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Materials for the Components in an Accelerator-driven Subcritical System

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Abstract: An accelerator-driven subcritical system (ADS) is mainly composed of a high beam intensity high-energy-ion accelerator, a high-power spallation target, and a subcritical reactor. An ADS is a key part of the accelerator-driven advanced nuclear energy system (ADANES), and its research and development (R&D) will play a very important role in promoting China's energy transformation and stimulating the innovative development of China's nuclear power industry. In this paper, the status and potential trends as well as material requirements for the R&D of ADS facilities are introduced. Next, the R&D progress and problems, development opportunities, and challenges of the key materials for the high-power spallation target and the subcritical reactor are intensively discussed. Finally, several countermeasures are proposed in the hope of pushing forward ADS facility construction and technological innovation of advanced nuclear fission energy, and promoting safe, efficient, and sustainable development of advanced nuclear fission energy in the future.

Keywords: accelerator-driven subcritical system (ADS); accelerator-driven advanced nuclear energy system (ADANES); key materials; subcritical reactor; high-power spallation target

1 Introduction

An accelerator-driven subcritical system (ADS) consists of an accelerator, a spallation target, and a subcritical reactor core (shown in Fig. 1). The working principle of an ADS is to bombard heavy nuclei with high-energy, high-current proton beams generated by accelerators. Such a process will generate high-energy, high-throughput spallation neutrons, which drive and maintain the operation of the subcritical reactor (the effective neutron multiplication factor k_{eff} is less than 1). Therefore, the fission reaction can progress and be sustained on the fissile material in the reactor core. An ADS has high intrinsic safety and promising application prospects in multiple fields such as the transmutation of nuclear waste, proliferation of nuclear fuel, and improvement of production capacity. Therefore, an ADS is an important direction in the future development of advanced fission power technology.

Currently, no ADS facility has been constructed in any country. The development of an ADS facility can reflect the comprehensive strength of the country, including its scientific and technological, economic, and industrial standards. In addition, it will also promote the development of industrial and defense technologies, drive technological advancement and industrial upgrading in many related industries, and ultimately generate huge social and economic benefits. As a result, many countries with advanced nuclear power technology, such as the USA, Japan, and Russia, greatly value the development of an ADS facility and have established a medium- to long-term development roadmap for an ADS based on the status of their nuclear power development. A series of ADS facility development plans have also been proposed by these countries following a step-by-step strategy [1].

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Furthermore, all of these countries expect to have their prototype facility constructed by around 2030. The Chinese government has also provided strong support to the development of an ADS facility. After analyzing the major requirements in the development of advanced nuclear power science and technology as well as the research progress and development trend of ADSs in China, the Chinese Academy of Sciences has proposed two concepts from the perspectives of technical feasibility and economic value for future promotion: (1) the ADS development roadmap in China [1] and (2) the original accelerator-driven advanced nuclear energy system (ADANES) [2]. ADANES (shown in Fig. 2) is composed of two systems including an accelerator-driven burner (ADB) and an accelerator-driven recycler of used fuel (ADRUF). ADANES integrates the functions of nuclear waste transmutation, nuclear fuel proliferation, and safe production of nuclear power. With these merits, ADANES is a strategic energy system that can provide thousands of years of safe, low-emission, and cost-effective energy.

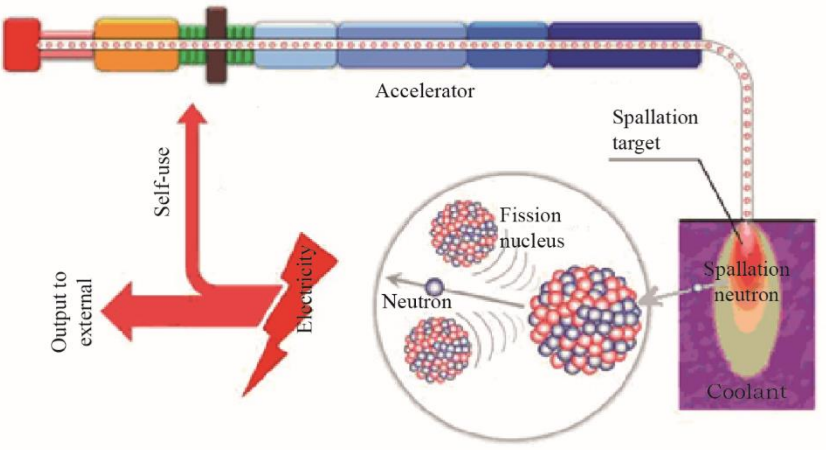

Fig. 1. Schematic diagram of the working principle of an ADS facility.

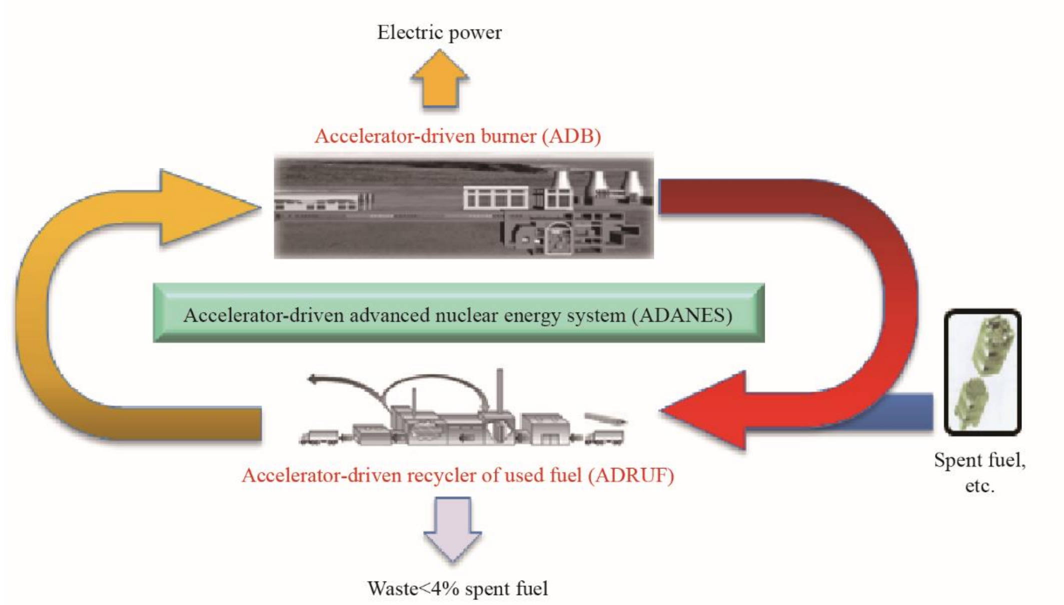

Fig. 2. Schematic diagram of the working principle of ADANES.

The development of an ADS facility, being an important part of ADANES, plays a critical role in promoting energy revolution, energy transformation, and innovative development of the nuclear power industry in China. With support from the "Future Advanced Nuclear Fission Energy—ADS Transmutation System" national project (referred to as "ADS Special Project") announced under the Strategic Advanced Science and Technology Pilot Project of the Chinese Academy of Sciences, China has made remarkable research progress and breakthroughs on superconducting proton linacs, heavy metal spallation targets, subcritical reactors and new fuel components, and nuclear power materials. Certain key technologies have already reached world-leading or advanced levels. China has also taken the lead in transforming these technologies from the basic research stage to the stage of engineering

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implementation (construction of an integrated ADS facility). The proposal and feasibility study report on the China initiative Accelerator Driven System (CiADS), a project under the *Medium and Long-Term Plan for Key National Technology Infrastructure Construction (2012–2030)*, was approved by the National Development and Reform Commission on December 2015 and January 2018. The construction of CiADS will be initiated in the near future, and once it has been completed, it will become the first megawatt-level integrated ADS system research facility in the world and carry significance as a milestone project.

Currently, material development is the major bottleneck in constructing an ADS facility. As an ADS is very different from existing nuclear power systems, the material used in a future commercial ADS facility will have to endure very harsh working conditions during its service. Existing well-established materials cannot satisfy the requirements for application in an ADS facility. Therefore, it is necessary to find or develop new materials for use in an ADS facility. In this paper, the research and development of ADANES is used as the context in which to discuss the material requirements of ADS components, key material development progress and current issues, the opportunities and challenges faced during development, and development strategies for future material development.

2 Materials used for the components in an ADS facility

Compared to existing reactors, an ADS is a more complex system that imposes greater demands on its components. As the material used for the accelerator is more well-established, this paper will focus on the materials used for the subcritical reactor, high power spallation target, and nuclear fuel in an ADS. Fig. 3 shows the major materials of the different components in an ADS.

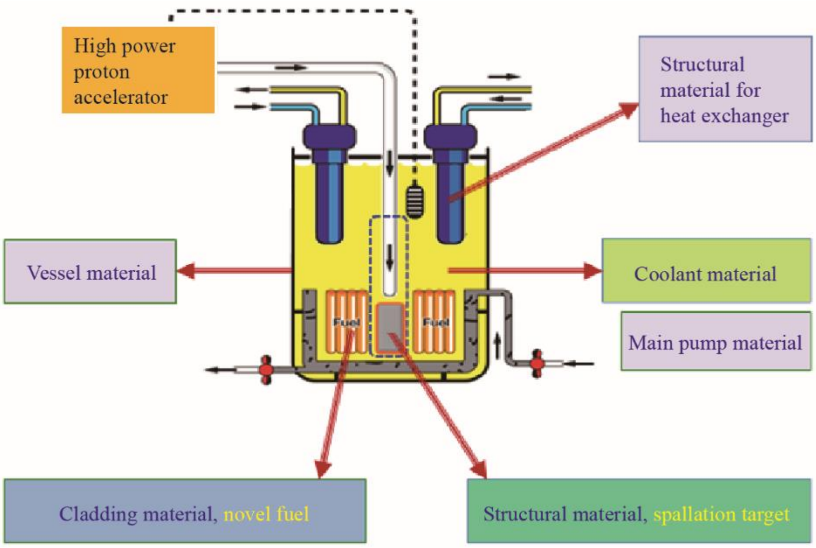

Fig. 3. Schematic diagram of material classification for different components in ADS facility.

2.1 Subcritical reactor material

The main function of the subcritical reactor system in an ADS facility is to achieve coupling with the accelerator and spallation target to generate a fast neutron field and to provide the nuclear reaction environment. The subcritical reactor system includes a main vessel, fuel components, internal reactor components, main pump, heat exchanger/steam generator, and refueling mechanism. To ensure proper operation of the reactor core, the core internals must be designed scientifically and manufactured precisely. In addition, the mechanical properties, thermal properties, and irradiation resistance of the materials used for core internals must satisfy stringent requirements. In general, the material selected for constructing the internal components of the reactor must satisfy the following criteria: excellent resistance to neutron irradiation; good thermal, mechanical, and anti-creep properties; good compatibility with the coolant; and good long-term stability [3].

Internationally, subcritical reactor design of an ADS mainly uses liquid lead (Pb) or lead-bismuth eutectic (LBE) as the coolant. The designed operating temperature ranges from 300–500 °C. Therefore, austenitic stainless steel or ferritic/martensitic (F/M) steel can be used as candidate materials for constructing the core components and the heat exchanger/steam generator. However, with continuous advancement in nuclear power technology, future reactors will operate at even higher temperatures. By that time, the existing alloy steel will not be able to satisfy the high-temperature working conditions. Therefore, alloy and toughened composite ceramic with superior high-temperature properties and excellent resistance to corrosion and irradiation will become promising candidate materials for constructing the internal components in the reactor.

2.2 High power spallation target material

In an ADS, the spallation target is a core component that generates neutrons to drive the reactor, thereby maintaining stable operation under subcritical condition. The coupling of the spallation target with the high-current proton accelerator system can guide the high-energy proton beam to hit the spallation target. The corresponding spallation reaction will produce high-energy spallation neutrons that drive the subcritical reactor to work through the coupling between the spallation target and the reactor. According to the morphology of the target material used to produce spallation neutrons, the spallation target can be classified into three types internationally: solid target, liquid target, and particle flow targets. Among them, the particle flow spallation target is a novel spallation target proposed originally by the scientists at the Institute of Modern Physics of the Chinese Academy of Sciences [4]. This spallation target inherits the advantages of both solid and liquid targets and is capable of withstanding beam powers at tens of megawatts. It is the most promising high-power spallation target candidate for use in a future commercial ADS facility.

The primary materials of the spallation target include the target material for generating the spallation neutron, the structural material of the target, and the spallation target–accelerator coupled proton beam window (proton beam window) material. The target material used for the high power spallation target must be able to produce a large amount of neutrons and possess good thermodynamics properties. The structural material of the target and the target material for generating neutrons should be resistive to strong irradiation and high temperature. The proton beam window material must be able to withstand high power beam bombardment. Finally, the energy accumulated in the deposits during the spallation reaction must be removed in time to ensure proper operation of the system.

2.3 Nuclear fuel material for an ADS

The nuclear fuel and the cladding material are the most important materials in an ADS. They must be able to withstand extremely harsh working environments such as high temperatures, strong corrosion from the coolant, strong neutron irradiation in the reactor, and a high level of stress. Completely new nuclear fuel components need to be developed based on ADANES. The material development for nuclear fuel should target improving the utilization rate of the resources. The cladding material of the nuclear fuel protects the fuel from being corroded chemically and mechanically by the coolant, and prevents the fission product from entering the coolant loop.

In terms of nuclear fuel, carbide ceramic nuclear fuel pellets are the main candidate regenerative nuclear fuel. The first step is to remove the fission products and neutron poisons from the spent nuclear fuel by an advanced dry head-end process. The next step is to prepare regenerated transmutation nuclear fuel pellet that contains uranium (U), plutonium (Pu), and minor actinides, which will be used repetitively in the ADS facility.

In terms of the cladding material of the nuclear fuel, the ideal candidate must be selected based on a comprehensive evaluation of reactor characteristics such as the operating temperature, the coolant type, the neutron flux and energy spectrum, the fuel cycle, and the reactor service life. Until now, preliminary choices have been made for fuel cladding materials in most liquid lead/LBE cooled reactor designs. For example, the EU and the US have selected 15-15Ti or T91 and F/M steel with D9 or Si additives, respectively, as the candidate cladding materials for lead-cooled fast reactors [5]. Russia has developed a type of F/M steel with 1.3% Si (there are no corresponding steel grades in other countries currently) as the fuel cladding material for its SVBR-100 lead-cooled reactor.

3 State-of-the-art development of materials for components in an ADS

3.1 Subcritical reactor material

Austenitic stainless steels such as 304L(N) and 316L(N) have good mechanical properties at high temperatures as well as excellent processing and welding properties. In addition, abundant international experience has been accumulated on the use of austenitic stainless steels. Therefore, they are considered candidate structural materials for building the main components in the liquid lead/LBE-cooled reactor. However, 304L(N) and 316L(N) stainless steel possess low radiation damage limits less than 50 dpa and operating temperatures less than 500 ℃. In addition,

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these materials have a poor resistance to liquid metal corrosion. Therefore, 316L(N) austenitic stainless steel is generally used for components operating at a low temperature and low irradiation in the reactor, such as the main reactor vessel, refueling mechanism, core support, and lower grid plate. F/M steel, represented by T91, is another candidate material for building the main components in the reactor. This type of steel exhibits high thermal conductivity, small thermal expansion, excellent creeping properties, and no stress corrosion cracking (SCC) phenomenon. Therefore, it can be used as the structural material for the heat exchanger/steam generator in a lead-cooled fast reactor. For example, EP302-M has been used as the structural material for the heat exchanger/steam generator in the BREST-OD-300 reactor in Russia. The DLFR reactor developed by Westinghouse Electric Corporation in the US uses coated 316L or 347 as the structural material for its heat exchanger/steam generator. In recent years, the Institute of Modern Physics and Institute of Metal Research of the Chinese Academy of Sciences have developed SIMP steel suitable for use in a lead-cooled fast reactor with the support of the Pilot Projects from the Chinese Academy of Sciences. This steel has a stronger resistance to LBE corrosion, high temperature oxidation corrosion, and ion radiation than T91 steel.

The main pump is a key component in lead-cooled fast reactor. The core parts of the pump such as the impeller and blade edge may reach a line speed of tens of meters per second under normal operating conditions. Therefore, the main pump suffers from a very serious liquid heavy metal abrasion phenomenon. Ferritic steel coated with ternary transition metals such as carbide ceramic material (Ti_3SiC_2), Al or Ta coated T91/316L, and Ti_3SiC_2 coated ferritic steel can be used as the structural materials for the main pump [5].

The current research on ceramic components in the reactor is still at its infancy. A number of studies have been performed to improve the properties of ceramics both in China and abroad. These include phase change and whisker/fiber toughening, thermal conductivity improvement, and wear resistance enhancement. Other studies have assessed the irradiation property of candidate composite ceramics (e.g., SiC and SiC_f/SiC) including the irradiation-induced change in crack propagation resistance, thermal conductivity, and mechanical properties; radiation swelling and residual stress; and helium bubbling behavior. In general, however, only limited types of materials have been explored with insufficient comprehensive evaluation results. A large amount of research work is still required in the future.

3.2 High-power spallation target material

3.2.1 Component material of the spallation target

At present, different types of ADS spallation targets are designed with different structural and beam window materials. During the operation of ADS, a large amount of heat and a high irradiation dose will be generated when the high-power beam passes through the proton beam window. Therefore, the beam window must exhibit excellent thermodynamic properties and strong resistance to irradiation. According to the past spallation proton source projects, the candidate materials for the beam window includes austenitic steel (316L), martensitic steel (T91), nickel-based alloy (Inconel 718) or aluminum-based alloy (A5083-O, AL6061-T4, Al-Mg_3, etc.), titanium alloy (Ti92.5-Al5-V2.5) or vanadium alloy (V92-Cr4-Ti4), beryllium–carbon-carbon double-layer composite (design concept), and W-Re alloy. For example, Inconel 718 has been successfully used for constructing the proton beam window in the ISIS spallation neutron source in the United Kingdom (UK) and the LANSCE spallation neutron source in the US. Theoretical calculations have demonstrated that Inconel 718 can withstand a maximum irradiation dose of 10 dpa with a corresponding irradiation energy of 7500 MW/h. For practical application in the neutron source device in ISIS, Inconel 718 has withstood an irradiation dose of 34 dpa without any issue during the operation of the facility [6]. $AlMg_3$ has been used to build the safety cavity of the target in the SINQ spallation neutron source in Switzerland. Al5083 has been used as the beam window material for the spallation neutron source in Japan. As aluminum-based alloys exhibit superior performance over nickel-rich alloys in high-irradiation environments, Al6061-T4 has been used as the raw material for the second-generation proton beam window. The service life of Al6061-T4 does not depend on the level of atomic displacement damage. Instead, it is more affected by the rate of helium production. Based on theoretical calculation, the aluminum-based proton beam window can withstand a helium concentration of at least 2000 appm. The service life of the material is around 2 years under a beam power of 2 MW and an operation time of 5000 h per year. However, whether these materials can be used in a real ADS facility remains to be validated.

3.2.2 Material for spallation targets

The materials used for spallation targets can be generally divided into liquid metal and solid metal. The solid target materials include tungsten and tungsten alloy. The liquid target materials include liquid lead, LBE, and mercury. Solid targets suffer from poor heat transfer performance and are not suitable for high-power spallation target projects. Liquid targets such as liquid LBE exhibit excellent neutron and thermodynamic properties, low vapor pressure, and low chemical activity. Owing to these merits, the liquid target has attracted attention around the world. However, there are several issues associated with liquid targets, including unstable fluid mechanics, potential leakage risks, and a strong temperature–corrosion effect on the structural material. In addition, the irradiation of the proton beam on LBE can easily produce polonium which is extremely toxic. Furthermore, the bombardment of a high-energy proton beam on the liquid target will generate a strong shockwave that will accelerate material fatigue and aging. These insurmountable challenges greatly restrict the development of the liquid target.

The particle flow target inherits the advantages of both the liquid and solid spallation targets. It uses solid particles as the target material for generating neutrons. Currently, the materials used for the spallation target are primarily tungsten-nickel alloy spheres with a high specific weight. Tungsten-based alloys can be prepared easily at low cost and have excellent mechanical properties. Considering the fluidity of the target spheres and the heat transfer performance of the particle flow target, the results of numerical simulations revealed that using a diameter of ϕ1 mm for the particle sphere can yield a superior overall performance. At present, researchers have established an experimental platform and conducted a series of experimental studies on particle flow, heat transfer, collective friction and wear of particle flow, and the beam-target coupling behavior. The feasibility of the particle flow target and corresponding materials have also been verified preliminarily. Nevertheless, owing to insufficient experimental data, more in-depth research efforts are still required in the future.

3.3 Nuclear fuel material used in an ADS

3.3.1 Novel nuclear fuel material

The traditional “separation–transmutation” process refers to the separation of uranium and plutonium from the spent fuel by the Purex process. Subsequently, all MAs (Np, Am, and Cm) remaining in the highly radioactive waste and the fission product with a long lifespan will be separated one by one. Finally, the MAs extracted from the waste will be added to nuclear fuel and combusted inside the ADS burner. The traditional ADS transmutation fuel contains only minor actinides without any uranium or thorium. These fuels can be categorized into metallic fuel, dispersed fuels, and ceramic fuels [7]. Among them, ceramic fuel can be further divided into oxide fuel, carbide fuel, and nitride fuel.

Oxide ceramic nuclear fuels have been widely used in pressurized water reactors. Such fuel exhibits a high melting point, isotropic expansion characteristic, good irradiation behavior, and excellent mechanical properties. However, it suffers from a low thermal conductivity and is prone to embrittlement. Carbide ceramic fuel has a relatively higher thermal conductivity as well as a smaller temperature gradient than oxide fuel. This feature enables a higher power density to be extracted from the reactor. The relatively high content of fissile nuclide in carbide fuel can reduce the volume of fuel required in the reactor when the volume reaches a critical value. In addition, uranium carbide can be mixed with plutonium and some minor actinides to form a binary co-dissolution system, forming a single-phase metal-carbide mixed fuel. The addition of Pu and MAs to the fuel can improve the fuel stability significantly. Therefore, carbide nuclear fuel is considered as the ideal nuclear fuel candidate for future reactors.

3.3.2 Cladding material of the nuclear fuel

Three different cladding materials are commonly used in the fuel assemblies of existing reactors in operation. These include the zirconium alloy used in pressurized water reactors, stainless steel and nickel-based alloy used in fast reactors, and graphite/SiC used in high temperature gas-cooled reactors. With development shifting towards high combustion consumption, long fuel cycles, and high safety levels in the nuclear reactor, traditional cladding materials will become incapable of satisfying the stringent requirement for use in future advanced nuclear systems.

In terms of the ADS, 15-15Ti steel is one candidate fuel cladding material for subcritical fast reactors that uses liquid PB/LBE as the coolant. It is a kind of new austenitic steel stabilized by Ti. Compared to 316 stainless steel, 15-15Ti steel has a slightly lower Cr content and greater Ni content, and contains a trace amount of Ti, which significantly improves the high temperature properties and anti-irradiation swelling properties of the material [8]. In addition, application experiences of using this material have already been collected from the high-throughput fast neutron flux research reactor (FFTF), the Phénix reactor, the Superphénix reactor, and the fast neutron research reactor BOR60. F/M steel, represented by T91, is another type of candidate cladding structural material for nuclear fuel. Compared to austenitic steel, F/M steel exhibits superb anti-irradiation swelling properties.

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However, it is prone to radiation hardening accompanied by an increase in the ductile-brittle transition temperature (DBTT) at low temperatures (<450 °C). At higher temperature, the radiation hardening/embrittling phenomenon becomes weaker or disappears. Past research has shown that F/M steel with 9% Cr (such as T91) exhibits better toughness at low temperature than F/M steel with 12% Cr [9].

Ceramic materials, such as SiC, ZrC, and other composite materials, have attracted great attention in the development of accident tolerant fuel (ATF) due to better high temperature properties and stronger resistance to irradiation corrosion than metallic material. Compared with traditional metallic cladding material, SiC-based ceramic material can withstand higher temperatures and stronger neutron fluxes; furthermore, it has a better resistance to corrosion and longer lifetime. However, changes in the radial temperature gradient and reactor power during the operation of SiC cladding will create thermal shock and irradiation swelling behavior, both of which can cause the cladding tube to expand in volume or even experience brittle fracture. ZrC ceramic possesses better resistance to irradiation and corrosion than SiC ceramic. However, its strength stability at high temperature and creeping performance under a combination of high temperature and irradiation need to be further improved. Apart from these aspects, the application of ceramic coating (e.g., Sic, ZrC, TiC, TiN) on alloy cladding tube has also received wide attention. Nevertheless, significant research efforts are still required on the preparation methods, processing procedures, and the performance validation in the later stages for ceramic coating.

3.4 Evaluation of the irradiation resistance of materials used in ADS

3.4.1 Evaluation of neutron irradiation effect

The irradiation property of a material is a key metric for determining if it can be eventually used in a reactor [10,11]. Since 1970, scientists in the US, EU, and Japan have started to collect the irradiation swelling, irradiation hardening, and irradiation embrittlement data of martensite/ferritic steel using neutrons generated by several different reactors. These include the experimental breeder reactor (EBR), FFTF, and high flux isotope reactor (HFIR) in the US, the high flux reactor (HFR) in Europe, the BOR60 reactor in Russia, and the JMTR in Japan. Specifically, the swelling rate of structural materials under different irradiation conditions were obtained experimentally [12].

Limited by reactor and hot cell availability as well as the social reality, the task of material evaluation under neutral irradiation has only been performed in few organizations possessing a reactor and hot-cell condition simultaneously. These include the Nuclear Power Institute of China and the China Institute of Atomic Energy. Specifically, these two institutes examined the mechanical properties of the material under small doses of neutron irradiation. In terms of material research, the low damage rate by neutrons in the reactor, long experimental cycle, and high experimental cost impose significant limitations on the task of evaluating the neutron irradiation of the material. Considering these constraints as well as the actual requirements of the ADS project, two approaches have been taken to evaluate the neutron irradiation effect. On the one hand, the authors have already evaluated the irradiation property of proton/spallation neutron on the material using a 25-MeV proton beam generated by the linear accelerator (LINAC) at the Institute of Modern Physics of the Chinese Academy of Sciences; on the other hand, through close collaboration with domestic and foreign research institutes, the irradiation property on the material in the reactor and under the Swiss spallation target environment [13] was evaluated. Specifically, an irradiation experiment with around 300 different small samples has been accomplished using STIP-VII and STIP-VIII targets.

3.4.2 Ion irradiation simulation

The selection of the candidate nuclear power material satisfying irradiation requirement can also be conducted by simulating neutrons with high-energy heavy ions. This approach has the following advantages: (1) The high-energy ion can penetrate the material deeply (greater than 100 μm) and form a wide irradiation damage flat area, providing the necessary condition for investigating the macroscopic mechanical properties of advanced nuclear power candidate materials under irradiation; (2) the high-energy ion can cause a high damage rate that helps to realize a high level of irradiation damage in a short time; and (3) irradiation by energetic inert gas ions can dope the solid with gas atoms, which simulates the transmutation He effect in the material; and (4) the sample exhibits a low activity after irradiation that makes it more convenient to process in a short time.

The use of energetic ion implantation/high-energy heavy ion irradiation can simulate the environment in the nuclear reactor, and performing the irradiation test on the candidate structural materials under such conditions can achieve a high level of irradiation damage and high concentration of He dopant in a short time. Therefore, the irradiation damage level of the candidate structural material during its entire service life can be evaluated. The

Lanzhou National Laboratory of Heavy-ion Accelerator in the Institute of Modern Physics of the Chinese Academy of Sciences is equipped with a series of ion accelerators including HIRFL-CSR, 320 kV platform, high current LEAF, and 25MeV-LINAC. In addition, the laboratory also possesses a supporting multifunctional irradiation terminal. This hardware, capable of producing H–U ions with keV–GeV energy, provides the necessary condition to conduct ion irradiation/implantation experiments to simulate the neutron irradiation effect on the nuclear materials, and to perform rapid selection and evaluation of candidate nuclear materials.

4 Problems and challenges faced in the material development of components for an ADS

4.1 Subcritical reactor material

The extremely harsh environment conditions in the reactor, such as high temperatures, strong irradiation, and strong corrosion, pose significant challenges to the limits of existing materials.

The material of fast reactors using liquid metal coolant is exposed to high temperatures and corrosion/abrasion. In a high temperature environment, F/M steel (e.g., T91) and austenitic stainless steel (e.g., 316L) both exhibit insufficient high temperature properties. For example, the creeping performance of F/M steel degrades substantially at a temperature greater than 550 °C. With the increasing operating temperature of the reactor, the corrosion of the material by liquid lead/LBE also becomes more severe [14]. When the temperature of the coolant exceeds 500℃ in the reactor core, the use of oxygen control technology to prevent structural material corrosion by liquid metal becomes infeasible. Surface treatment or passivation technology is an important method for resolving high temperature corrosion. However, considerable research is required to improve the maturity of the process and the long-term stability of the material properties. For the main pump used in the reactor, the abrasion on the pump impellers and blades due to the heavy liquid metal is the first problem that needs to be resolved. Currently, there is still a lack of experimental testing and sufficient data on the major candidate materials used for constructing the main pump in a lead-cooled fast reactor.

For the ceramic component materials to be used in future reactor cores, the main problems include poor toughness, low thermal conductivity, difficulties in material processing and joining, and a lack of evaluation of their irradiation corrosion properties. While certain progress has been made in research on material preparation, toughening mechanisms, physical properties, mechanical properties, and wear resistance, the toughness and manufacturability of ceramic materials are still much worse than those of the existing metallic materials, and fail to satisfy the requirements. Furthermore, studies on the preparation, processing, and feasibility analysis of ceramics and composite materials for different purposes are limited. It is necessary to develop evaluation techniques and computational simulations of ceramics and composite materials in nuclear power application environments.

4.2 High-power spallation target material

4.2.1 Component material for the spallation target

Both nickel-based alloy and steel possess better mechanical properties than aluminum-based alloy. However, aluminum-based alloy has the smallest density, high thermal conductivity, and a large specific heat capacity. In general, aluminum-based alloy exhibits better thermodynamic properties than nickel-based alloy and steel. However, aluminum-based alloy can only be used at a relatively low temperature and is not suitable for application in ADS, which operates at a high temperature. The application of nickel-based, iron-based, and vanadium-based alloy must take into account the helium embrittlement issue in a high-dosage irradiation environment and the corresponding mechanical stability issue.

Currently, the use of T91, 316L, titanium alloy, and vanadium alloy as candidate materials has only been evaluated for building proton beam windows. Inconel 718 and aluminum-based alloy have already been used in practical ADS facilities. Steel (T91, 316L) is primarily used in single-layer and windowless assembly design. Based on the theoretical calculation of the atomic displacement damage level and the He generation rate, both of these materials have a service life of 100 days. However, the service life of titanium alloy and vanadium alloy is around one year. Inconel 718 has relatively high hardness but can only accommodate a double-layer geometric design. Considering the atomic displacement damage level, the service life of Inconel 718 is around 1.5 years. Aluminum-based alloy generally uses a double layer or panpipe structure. According to the theoretical calculation of He generation rate, the service life of aluminum-based alloy is around 2 years (conservative estimation; some other studies estimated a service life of 3.5 years or even more based on the atomic displacement damage level). Therefore, the structural design of the beam window and selection of an appropriate material still require further investigation and validation.

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4.2.2 Particle flow spallation target material

As the particle flow spallation target is a novel spallation target, there is not much past techniques or experience that can be referenced during material development. While considerable validation work has been conducted so far, a large amount of data still needs to be collected. The particle flow spallation target still suffers from a series of unresolved issues including irradiation damage, embrittlement, and friction wear. The particle flow spallation target is essentially a solid target. The particle sphere may be damaged by irradiation when operating in a strong irradiation field, particularly a strong neutron irradiation field, for a long time; such irradiation damage will degrade the mechanical properties of the sphere. Although existing experiments have shown that tungsten alloy is a very resistive to wear, the circulation of a large number of target spheres in the target loop over a long time will create considerable collision, sourcing, and contact/rolling/sliding. These behaviors will still result in serious friction wear. In addition, more in-depth studies are required to optimize the composition of existing particle flow target materials and the preparation process of the target spheres in order to further improve the availability, safety, and reliability of the particle flow spallation target system.

4.3 Nuclear fuel material used in an ADS

4.3.1 Preparation of novel nuclear fuel

According to the principle of ADANES, the nuclear fuel used in an ADS facility should be transformed from the highly refined material with a low utilization rate used in the reactor of a traditional nuclear power plant to a coarse material with a high utilization rate. As shown by the ADRUF circulation schematic diagram in Fig. 4, this type of nuclear fuel can improve the utilization rate of uranium resources from the current level of “less than 1%” to “greater than 95%.” In addition, the amount of nuclear waste after processing is less than 4% of the initial spent fuel, and the radiation life has been reduced from hundreds of thousands of years to about 500 years.

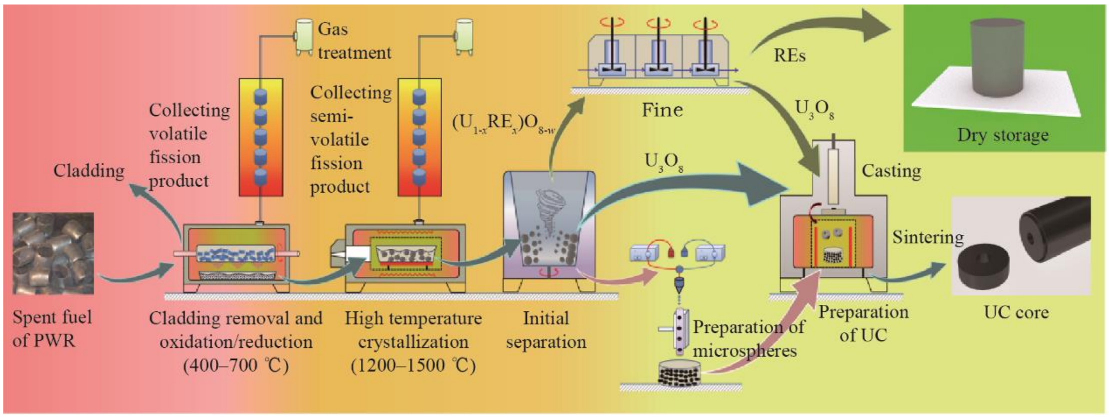

Fig. 4. Schematic diagram of the specific implementation route of the ADRUF cycle.

To realize advanced close-loop circulation of nuclear fuel, it is necessary to develop advanced transmutation technology that separates poisons from the neutron and converts spent fuel into regenerated transmutation nuclear fuel. Currently, the Institute of Modern Physics has collaborated with the Paul Scherrer Institute (PSI) in Switzerland to develop a rapid sol-gel process platform that combines the instant mixing feature without cooling at room temperature and microwave assisted heating. Using such platform, the researchers have successfully prepared uranium carbide nuclear fuel pellets [15]. These UC ceramic spherical pellets have a diameter of 675±10 μm and a density reaching 92% of the theoretical value. At the same time, to simulate the preparation process of regenerated nuclear fuel pellets from spent fuel, two types of metal-mixed carbide ceramic pellets have also been prepared successfully. Each type of pellet contains (1) 20% Ce in molar ratio and (2) 20% Ce and 10% Nd in molar ratio. The ceramic microsphere is an MC (M = U, Ce, and Nd) eutectic possessing UC cubic phase structure. The processing approach developed here can be used directly for preparing the regenerated carbide nuclear fuel pellets in the advanced close-loop fuel circulation system.

As spent fuel exhibits strong radioactivity and biological toxicity, the conversion of spent fuel into regenerated nuclear fuel must be performed in a closed glove box remotely. This makes it challenging to prepare regenerated nuclear fuel. Considerable amounts of research effort are still needed to improve the dry head-end process and the regeneration nuclear fuel preparation process.

4.3.2 Cladding material of nuclear fuel

Current lead-cooled reactors have irradiation damage and a relatively lower operating temperature. Existing austenitic steel (15-15Ti) and F/M steel can generally satisfy the material requirements for use in these lead-cooled reactors. However, further increasing the operating temperature and fuel consumption will impose significant challenges on the existing cladding material used in the reactor.

The cladding material used in the ADS lead-cooled fast reactor will be subjected to an irradiation dose of more than 200 dpa. No existing austenitic steel can satisfy the material requirements for the entire service life. Research has shown that the irradiation damage and irradiation swelling of HT9 at 420 ℃ can reach 200 dpa and 1% [16]. However, there is a lack of damage data for F/M steel under even higher irradiation doses. If the cladding temperature of the fuel exceeds 600 ℃, then both F/M steel (e.g., T91 and HT9) and austenitic stainless steel (e.g., 15-15Ti) will experience high-temperature degradation of their mechanical properties. Therefore, novel F/M steel, ODS steel, or SiC ceramic materials are the future research directions. Under a working condition with even higher temperature and stronger irradiation, corrosion by the liquid metal coolant will become a serious issue faced by the cladding material of the reactor fuel [17]. High temperatures will accelerate the corrosion of liquid lead/LBE on the material. The latest studies have also found similar effects from irradiation. However, there is still a lack of sufficient data to better understand this phenomenon. Further research is required to overcome these issues.

In terms of future ATF ceramic cladding materials, there are still many unresolved issues including a complex preparation process, anisotropic properties, brittle fracture, thermal shock fracture, and insufficient conventional and irradiation data. Owing to these issues, these ceramic cladding materials cannot satisfy the requirements for use in the reactor. More thermal data also needs to be collected for these materials. In addition, the comprehensive thermal physical performance of the ceramic cladding material under loss-of-coolant accident (LOCA) still needs to be evaluated by systematic studies.

4.4 Design, preparation, rapid selection, and evaluation of materials for an ADS

4.4.1 Design and preparation of the material

According to the strategic development planning for an ADS facility [1,2], there is a lack of research on the failure behavior, pattern, and intrinsic mechanism of the materials of an ADS facility under extreme conditions. At the same time, starting from the design optimization of material composition and the design optimization of the structure and component by computational simulation, past studies have failed to establish a proper connection between composition design, material structure, process, and performance evaluation. An accurate model for predicting the material properties is still lacking. During the design, preparation, and evaluation process of the material, there is a lack of common standards and specifications in China. Such issues make it difficult to compare and validate the data obtained from different sources. Furthermore, the databases of basic material parameters developed by different organizations in China are not shared among the organizations. This limitation results in low efficiency material development that severely affects the research and development progress of advanced nuclear material.

4.4.2 Rapid selection and evaluation of nuclear materials

Rapid selection and evaluation of nuclear materials can be achieved by irradiation in the reactor, simulating the irradiation with accelerator ions, and irradiation from novel neutron sources, such as spallation targets. However, if one expects to consider the total neutron flux and damage level of the candidate materials in an advanced nuclear power facility during the facility's entire service life, the level of neutron irradiation exposed to the material in the reactor will not be sufficient to satisfy the ever-increasing irradiation evaluation requirements for nuclear materials in a reactor. Furthermore, there is currently a lack of sufficient selection and evaluation platforms for nuclear materials both in China and abroad. Example platforms include the high-current neutron source irradiation device and the radioactive material processing and analysis testing platform. Such a deficiency severely hinders the development of novel nuclear materials and the selection/evaluation of candidate materials.

5 Recommendations for the material development for an ADS

5.1 Key research and development materials

5.1.1 Subcritical reactor material

For a future ADS facility, the possible candidate materials include novel F/M steel, ferrite (ODS) steel, SiC, SiC_f/SiC, or high temperature alloy.

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ODS steel is a candidate structural material that holds promise as a replacement for traditional F/M steel for application in future reactors with a high service temperature (> 650 °C). The allowable operating temperature of ODS steel can reach as high as 800 °C. At the same time, ODS steel exhibits excellent resistance to irradiation. However, further research efforts are still required on the industrial production, processing techniques, and comprehensive performance evaluation of ODS steel.

SiC and SiC_f /SiC ceramic materials also exhibit excellent high temperature properties. In addition, they are highly compatible with liquid lead. However, the material structure and performance data of these materials under high temperatures, such as 1000 °C and high irradiation doses (> 30 dpa) are still lacking. Extensive research is still required on (1) the development of novel composite ceramics with high toughness and high thermal conductivity; (2) the fine processing and joining technique of ceramics; (3) the evaluation of thermodynamic properties and irradiation resistance; (4) compatibility with the coolant; and (5) the evaluation of the structural damage and performance degradation under the combined effects of irradiation/corrosion.

5.1.2 High-power spallation target material

The material used for the spallation target beam window should be developed with the following characteristics: high strength, high thermal conductivity, strong resistance to irradiation, strong resistance to thermal shock, and a good manufacturability (irregularly shaped pieces).

Interim progress has been made on the research and development of the target material. However, there is still a lack of sufficient experimental data. The performance of these materials also requires improvement. It is necessary to further optimize the composition and structural design of materials to develop novel materials with a high neutron generation rate, strong irradiation resistance, and a stable structure and performance. These materials will ultimately satisfy the requirements for industrialization of the ADS.

5.1.3 Nuclear fuel material used for the ADS

The dry processing technique of the spent fuel and preparation technique of regenerated nuclear fuel should be further optimized and improved. Simulated nuclear fuel pellets have already been produced from a rapid sol-gel process platform that combines the instant mixing feature without cooling at room temperature and microwave-assisted heating. Based on this technology, further research should be conducted to explore the preparation techniques of regenerated nuclear fuel pellets from spent fuel and to realize the preparation of regenerated carbide nuclear fuel pellets for ADS.

It is also necessary to develop the cladding material of accident tolerant fuel (ATF) in ADS. Special attention should be paid to the development of toughened composite ceramic cladding material.

5.2 Construction of high-performance material research platforms

5.2.1 High-current neutron source irradiation platform

China has the fastest growing nuclear power facilities in the world. With the initiation of multiple projects on advanced nuclear facilities, it is necessary to construct a high-current neutron source irradiation test platform for developing irradiation-resistant material and new domestic fuel assembly. We recommended placing special focus on the construction of a high-current ion accelerator and high-current neutron source device with subcritical blankets. These devices can be used to conduct the neutron irradiation experimental research on new nuclear fuel and materials. This way, the necessary requirements can be satisfied for the development and evaluation of materials used in ADS, irradiation testing of new nuclear fuels, and preliminary testing of regenerated fuel components.

5.2.2 Research platforms for material design and rapid selection by ion irradiation

It is necessary to develop a material design research platform and to optimize the design of material composition, material structure, and the components by computational simulation. The platform can build a close connection between compositional design, material structure, and performance evaluation to establish an accurate model for predicting material properties.

The evaluation and testing of materials' irradiation performance is restricted by a number of adverse factors including a low neutron damage rate, long test cycle, high test cost, and limited hot cells. Considering these hindrances, the existing large-scale neutron/ion irradiation device should be improved along with the corresponding material irradiation and performance test and analysis platforms. Such an improvement will provide the necessary conditions for conducting a large amount of evaluation experimental work.

An important task is to construct a basic material property database. In addition, the computational simulation should be integrated with experimental research using standardized data. Combining these two tasks will allow us to develop an underlying connection between the material composition, structure, and processing technique, and properties. These approaches will accelerate the evaluation and selection of new materials.

5.2.3 Radioactive material treatment and analysis test platform

The various types of neutron sources can be used to conduct investigations on the irradiation damage mechanism of nuclear material, research and development of irradiation-resistant material, and evaluations of these materials. Owing to the high radioactivity of the material, the neutron irradiation research platform must be equipped with a standardized large/small size hot cell for storing, cooling, analyzing, and testing the highly radioactive materials remotely. A major task is to develop a radioactive material treatment and analysis test platform that comprises a full-scale hot cell and a semi-hot cell. At the same time, a nuclear material test standard system following uniform specifications should be developed independently for evaluating and comparing the material properties over different irradiation platforms. Taking advantage of such a platform, more research activities could be conducted on (1) the post-processing of dried spent fuel in a pressurized water reactor and the associated processing technique, (2) the preparation of transmutation elements and the associated processing technique, and (3) testing of spent fuels. These tasks will meet the demands for developing new fuel material, processing the nuclear fuel after circulation, and conducting research on the nuclear material.

5.2.4 Material evaluation database platform

The material evaluation database is the basis for designing an ADS facility. The development of nuclear material takes a long time. To ensure the reliability and effectiveness of the material data, a basic data and irradiation evaluation database platform must be developed for different materials. Such a platform will reflect the quality and maturity of the material data. Based on the independent development of the standard nuclear material test system, we should strengthen the close collaboration between industry and academia. By developing a standardized data and sharing system, a shared material database will be eventually established. Such a database will have a profound impact on the research and development of novel nuclear materials and advanced nuclear power systems in China in the future.

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