is demanded of nuclear power materials (structural materials of the nuclear island, nuclear fuel materials, and post-processing materials). Therefore, these materials must undergo special assessment and long development cycles, which requires substantial financial investment as well as repeated engineering validation. Under the current research proposal system (five-year plan), it is difficult to initiate and accomplish a full chain of nuclear power material research plans continuously and completely. Therefore, the localization processes of nuclear material technology have often been left unfinished mid-way. The integration of nuclear material technology with other advanced technologies such as additive manufacturing has also been restricted for the same reason.

4 Strategic support and safeguard recommendations to promote material development for new generation nuclear power

Conducting multiple studies on different types of reactors simultaneously in China depletes nuclear materials, compromises R&D, and wastes relevant resources. The long-term planning and strategic layout of nuclear power technology development should be further strengthened in China. Until 2030, large-scale advanced PWR Generation III nuclear power technology should be prioritized in the development of nuclear technology. Overall planning with specific points of focus should be carried out for the research and development of Generation IV and future nuclear power technology. The scientific assessment of the development of nuclear power technologies should be strengthened. Specifically, comprehensive argumentation and validation are required to determine which technologies are at the basic research stage, which technologies are at the applied research stage, and how to coordinate and promote the progress of research on different technologies. In light of these ideas, the following strategic support and safeguard recommendations are proposed to promote the development of materials for new-generation nuclear power [3].

4.1 Establish a professional guidance committee for the material development for new-generation nuclear power in China

The establishment of a professional guidance committee for the material development for new-generation nuclear power in China is recommended. This committee, independent of power enterprises, should consist of responsible scientists and relevant leaders of pertinent departments. The main task of the committee is to formulate a national material development strategic plan for new-generation nuclear power based on the medium- and long-term development plan for nuclear power in China. This will build consensus in the nuclear power industry and prioritize material development at the national planning level. Specifically, the committee should formulate short-, medium-, and long-term development goals, and specific tasks from four aspects including science, technology, engineering, and industry for the material development for new-generation nuclear power. In addition, the goals and specific tasks over the medium- and long-term described above should be dynamically adjusted every five years. This arrangement will ensure sustained, ordered, and effective material development for new-generation nuclear power in China.

4.2 Establish a special national fund or special science and technology project plan for nuclear power materials with stable and prolonged support

The implementation of major national science and technology projects on large-scale advanced PWRs and HTGRs has considerably promoted the advancement of nuclear power material technology and enhanced the core competitiveness of equipment manufacturing in China. It is recommended to establish a special national fund or special science and technology project plan for nuclear power materials with stable and prolonged support. This fund or project plan can be operated by the relevant departments of national authorities independent of power enterprises. The required funds can be sourced from national budgets, corporate financing, and social financing. With the support from this fund or project plan, the professional guidance committee on the material development for new-generation nuclear power suggested above will be able to determine the short-, medium-, and long-term development goals, and the sustained, ordered, and effective accomplishment of specific tasks. Ultimately, this will guarantee supported, continuous, forward-looking, strategic, and innovative material development for new-generation nuclear power. This is also key to realizing the strategic planning of nuclear power technology development in China. Under the unique international environment in which China is rising as a major power, providing stable and prolonged support in the form of funding or special research projects will become increasingly important for establishing a new-generation nuclear power material system with independent intellectual property rights and self-sufficiency. These plans carry strategic significance for the sustainable development of nuclear engineering in China.

4.3 Create an advanced and complete standard system for new-generation nuclear power materials in China

The first batch of Generation III million-kilowatts PWR projects were all built in China. During the engineering process, most of the technical issues related to the main facilities in the nuclear island were resolved by China independently or cooperatively with other participating countries. Much valuable experience and lessons were acquired from these PWR projects. Currently, China already possesses the necessary conditions to establish a full advanced standard system for new-generation nuclear power materials based on the ASEM standard, RCC-M standard, and the current energy industry standards in China. Under the premise of ensured nuclear safety, an appropriate extent of advanced material standard specifications, which consider the level of advancement and economic value of nuclear power materials, will promote the advancement of nuclear power material technology and product technology in China, thereby strengthening the core competitiveness of the high-end equipment manufacturing industry in China. The formulation of a unified national standard system (including material testing, characterization, and assessment standards) for new-generation nuclear power materials that considers both advancement and maturity will lay a solid foundation for exporting China’s nuclear power technology to other countries and lead to global nuclear power technology development.

4.4 Construct a shared national engineering-level irradiation experimental facility

Engineering-level irradiation testing is a bottleneck that restricts the development and engineering applications of nuclear power materials in China. A shared national engineering-level irradiation experimental facility (center) for nuclear materials should be constructed in China as soon as possible. Through optimized and improved efficiency, the experimental facility will accelerate the engineering applications of nuclear power materials and promote material innovations. In the long run, the 300,000 kW Qinshan Phase I reactor, which is about to reach its designed lifespan, can be converted into an engineering-level experimental research reactor.

4.5 Continue international cooperation in material development for new-generation nuclear power under the principle of independence

Under the new international environment and circumstances, the spirit of independence and self-reliance must be maintained and carried forward for nuclear engineering development in China. At the same time, international cooperation in the fields of nuclear fuel materials and post-processing of used fuel should continue to be carried out actively under the major international cooperation nuclear power projects planned by the Chinese government.

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