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Overall Development Strategy of China's New-Generation Nuclear Fuel

Li Guanxing[1], Zhou Bangxin[2], Xiao Min[3] , Jiao Yongjun[4], Ren Zhongming[2]

1. Chinese Nuclear Society, Beijing 100045, China
2. Shanghai University, Shanghai 201800, China
3. China Nuclear Power Technology Research Institute, Shenzhen 518031, Guangdong, China
4. Nuclear Power Institute of China, Chengdu 610000, China

Abstract: This study analyzes the global status of and development trends of pressurized water reactor (PWR) fuel and material technology, fast reactor and other advanced reactor fuel technology, and material technology related to nuclear fuel cycles. In addition, it proposes corresponding targets, roadmaps, and key tasks. PWR has been the dominant reactor type for nuclear power generation and energy structure transformation in China for a relatively long time. As an important foundation for the development of PWRs, nuclear fuels and materials have basically achieved localization, but still lack self-reliance in brand. China's fast reactor and fast reactor nuclear fuel development as well as its nuclear fuel cycle industry face significant development opportunities and challenges. This paper proposes suggestions for the development of nuclear fuels and materials for PWRs, fast reactors, and nuclear fuel cycles in China.

Keywords: nuclear fuel; nuclear materials; light water reactor; pressurized water reactor; fast reactor; nuclear fuel cycle

1 Introduction

The sustainable development of nuclear fission energy relies on three important factors: maximizing the use of uranium resources, ensuring safety in nuclear power generation, and the safe disposal of nuclear waste. An effective approach to resolve these challenges is to develop fast reactor technology. In addition to upgrading pressurized water reactor (PWR) technology and promoting its application, the development of fast reactor nuclear power technology should also be promoted in China. By realizing coordinated PWR–fast reactor development and establishing a closed nuclear fuel cycle system, uranium resources can be fully exploited while also minimizing the generation of high-level radioactive waste. Such an approach can effectively eliminate the environmental hazard of nuclear waste and ensure the sustainable development of nuclear power.

In March 2016, the National Development and Reform Commission (NDRC) and National Energy Administration (NEA) jointly released the *Energy Innovation Action Plan (2016–2030)* [1]. In this action plan, innovation in advanced nuclear energy technology was given priority. The nuclear fuel system, being the core component of a nuclear reactor, plays a critical role in improving the economic value of the nuclear power plant and ensuring its safety. The nuclear fuel system is composed of the fuel assembly, fuel-related components, and structural materials.

The utility requirement document (URD) announced in the United States (US), as well as the European utility requirement (EUR) announced in Europe, have put forward greater demands on the economic value, reliability, and safety of the improved Generation II and Generation III nuclear power plants [2,3]. These requirements have driven the

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Corresponding author: Xiao Min, Senior Researcher from China Nuclear Power Technology Research Institute. Major research fields include nuclear reactor safety, reactor core design, nuclear materials and fuel recycle. E-mail: xiaomin@cgnpc.com.cn

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improvement and continuous development of fuel assembly towards higher fuel burnup, longer refueling cycles, increased safety margins, and better reliability. The development of the fuel assembly design technology and material technology are closely correlated to and influence one another. An advanced design can maximize advantages and minimize disadvantages and is conducive to fully exploiting the characteristics of the material. Good material properties can expand design concepts and is conducive to the successful realization of design targets. Developing advanced nuclear fuels and their corresponding materials is critical for ensuring the safe and effective development of nuclear power.

“Research on the Development Strategy of Nuclear Fuel Technology” is a major special topic under the major consultation project “Research on the Development Strategy for New-Generation Nuclear Power Materials” managed by the Chinese Academy of Engineering [4]. “Research on the Development Strategy of Nuclear Fuel Technology” covers three aspects, including the fuel for PWRs, the fuel for fast reactors, and the fuel cycle material. The project incorporates the following three special topics: (1) research on the development strategy of fuel technology for PWRs, (2) research on the development strategy of fuel technology for fast reactors and other advanced nuclear power systems, and (3) research on the development strategy of nuclear fuel cycle materials. This report covers the reports for the three special topics described above and is a comprehensive report for “Research on the Development Strategy of Nuclear Fuel Technology.”

2 Global trend of nuclear fuel development for PWRs

2.1 Continuous design improvement of UO2–Zr fuel for PWRs

Nuclear power giants, represented by the US, France, and Russia, have developed their own commercial fuel assembly brands such as ROBUST, AFA3G AA, and TVS-2M for their commercial PWRs. Their design targets have been to improve the fuel burnup to around 60 GWd/tU and the refueling cycle length to at least 18 months. Fuel reliability requirement is also increasing continuously. Since the Fukushima Daiichi nuclear disaster, improving the capability of nuclear fuel components against severe accidents has become a new development direction.

Currently, the advanced fuel assembly technology used in nuclear power plants in China mainly includes the AFA series fuel imported from France and the AP1000 fuel imported from US. Although the fuel assembly can be fabricated in China locally, the main materials used in the fuel assemblies, in particular the zirconium alloy, still need to be imported from other countries. The self-owned advanced fuel assembly brand in China is still under research and development, and there is still a significant distance to go before large-scale commercial application can be realized. Realizing the commercial application of the self-owned advanced fuel assembly brand is an important indication of China’s status as a nuclear power giant.

While many countries have started to research the ATF fuel since the Fukushima Daiichi nuclear disaster, efforts to improve and develop fuels based on the existing UO2–Zr fuel system have not reduced. For example, Westinghouse Electric Corporation has developed the AP1000 fuel assembly for Generation III nuclear power and the next-generation fuel assembly. Areva in France has developed the next-generation GAIA fuel assembly recently. Russia has developed the 17 × 17 TVS-K square-shaped assembly.

While the design of nuclear fuel assembly in China was initiated significantly later than that in the US, France, and Russia, rapid progress in China has been achieved recently. Currently, the fuel assembly models under research and development in China include the following: the CF series fuel assembly, STEP series fuel assembly, and CAP1400 fuel assembly. Among them, the CF series fuel assembly has undergone relatively fast development. The CF2 fuel assembly will be used in the first K2/K3 reactor. The cladding material used in the CF3 fuel assembly is an independently developed zirconium alloy named N36, with a maximum fuel burnup of 52 GWd/tU. This fuel assembly will be used for refueling in the K2/K3 reactor after its development is completed. The China National Nuclear Corporation initiated design research of the CF4 fuel assembly in 2016 with a target fuel burnup of 60 GWd/tU, and N45 alloy will be used as the cladding material of the fuel.

The development of PWRs requires cladding material with excellent properties, including strong resistance to corrosion, hydrogen absorption, irradiation, and creeping. As shown by most research studies on the improvement of zirconium alloy worldwide, adjusting the composition of the alloy, improving the processing technique, and developing new alloy are still the major directions in the development of zirconium alloy. In terms of alloy composition, the Zr-Sn-Nb alloy are the mainstream of development, comprising low content of Sn and suitable amounts of Nb and Fe as the

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main alloy elements. In addition, proper components can be added to the alloy based on Zr-1Nb. In terms of processing technique, the primary issue of the compositional uniformity of the zirconium alloy is caused by (1) increasing the number of metal elements but reducing the content of each element and (2) preparing large ingots. In addition, large deformations and a low temperature processing method are also prominent issues in the processing technique. In terms of the microstructure, the second phase should be controlled at a scale of tens of nanometers and distributed uniformly.

2.2 Development of cutting-edge nuclear fuel and material technology

2.2.1 New ATF fuel for PWRs

The concept of ATF fuel was first proposed by US after the Fukushima Daiichi nuclear disaster [5]. Since then, many countries including the US, European countries, China, Japan, and South Korea have conducted ATF fuel research. The ATF fuel pellets include high uranium density fuel (U_3Si_2, UN, and UC), metallic fuel, and fully ceramic microencapsulated (FCM) fuel. The materials used for ATF cladding include SiC/SiCf composite materials, FeCrAl (including oxide dispersion strengthened FeCrAl), molybdenum alloy, and coated zirconium alloy.

In April 2017, Westinghouse Electric Corporation made the first official announcement of its ATF fuel brand EnCore^{TM} to the world. This fuel will use U_3Si_2/UN fuel pellet and SiC composite cladding [6,7].

France has also finalized its technical route for developing ATF fuel. The short-term targets include the zirconium alloy coating and the UO_2 pellet improvement. The long-term targets include the development of the metallic fuel of Lightbridge (LTBR) [8] and SiCf composite cladding.

2.2.2 Metallic fuel for PWRs

Metallic fuel has excellent thermal conductivity and is one of the promising nuclear fuel candidates for PWRs in future [9].

U-Mo fuel exhibits excellent thermal conductivity, high uranium density, and better safety. Since the middle of the 1990s, the US, France, and Russia have conducted research on U-Mo alloy fuel consecutively [10,11]. In recent years, the LTBR Corporation has conducted in-depth research and development on the integrated U-Zr alloy metallic fuel. Compared with traditional UO_2 fuel, this new design can reduce the central temperature of the fuel rod by almost 900 °C, which greatly improves the safety margin of the fuel. This is the reason why metallic fuel can greatly increase the power of the reactor core. Such an innovation also laid the foundation for improving the power of nuclear power plants [9].

Framatome in France and LTBR Corporation in US have formed a joint venture to promote the commercialization of metallic fuel for PWRs. If PWR would take the lead in using metal fuel, then substantial changes would occur in the fuel technology for PWRs. The PWR metallic fuel developed by LTBR Corporation could be used earlier than ATF.

In addition to ATF fuel and metallic fuel, high entropy alloys, material genetic engineering, and multi-scale analysis and testing technology of nuclear fuel are also cutting-edge fields and development trends for nuclear fuel and materials globally [12].

2.3 Goal and road map of nuclear fuel and material development for PWRs in China

It is necessary to conduct continued research on the improvement of UO_2 fuel and the development of new zirconium alloy cladding to realize domestic production and commercial applications of advanced fuel assembly with self-owned brands.

It is important to conduct active research on ATF fuel and to finalize the corresponding technical routes gradually. In addition, ATF fuel should be capable of being used in engineering applications. It is expected that the advanced fuel assembly and materials with self-owned brands can be used in reactors at a small scale in 5 years and at a large scale in 10 years, respectively. It is expected that breakthroughs in the key technologies can be achieved for advanced fuels such as ATF fuel in around 5 years. In around 10 years' time, advanced fuels such as ATF should be capable of being used in reactors.

3 Global trend of fuel technology development for fast reactors and other types of advanced reactors

There are two major types of fuel used in fast reactors globally: ceramic fuel and metallic fuel. Oxide ceramic fuel technology, in particular mixed oxide fuel (MOX), is the most mature technology and the mainstream fuel currently used in fast reactors.

At present, metal fuel, nitride fuel, and carbide fuel are under development for fast reactors globally. These types of fuels have a higher breeding ratio than the oxide fuel [13].

Metallic fuels have high thermal conductivities, low fuel temperatures, and high safety margins. The irradiation swelling issue of metallic fuel can be inhibited by improving the material technology. Metallic fuel is generally acknowledged as one of the main fuel types for fast reactors in future [14–16].

The fabrication process of metallic fuel is even more simplified. After pyroprocessing (with the separated metals being U and Pu), metallic materials can be better used to produce new fuel directly and form an integrated fuel cycle system.

The study on metallic fuel is focused on U-Zr alloy and U-Pu-Zr alloy. Metallic fuel is generally composed of the binary alloy U-10Zr or the ternary alloy U-Pu-10Zr. Oxide fuel and metal fuel become transmutation fuels after adding minor actinides to them.

Mixed plutonium–uranium nitride fuel and carbide fuel are new types of nuclear fuel under development. The plutonium–uranium densities in UPuN and UPuC are higher than that in oxide fuel (the content of U in UN is 35% higher than that in UO_2). In addition, UPuN and UPuC exhibit high breeding ratios, short breeding times, high thermal conductivities (10 times higher than UO_2), and excellent compatibilities with sodium coolant and stainless steel cladding [17,18].

Many countries have carried out the development and application of carbide and carbide fuel. The US, France, Russia, and India have all conducted research and development on several types of carbide and carbide fuels [19,20]. Nitride uranium-plutonium (MNUP) was selected as a candidate fuel for fast reactors in Russia (besides MOX) in the future [19,20]. The experimental fast reactor FBTR in India uses (U, Pu) C carbide as its fuel [21].

Owing to various reasons, the research and development progress on fast reactors and corresponding nuclear fuels has been forced to slow down in European countries, the US, and Japan [22,23]. The research plans for fast reactor and fuel cycle in Russia, despite being delayed, remain unique in the world. Both the BN-600 and BN-800 fast reactors in Russia are designed to use MOX fuel. Currently, the use of MOX fuel in fast reactors in Russia remains limited, and the number of fast reactors using MOX fuel is expected to increase gradually in the future.

To promote the development of next-generation nuclear power technology and the realization of closed fuel cycle, Russia has recently announced a “Breakthrough” project. The primary objective of this project is to develop sodium-cooled fast reactors, lead-cooled fast reactors, MOX fuel, MNUP fuel, and integrated fuel cycling systems. MNUP fuel is a part of the closed fuel cycle “Breakthrough” project in Russia. MNUP fuel (type ETVS) has already undergone partial irradiation tests. MNUP fuel will be used in BREST-OD-300 (lead-cooled fast reactor) and BN-1200 (sodium-cooled fast reactor).

In the past, the main research task in Russia was developing MOX for fast reactors. Recently, the development strategy in Russia has shifted towards research on two items simultaneously. A uranium–plutonium REMIX fuel (regenerated uranium–plutonium mixture with enriched uranium added) similar to MOX fuel will be used in VVER1000. Different from MOX in France, which is used for one recycle in the reactor, the REMIX fuel can undergo multiple recycles in the reactor (through multiple reprocessing), which represents an innovation in MOX fuel [24]. Russia has also recently proposed the idea of dual-component nuclear power system that consists of one fast reactor and two light-water reactors. Such a combination can allow the reactors to draw on each of their strengths to improve efficiency [25].

The CDFR600 fast reactor in China will also uses MOX fuel. The molten salt reactor in China will first use solid fuel, and an improved TRISO fluidized-bed fuel will be developed for the molten salt reactor in later stages.

Currently, improved austenitic stainless steel, ferrite–martensitic stainless steel, and nickel-based alloy are generally selected as the cladding material of the fuels in fast reactors. Some countries are now developing more advanced ODS stainless steel.

For molten salt reactors, the development of novel alloys with a strong resistance to high temperatures/molten salt corrosion, bimetallic composite materials, ceramic-based composite materials such as C/C and SiC/SiC, and ultrafine-grain nuclear graphite with high density are the current hot research topics.

4 Goal of nuclear fuel development for fast reactors in China

MOX fuel: The goal is to develop the production capacity of MOX fuel assembly and complete the production and loading of MOX fuel assembly in the first demonstration fast reactor by 2025. The maximum fuel burnup of the MOX

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fuel assembly in the demonstrative fast reactor is expected to reach 100 GWd/tHM.

Metallic fuel: The goal is to master the processing technique of U-Zr alloy. The irradiation test of U-Zr alloy metallic fuel assembly is expected to be finished before 2030, and fuel burnup is expected to reach 150 GWd/tHM.

The fuel for fast reactors and other advanced reactors: The goal is to start the research and development of multiple advanced fuels including nitride, carbide, U-Pu-Zr, and U-Pu-Am-Zr alloy. Breakthroughs should be made in the processing technique and the key technologies.

Novel cladding and structural materials: Breakthroughs should be made in the key manufacturing technologies of the structural materials for fast reactors to enable their application in demonstrative fast reactors. The manufacturing technique of advanced ferritic steel should be mastered to provide qualified materials for the travelling wave reactor. Research and development tasks should also be performed on ODS steel with the goal of making breakthroughs in key technologies to provide structural materials of fuel assembly with improved performance for advanced reactors.

Fuel for molten salt reactor: The goal is to develop a medium-scale production capacity of the fuel by 2022, to realize large-scale (ten tonnes) production by 2025, and to realize industrial level (hundred tonnes) application by 2030.

5 Global trend of the development of nuclear fuel cycling material

China has an almost complete nuclear fuel cycle industry. However, the industry level in China continue to fall behind those of developed countries (such as France) in terms of facilities, processing techniques, and materials. From the material perspective, the key steps in the nuclear fuel cycle include the enrichment of uranium, the reprocessing of spent fuel, and the disposal of the radioactive waste.

The advanced materials in the field of uranium enrichment include metal-based composite materials and carbon fiber composite materials such as ultra-high strength aluminum alloy material and fiber reinforced magnesium alloy. The key facility materials for hydro-reprocessing include dissolver material, shearing machine material, and shielding material.

The materials related in pyroprocessing include structural materials resistive to high temperature and molten salt corrosion (such as Ti35), alloy materials resistive to high temperature and chlorine corrosion, high temperature resistant crucible materials, and electrode materials resistive to high temperature and corrosion. They key research directions include the development of Inconel625 nickel-based high temperature alloy steel, a tantalum carbide crucible, a yttria-stabilized zirconia (YSZ) coated metal or graphite crucible, and a TiB2 coated graphite electrode.

The reprocessing material for thorium-based molten salt reactors under research include (1) the alloy material GH3535 for building the reactor of volatile fluorides and (2) nuclear graphite material with high density.

The research focus of material development for the treatment of radioactive waste include (1) the development of high temperature resistant material for cold crucible and (2) the development of vitrification substrate such as glass substrate, glass ceramic, and ceramic materials.

6 Recommendations for nuclear fuel and material development in China

A new round of competitions in advanced nuclear fuel have already started worldwide. China should actively plan research and development activities around advanced fuels such as ATF fuel and nitride materials as well as advanced structural materials for fuel assembly such as ODS steel. It is important to improve the capability of self-reliant innovation and industry development for nuclear fuel and materials in China. China should also develop its own brands of advanced fuels and materials used in nuclear power systems. Fuels and materials with improved performance should be provided to promote the development of advanced nuclear systems. With these efforts, China should seek to reach advanced international standards in terms of the fuel and materials used in advanced nuclear power system, and to ultimately take the lead in the development of fuel and materials for advanced nuclear power systems internationally.

6.1 Nuclear fuel and materials for PWRs

For a long time in the 21st century, PWR is the primary type of reactor in the nuclear power generation and for energy structure transformation in China. It is recommended that China further strengthen its support for the development and application of advanced fuel assemblies and cladding materials of independent brands. These research efforts will lay a solid foundation for supporting the safe and effective development of nuclear power in China as well as the export of Chinese nuclear power technology to the world. While promoting the construction of PWR, China should also start planning an improvement of its manufacturing capacity for nuclear fuel as early as possible to satisfy the requirements for sustainable development and the need to export the nuclear power technology of China.

China should also make early plans of technical facilities for nuclear fuel testing to develop a systematic and well-established fuel test system (including testing under accident condition). A world-class nuclear fuel research and development system should be established with advanced technology and complete facilities to meet the software and hardware demands for the development of nuclear fuel.

China should actively make research and development plans for advanced fuels, such as ATF, as well as other fields including high entropy alloy, material genetic engineering, and multi-scale analysis of nuclear fuel. Significant efforts should be devoted to the enhancement of revolutionary nuclear fuel and material technology innovation as well as the industrial development capabilities in China. These efforts will enable China to realize early applications of self-owned advanced nuclear fuel and materials while taking the lead in the global development of advanced nuclear fuel and materials.

6.2 Nuclear fuel and materials for fast reactors and other advanced reactors

In response to the major engineering needs such as the demonstration fast reactors initiated by the country, it is recommended that the Chinese government provide strong support to the research and development of (1) advanced nuclear fuels such as MOX fuels, metallic fuels, nitride fuels, and molten salt reactor fuels, and (2) the structural material of advanced fuel assembly such as ODS steel. Key technologies and manufacturing techniques should be developed for nuclear fuel and materials. These efforts will satisfy the fuel and material requirements for major engineering projects and enable China to take the lead in the design, manufacture, and development of the material technology of fast reactor fuel in the world by 2030.

The development of fast reactors and the reprocessing techniques of spent fuel face significant technical challenge and require substantial financial investment. To reduce investment risks and improve economics, it is recommended that China learn from the experiences of France and Russia to adopt a fuel cycle transition mode combining pressurized water reactors and fast reactors in the initial stage of the closed fuel cycle. In addition, feasible top-level design and scenario design should be planned at the same time.

6.3 Nuclear fuel cycle and materials

In December 2016, a meeting was hosted at the State Council of the People’s Republic of China on the reproccessing of spent nuclear fuel. Strategic planning was made during this meeting on the industrialization of nuclear fuel cycle and spent fuel reprocessing. The development of an advanced industrialized system for nuclear fuel cycle has already been initiated in China. The planning and construction of large-scale commercial spent fuel reprocessing facility and MOX fuel manufacturing plants should balance the elements of advancement, maturity, and economics of the technology. Material development for key stages in the fuel cycle is necessary as it supports the development of an industrialized system of nuclear fuel cycle. It is recommended that China establish an overall plan that supports the innovation and development of relevant materials strategically and systematically, thereby ensuring the smooth construction of an industrialized system for nuclear fuel cycle.

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