Research Progress on Metallic Fuel for Integrated Fast Reactors:Characteristics,Challenges,and Future Prospects

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The closed fuel cycle system of an integrated fast reactor can improve the utilization rate of uranium resources and reduce the production of high-level radioactive waste.The closed fuel cycle system of an integrated fast reactor using metallic fuel,which features high thermal conductivity,high fission atom density,and high breeding ratio,can effectively enhance the inherent safety and economy of the fast reactor.However,challenges remain in the radiation protection of equipment and facilities in high-dose gamma-ray and neutron environments,as well as the control of mass loss of volatile transmutation nuclides(especially Am)in the engineering manufacturing process of metallic fuel containing minor actinides(MA).In the future,the performance of metallic fuel can be further improved by developing new structural materials and designing complex component metallic fuel elements.This paper reviews the characteristics,preparation technology,application status,challenges,and future development directions of metallic fuel,providing a reference for the commercial application of the closed fuel cycle system of an integrated fast reactor.

Keywords:Metallic fuel,Integrated fast reactor

1.Introduction

Under the guidance of the“dual-carbon”strategic goals and the“14th Five-Year” national clean energy development plan,the development of advanced nuclear energy systems has become an important support for China’s energy structure transformation.China’s nuclear energy development adheres to the“thermal reactor—fast reactor—fusion reactor”three-step development strategy.The core technological path of the“second step”in this strategy is not only key to building a closed fuel cycle system but also marks a strategic breakthrough in the industrialization of China’s fast reactor industry.Metallic fuel,as a core component of an integrated fast reactor,directly affects the safety and operational efficiency of the integrated fast reactor.Breakthroughs in metallic fuel are one of the core foundations for the engineering of integrated fast reactors.

2.Characteristics of Metallic Fuel

Metallic fuel has several advantages,including high thermal conductivity,high fission atom density,high breeding ratio(1.24 for metallic fuel,compared to 1.05 for oxide fuel),small Doppler coefficient,and relatively simple manufacturing processes.Moreover,metallic fuel can be recycled using melt refining or electrorefining,allowing the recovery of U,Pu,and minor actinides for return to the reactor for incineration.The recycling process is simple,can remove a large number of fission products,and is both economical and conducive to preventing nuclear proliferation.However,metallic fuel also has some disadvantages compared to other types of fuel,such as low melting point,strong core-cladding chemical interaction,and severe irradiation swelling.To increase the solid-phase temperature of U and U-Pu fuels,as well as the eutectic temperature between the fuel and the stainless steel cladding,alloying elements(such as Zr and Nb)are added to the fuel.U-Pu-Zr metallic fuel can improve the breeding ratio and significantly enhance the utilization rate of uranium resources,thereby improving the safety and economy of the closed nuclear fuel cycle.This makes it an inevitable choice for establishing a closed cycle of metallic fuel in fast reactors.

3.Preparation Technology of Metallic Fuel

3.1 Manufacturing Processes

The core of metallic fuel is usually prepared by casting,including injection casting,centrifugal casting,continuous casting,and gravity casting.The United States has completed irradiation tests on more than 13,000 metallic fuel rods.Japan has achieved industrial-scale production of U-Zr alloy fuel,and the development of U-Pu-Zr fuel has reached a small-scale pilot production level.Six U-Pu-Zr metallic rods have completed irradiation tests in the JOYO fast reactor.

3.2 Technical Difficulties

Metallic fuel alloys have a relatively large solidification range.For example,the liquidus temperature of the U-19Pu-10Zr alloy is 1300°C,while the solidus temperature is 1080°C,resulting in a solidification range of 220°C.This can lead to micro-shrinkage effects and loss of process control during solidification.The engineering manufacturing process of metallic fuel also faces the issue of volatile transmutation nuclides(especially Am).Therefore,the manufacturing process of metallic fuel,which has characteristics such as high radioactivity,active metals(uranium,plutonium,sodium),and high heat release,poses challenges in terms of operational difficulty and high safety requirements.

3.3 Current Progress

China initiated preliminary research on U-Zr alloy fuel and cladding materials in 2011,determining the technical plan for the preparation of U-Zr alloy core and conducting research on the melting and casting processes of U-Zr alloy core.Alloy cores of different diameters were melted and cast,and analyses of density,chemical composition,and microstructure were carried out.Recently,supported by the integrated fast reactor project,the trial device for injection casting of U-Pu-Zr metallic fuel and the hot test casting furnace have been completed.Injection casting experiments of U-Zr and U-Ce-Zr simulated materials have been conducted.In addition,the development of continuous casting experimental devices has been synchronized,and continuous casting experiments of ternary simulated materials have been completed,laying the foundation for the engineering preparation of metallic fuel.

4.Conclusions and Prospects

Metallic fuel is a key technology for integrated fast reactors,and its breakthrough is a crucial path to achieving a closed fuel cycle.A series of research and development activities on metallic fuel have been carried out,including the development of injection casting and continuous casting process equipment,and the development of improved ferritic-martensitic steel cladding materials.In the future,oxide dispersion strengthened(ODS)steel will be used as an alternative cladding material for integrated fast reactors.Meanwhile,efforts will be accelerated to conduct feasibility studies on innovative solutions such as low effective density,central hole design,cladding inner wall coating,close-fit design,and vented design.