

Review

Advancements and Development Trends in Lead-Cooled Fast Reactor Core Design

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Abstract: Motivated by the growth of global energy demand and the goal of carbon neutrality, lead-cooled fast reactors, which are core reactor types of fourth-generation nuclear energy systems, have become a global research hotspot due to their advantages of high safety, nuclear fuel breeding capability, and economic efficiency. However, its engineering implementation faces key challenges, such as material compatibility, closed fuel cycles, and irradiation performance of structures. This paper comprehensively reviews the latest progress in the core design of lead-cooled fast reactors in terms of the innovation of nuclear fuel, optimization of coolant, material adaptability, and design of assemblies and core structures. The research findings indicate remarkable innovation trends in the field of lead-cooled fast reactor core design, including optimizing the utilization efficiency of nuclear fuel based on the nitride fuel system and the traveling wave burnup theory, effectively suppressing the corrosion effect of liquid metal through surface modification technology and the development of ceramic matrix composites; replacing the lead-bismuth eutectic system with pure lead coolant to enhance economic efficiency and safety; and significantly enhancing the neutron economy and system integration degree by combining the collaborative design strategy of the open-type assembly structure and control drums. In the future, efforts should be made to overcome the radiation resistance of materials and liquid metal corrosion technology, develop closed fuel cycle systems, and accelerate the commercialization process through international standardization cooperation to provide sustainable clean energy solutions for basic load power supply, high-temperature hydrogen production, ship propulsion, and other fields.

Keywords: lead-cooled fast reactor; nuclear fuel; nuclear materials; assembly structure; core arrangement



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1. Introduction

Under the continuous growth of global energy demand and the urgent requirement for clean and low-carbon transformation, nuclear energy, as an efficient and low-carbon form of clean energy, plays an increasingly important role in the global energy structure [1,2]. Among them, the lead-cooled fast reactor, an advanced reactor type of the fourth-generation nuclear energy system, has become a hot spot in the research and development of the international nuclear energy field due to its outstanding advantages, such as high inherent safety [3], good economic performance [4], and excellent nuclear fuel transmutation capability [5].

The development of lead-cooled fast reactors has undergone several stages. In the 1960s, the former Soviet Union developed a nuclear submarine power system using lead-bismuth eutectic (LBE) as the coolant, with the “Alfa-class” nuclear submarine being a

representative work [6]. However, problems such as the easy solidification of LBE, corrosion of the in-reactor structure, and generation of radioactive ^{210}Po led to the decommissioning of nuclear submarines in the 1990s. At the beginning of the 21st century, the lead-cooled fast reactor was selected as a candidate reactor type for the fourth-generation nuclear energy system because the lead-based coolant can operate at high temperatures near atmospheric pressure, which simplifies the reactor design. In 2010, the International Forum for Fourth Generation Nuclear Energy Systems established an Interim System Steering Committee for Lead-Cooled Fast Reactors to promote international cooperation [7]. After 2010, the technology of lead-cooled fast reactors was developed at an accelerated pace. The European Union developed the European Lead-cooled System (ELSY), which adopts a pool-type structure to optimize the fuel cycle [8]. Russia has designed a medium-sized lead-cooled fast reactor, BREST-OD-300 [9], which is planned to be operated in 2026. The United States introduced the small modular lead-cooled fast reactor (SSTAR) [10], which is suitable for power supply in remote regions. In 2023, Belgium, Italy, Romania, and the United States jointly signed an agreement to construct demonstration reactors in Mol, Belgium, and Romania. The evolution of lead-cooled fast reactors from their early applications to future nuclear energy systems demonstrates remarkable achievements in technological progress and international cooperation, and they have broad development prospects.

As an innovative nuclear energy system, lead-cooled fast reactors have multi-dimensional technical advantages. In terms of nuclear fuel management, the dynamic matching mechanism between the fast neutron spectrum and closed fuel cycle overcomes the physical limitations of traditional thermal reactors [11]. A recyclable nuclear fuel breeding path is formed through the efficient conversion of ^{238}U and deep transmutation of actinide nuclides [12]. While significantly improving the resource utilization rate, it reduces the long-term environmental burden of highly radioactive waste at the source. Regarding the engineering characteristics of the reactor core, compared with sodium-cooled fast reactors, lead-based coolants have a weaker neutron moderation ability [13]. This not only ensures a harder, fast neutron spectrum and a larger breeding ratio but also allows for a larger pitch design between the fuel elements, thereby reducing the possibility of flow channel blockage. In terms of safety, the chemical inertness of lead fundamentally avoids the risk of coolant-reactor instability. Combined with excellent heat transfer performance and natural circulation ability, even under extreme accident conditions, the system can still spontaneously suppress the temperature increase through passive heat conduction and negative feedback effects. Therefore, lead-cooled fast reactor technology provides an innovative path that combines economic efficiency and reliability for the large-scale and sustainable development of nuclear energy.

Lead cooling systems represent a core direction of fourth-generation nuclear energy technology [14], with a development trajectory spanning multi-dimensional breakthroughs in technical exploration, material innovation, and engineering practice. In the 1960s, the Soviet Union developed nuclear submarine power systems using LBE as a coolant, with the Alpha-class nuclear submarine serving as a representative example [15]. However, issues such as LBE's tendency to solidify, corrosion of in-core structures, and production of radioactive ^{210}Po led to the retirement of these submarines in the 1990s [16]. The United States has shifted to sodium-cooled technology due to corrosion challenges in stainless steel. In the 21st century, the application of ODS steel has overcome corrosion hurdles [17]. In 2002, LFRs were listed as one of the six candidate reactor types by the GIF, prompting renewed R&D efforts in China, Russia, Europe, the U.S. [18–20], and other regions. Currently, Russia is advancing the construction of the BREST-OD-300 pure lead-cooled demonstration reactor, designed for 300 MW electric power, with a planned criticality in 2027 [21,22]. China's CLEAR project focuses on a 125 MW modular lead-bismuth-cooled fast reactor,

achieving the industrial production of CLAM steel resistant to lead-bismuth corrosion, with an operational target of 2030 [23,24]. Europe's MYRRHA is a 100 MW thermal power lead-bismuth-cooled multipurpose research reactor integrating nuclear waste transmutation and material irradiation functions and is scheduled for commissioning in 2035 [25,26]. The U.S. The ^{100}Xe lead-cooled version incorporates TRISO fuel technology from high-temperature gas-cooled reactors, designed for 80 MW electric power with planned deployment in the early 2030s, forming a multipolar R&D landscape [27–30].

The development journey of LFRs from early applications to future nuclear energy systems has achieved remarkable advancements in technological progress and international cooperation, with broad development prospects. The GIF and the European lead-cooled system research network have formulated the Lead-Cooled Fast Reactor Design Safety Guidelines [31], unifying key safety standards, such as the requirement for passive residual heat removal capability to be maintained for at least 96 h. The commercialization roadmap shows that demonstration reactors in various countries will be commissioned successively between 2025 and 2030. From the 2030s, modular reactors will be gradually deployed at scale in scenarios such as power supply for island communities and heat supply for industrial parks. After 2040, they may be integrated with nuclear fusion technology to form a hybrid reactor model, which would further enhance the nuclear waste transmutation efficiency. With their passive safety design, efficient fuel cycle, and nuclear waste volume reduction capabilities, lead-cooled systems are poised to become a core pillar of the global low-carbon energy transition by the mid-21st century, providing sustainable solutions to address energy shortages and radioactive waste disposal challenges.

As an innovative technology representative of the fourth-generation nuclear energy system, the ADS integrates three key components in its core architecture: a high-energy proton accelerator, a heavy-metal spallation target, and a subcritical reactor [32–35]. The system uses Pb or LBE as the primary cooling medium. Its operating mechanism is based on high-energy proton beams (0.8–1.6 GeV) generated by an external accelerator that bombards heavy-metal targets, such as tungsten or lead, producing broad-spectrum neutrons with a peak energy of approximately 2 MeV through spallation reactions. These externally sourced neutrons are injected into a subcritical core with an effective multiplication factor of 0.95–0.98, driving controlled fission reactions in the nuclear fuel and enabling sustained energy output. Through physical mechanism design, this technology achieves dual breakthroughs in enhancing the inherent reactor safety and nuclear waste transmutation capabilities. ADS holds significant strategic importance, and its commercialization will reshape the nuclear energy industry landscape: it can reduce global high-level radioactive waste from spent fuel by 95% while increasing uranium resource utilization from 1% to over 60%. When extended to thorium-based fuels, its resource support capacity can reach the millennium scale. Modular ADS can also be deployed in off-grid areas, such as islands and polar regions, to meet energy demands in specific scenarios. With the advancement of projects like China's CiADS [36,37] and Europe's MYRRHA, ADS is expected to enter the engineering demonstration phase in the 2030s and gradually achieve commercialization after 2040, providing an ultimate solution for energy transition under low-carbon goals.

Globally, multiple facilities dedicated to leading technology research have been established, providing the scientific community with a full-chain research platform spanning material characteristics, thermal hydraulics, and system integration. The core facilities and functions are as follows: China has achieved notable results in lead-bismuth technology research facilities. The KYLIN-II loop [38] at the Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, is the world's largest liquid lead-bismuth experimental platform, capable of multi-functional research, including material corrosion, thermal-hydraulic testing, and safety experiments. It is open to domestic and international

users through a major national science and technology infrastructure project. The Venus-II zero-power reactor at the China Institute of Atomic Energy is the world's first zero-power reactor of its kind, supporting core physics research through a national nuclear facility-sharing platform [39–41]. Europe is characterized by interdisciplinary and collaborative facilities. The MYRRHA research facility at SCK-CEN, as an ADS prototype, integrates an accelerator and subcritical reactor and is open via the EU Horizon program to focus on nuclear waste transmutation and material irradiation research [42]. Russia focuses on closed fuel cycles and extreme-environment applications. The BREST-OD-300 lead-cooled fast reactor at the Siberian Chemical Combine is open for cooperation under the Belt and Road Initiative and verifies closed-cycle technologies for efficient uranium resource utilization. The SVBR-100 lead-bismuth fast reactor [43,44], a modular design suitable for polar regions, is open through BRICS cooperation mechanisms to test material performance in extreme environments. Additionally, international platforms such as China's National Research Facility Management Platform, the European Open Science Cloud (EOSC), and International Atomic Energy Agency (IAEA) cooperation programs further integrate cross-institutional resources and provide access channels. These facilities cover the entire process from basic material research to engineering system integration, driving global collaborative innovation and sustainable development in leading technology.

The core design of lead-cooled fast reactors is of great significance. An optimized design can promote the engineering and commercialization of lead-cooled fast reactors, improve their operational performance and safety, reduce costs, and enhance market competitiveness. It can also boost the development of disciplines such as materials science and neutron physics and provide theoretical support for the innovation of nuclear energy technology. Against the backdrop of the global energy transition and efforts to address climate change, lead-cooled fast reactors, as a clean and low-carbon energy technology, play a crucial role in achieving carbon neutrality and promoting the transformation of the energy structure. The core design of lead-cooled fast reactors involves several key elements. This paper focuses on five aspects: the selection of nuclear fuel, coolant materials, cladding and structural materials, and the structural design of assemblies and core arrangement. This study reviews the research progress on the core design of lead-cooled fast reactors, analyzes the impact of various factors on core performance, and provides a reference for the design, research, and development of lead-cooled fast reactor cores.

2. Selection of Nuclear Fuel

In lead-cooled fast reactors, the selection of nuclear fuel plays a crucial and decisive role in the operating characteristics, safety, and economic efficiency of the reactor. This section introduces the common types and characteristics of nuclear fuels and analyzes the factors influencing the selection of nuclear fuels.

2.1. Common Types and Characteristics of Nuclear Fuel

This section classifies nuclear fuels based on the types of compounds of fission heavy nuclei and the types of fission heavy nuclei themselves and analyzes the characteristics of each type of fuel.

2.1.1. Classification by Compounds of Fission Heavy Nuclei

Nuclear fuels can be classified according to the compounds of fission heavy nuclei into four types: oxide fuels [45], carbide fuels [46], nitride fuels [47], and metallic fuels [48]. Table 1 lists the material properties of these four types of fuels [49]. Oxide fuels are currently the most widely used, with the most mature technology and the richest experience, and they are preferred nuclear fuels for various reactors. However, the thermal conductivity of oxide

fuels is significantly lower than that of the other three fuel types. Carbide fuels have high thermal conductivity, a flatter temperature gradient than oxides, and better compatibility with lead/lead-bismuth. However, they produce a large amount of fission gas products, leading to fuel expansion. Nitride fuels have the highest thermal conductivity and melting point, good neutron economy, and high thermo-hydraulic safety characteristics and are currently considered to be better accident-tolerant fuels. However, they involve nitrogen purification technology, lack manufacturing experience, and are still in the research stage. Metallic fuels have good thermal conductivity and corrosion resistance, can withstand stress, achieve a harder neutron energy spectrum, and increase the breeding ratio of nuclear fuels. However, they have low melting points and poor irradiation stability. Uranium-containing fuels require highly enriched uranium, which is not conducive to preventing nuclear breeding. In addition, when metallic fuel reactors operate at low power, there are large fluctuations in reactivity during burnup. Considering the performance in all aspects, nitride fuels are more consistent with the fuel performance requirements of small modular lead-cooled fast reactors.

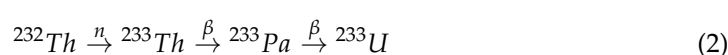
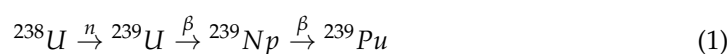
Table 1. Material properties of the four types of fuel [49].

Physical Parameters	Oxide Fuel	Carbide Fuel	Nitride Fuel	Metallic Fuel
Density, g/cm ³	10.28	12.18	12.92	14.17
Melting point, K	3000	2575	3035	1350
Thermal conductivity, W/(m·K)	2.3	20	26	16
Thermal expansion coefficient, K ^{−1}	1.2×10^{-5}	1.2×10^{-5}	1.0×10^{-5}	1.7×10^{-5}
Heat capacity, J/(g·K)	34	26	26	17

2.1.2. Classification by Fission Heavy Nuclei

Uranium metal is one of the earliest nuclear fuels [50]. In terms of fission characteristics, ²³⁵U in uranium metal is a fissile nuclide that can undergo fission under the action of neutrons, releasing a large amount of energy. Transuranic elements are also an important assembly of nuclear fuels in lead-cooled fast reactors [51]. Transuranic elements refer to elements with atomic numbers greater than 92, such as plutonium (Pu), neptunium (Np), and americium (Am). Most of these elements are radioactive, and their half-lives vary. In terms of fission characteristics, some nuclides among transuranic elements, such as ²³⁹Pu, exhibit good fission performance. Their fission cross-sections are relatively large, enabling them to efficiently undergo fission reactions under the action of fast neutrons and to release a large amount of energy. However, the use of transuranic elements also faces many challenges [52]. The separation and purification technologies for transuranic elements are complex and costly. Most of these are highly radioactive and toxic, posing significant potential hazards to the human body and environment.

The core fuel cycle breeding strategies mainly include two types: the U-Pu [53] and Th-U cycles [54].



The former realizes fuel breeding by converting ²³⁸U to ²³⁹Pu, and the latter achieves fuel breeding by converting ²³²Th to ²³³U. Based on this, fuels are classified into four categories according to the composition of the fission-heavy nuclei in the fuel: the U series, the U-Pu series, the Th-U series, and the Th-Pu series. Liu Zijing et al. [55] analyzed and compared the performances of four kinds of fuels, namely UO₂, MO_x (PuO₂-UO₂), UO₂-ThO₂, and PuO₂-ThO₂. The results show that in a relatively soft energy spectrum, the Th-based fuel core has a stronger breeding capacity, larger negative reactivity coefficient, greater

thermo-hydraulic safety margin, and stronger fission product retention ability. Further research revealed that the PuN-ThN fuel has the best core burnup characteristics among the Th-based fuels. It can obtain a strong breeding capacity under relatively loose lattice conditions, reduce the fuel loading amount, ensure inherent safety, and take into account the design requirements of long core life, miniaturization, and natural circulation [56–59]. However, the effective delayed neutron fraction of the core is relatively small, which is not conducive to reactivity control.

2.1.3. Classification by Inert Matrix Fuel

Inert matrix fuels for lead-cooled fast reactors (LFRs) provide a new pathway for nuclear energy utilization and nuclide transmutation in high-temperature and high-radiation environments through a composite structure of non-fissile inert carriers and fissile nuclides, comprising three main systems [8,60–64]. Table 2 shows the characteristics of inert matrix fuels.

Table 2. Characteristics of inert matrix fuels.

Type of Fuel	Material Components	Core Advantages	Key Challenges
cercer	- Inert matrix: MgO/Al₂O₃/ZrO₂ - Fission phase: UO₂/PuO₂	- High melting point - Excellent chemical stability - Controllable transmutation efficiency	- Thermal expansion coefficient mismatch - It is necessary to introduce a transition layer to alleviate cracking.
cermet	- Metal matrix: W/Mo/Fe-Cr-Al - Ceramic fission phase: UC/UN	- High thermal conductivity - Strong retention ability of fission gas	- High-temperature interfacial reactions - Degradation of high-temperature mechanical properties of metal phase
metmet	- Refractory alloy: W-Mo matrix; Pu-Zr fission phase - Functionally graded material: Pu-Zr/W-Mo/FeCrAl gradient structure	- Extreme high-temperature stability - Strong stress dispersion ability	- The preparation process is complicated - The interface bonding strength is insufficient

The first category is cercer, which uses high-temperature-resistant ceramics such as MgO, Al₂O₃, and ZrO₂ as inert matrices to support fissile nuclides like UO₂ and PuO₂, forming composite fuel pellets. These materials exhibit high melting points—for example, the MgO matrix melts at 2852 °C—making them more adaptable to the high-temperature conditions of LFRs than traditional fuels. Additionally, by regulating the loading ratio of PuO₂, the transmutation efficiency of the minor actinides can be controlled. For instance, the MgO-UO₂ system developed by France’s Cadarache Laboratory achieves a 30% increase in the minor actinide transmutation rate under specific irradiation doses compared to traditional fuels. However, current challenges include addressing the mismatch in the thermal expansion coefficients between the matrix and fission phases, which can be mitigated by introducing transition layers to reduce the risk of irradiation-induced cracking.

The second category is cermets, which use metals such as W, Mo, and Fe-Cr-Al as the matrix combined with ceramic fission phases like UC and UN. These materials integrate the high thermal conductivity of metals with the corrosion resistance of ceramics. The thermal

conductivity of W-based cermets is approximately 170 W/m·K, which is more than 10 times that of traditional UO₂ fuel, allowing for higher linear power densities. They also exhibit a significant adsorption capacity for gaseous fission products. For example, the Fe-Cr-Al/UN system developed by the U.S. The Argonne National Laboratory (ANL) showed a fuel swelling rate of less than 2% under irradiation at 1200 °C. However, interfacial reactions between the metallic and ceramic phases at high temperatures, such as the formation of W₂C from W and UC, remain key challenges that restrict their engineering applications.

The third category is metmet, which achieves performance synergy through bimetallic composite structures. For example, refractory metal alloy matrices like W-Mo support Pu-Zr alloy fission phases, leveraging W's high melting point and Mo's irradiation-resistant toughness to maintain structural integrity at 1500 °C. Functionally graded materials adopt compositional gradient designs—such as Pu-Zr, W-Mo, and Fe-Cr-Al layers sequentially arranged from the fuel core to the cladding—which can reduce thermal stress by over 40%. However, the fabrication processes for these materials, such as powder metallurgy, hot isostatic pressing, and vapor deposition, are highly complex and remain in the conceptual design phase.

The current core development directions for inert matrix fuels focus on multi-physics coupling design, establishing cross-scale models through the integration of first-principles calculations and experimental characterization to achieve precise regulation of fuel performance, introducing advanced manufacturing technologies such as selective laser melting and atomic layer deposition for the controlled fabrication of complex structures, and developing multi-dimensional compatibility evaluation systems covering high-temperature mechanical properties, irradiation damage mechanisms, and corrosion behavior. Breakthroughs in these areas will provide safer and more efficient fuel solutions for ADS, and synergistic optimization with LBE coolants is expected to propel nuclear energy toward the ultimate form of closed fuel cycles with minimal radioactive waste.

2.2. Influencing Factors of Nuclear Fuel Selection

The selection of nuclear fuel, which is a key scientific issue in nuclear energy system engineering, requires careful consideration of various factors, such as nuclear reaction characteristics, breeding performance, fuel cycle, and cost-effectiveness. From the perspective of neutron physics, fissile nuclides such as ²³⁵U and ²³⁹Pu undergo fission after absorbing neutrons and releasing additional neutrons to maintain the chain reaction. The content and distribution of fissile nuclides in nuclear fuel must ensure the generation of sufficient neutrons to maintain stable reactor operation. Therefore, the neutron absorption cross-section of nuclear fuel should not be too large so as not to reduce the neutron utilization rate. In terms of breeding performance, fast reactors can achieve nuclear fuel breeding; that is, more fissile nuclides are produced than are consumed. The breeding performance of nuclear fuel depends on factors such as the content of convertible nuclides, the neutron energy spectrum of the reactor, and the distribution of neutron flux. The breeding ratio of fast reactors can be increased by optimizing the loading ratio of convertible nuclides. The technical complexity of the fuel cycle system is reflected in the management of radioactive substances during reprocessing. The difficulty of reprocessing spent fuel varies significantly for different nuclear fuels. For example, the reprocessing of metallic uranium fuel is relatively simple, while the reprocessing of ceramic fuel is more difficult. In addition, the safety and long-term storage of nuclear waste must be considered. The key challenge of a closed fuel cycle lies in the efficient separation and transmutation of actinides, which involves the integration of multidisciplinary technologies, such as radiation protection and material corrosion. In terms of cost-effectiveness, the cost of nuclear fuel covers various aspects, such as raw materials, processing, transportation, and reprocessing. The cost of

raw materials is related to the natural abundance and acquisition difficulty of nuclides, and the processing cost is related to the preparation process and processing difficulty. When making a selection, it is necessary to comprehensively consider the cost factors and the impact of the performance of nuclear fuel on the economic operation of the reactor.

3. Selection of the Coolant

Lead-based cooling materials mainly include two types: liquid lead and liquid lead-bismuth eutectic (45% Pb and 55% Bi). This section introduces the material properties of lead-based coolants. On this basis, the relevant technical problems of lead-based coolants and the research progress of the solutions are sorted.

3.1. Characteristics of Lead-Based Coolants

Lead and lead-bismuth eutectics exhibit unique physical properties when used as coolants in lead-cooled fast reactors, and these properties have a profound impact on the thermohydraulic and neutronic performance of the reactor. In order to fully demonstrate the characteristics of liquid metals, sodium is also used as a comparison object. Table 3 lists the material properties of the liquid metals [65].

Table 3. Properties of liquid metal coolants [65].

Physical Parameters	Lead	Lead-Bismuth Eutectic (LBE)	Sodium
Absorption cross-section, 10^{-28} m^2	0.17	0.0946	0.530
Moderating power, m^{-1}	3.48×10^{-5}	2.88×10^{-5}	8.62×10^{-5}
Moderating ratio	0.58	1.58	0.66
Melting point, $^{\circ}\text{C}$	327.5	125	98
Boiling point, $^{\circ}\text{C}$	1750	1670	883
Density, kg/m^3	10,480	10,150	847
Heat capacity, $\text{kJ}/(\text{kg}\cdot\text{K})$	0.15	0.15	1.3
Thermal conductivity, $\text{W}/(\text{m}\cdot\text{K})$	16	13	70
Thermal expansion coefficient, $10^{-6}/\text{K}$	108	123	71

A comparison of the physical properties of lead and lead-bismuth eutectic reveals significant differences between the two in terms of neutronics, thermodynamics, and thermophysical properties. In terms of neutronic performance, the neutron absorption cross-section of lead is 44% higher than that of the lead-bismuth eutectic, indicating that the latter has a lower neutron absorption rate and is more conducive to maintaining the neutron economy of the reactor. Regarding thermodynamic properties, the melting point of the lead-bismuth eutectic is 62% lower than that of lead, which significantly shortens the preheating time for reactor startup and reduces the probability of coolant solidification. Although the boiling point of liquid lead is higher than that of the lead-bismuth eutectic, it is difficult for the coolant temperature in the reactor core to reach such a level. The thermal conductivity of lead is 23% higher than that of the lead-bismuth eutectic, which is beneficial for heat transfer in the core. The coefficient of thermal expansion of the lead-bismuth eutectic is 14% higher than that of lead, which is conducive to the natural circulation of the coolant.

Compared with the lead-bismuth eutectic, liquid lead, as a coolant, has a lower generation rate of ^{210}Po , weaker corrosion effect, and lower cost [66,67]. In a neutron irradiation environment, the generation rate of the highly radioactive and toxic substance ^{210}Po in the lead system is 2 to 3 orders of magnitude lower than that in the lead-bismuth eutectic. This characteristic can effectively improve the operational safety of the reactor and reduce the difficulty of its operation and maintenance. From the analysis of the material corrosion mechanism, the dissolution rates of elements such as Fe, Cr, and Ni in lead are

lower than those in bismuth. Under the same temperature and flow rate conditions, the corrosion effect exhibited by lead was significantly weaker than that of the lead-bismuth eutectic. In terms of economic cost, the price of bismuth is approximately 10 times that of lead. This cost difference significantly reduces the construction cost of a lead-cooled reactor compared to that of a lead-bismuth reactor.

Overall, the lead-bismuth eutectic performs better in terms of neutron absorption, moderating ratio, and startup flexibility. However, considering the generation of radioactive poisons, corrosion effect, and economic efficiency of the material, lead is more suitable than the lead-bismuth eutectic as a coolant for lead-cooled fast reactors. However, the material technology is not sufficiently mature. To achieve a large coolant temperature difference and take into account issues such as coolant solidification, lead-bismuth eutectic remains the mainstream choice as the coolant for lead-cooled fast reactors. Nevertheless, with the continuous development of material technology, the coolant will definitely transition from the lead-bismuth eutectic to liquid pure lead.

Compared with sodium, lead exhibits low chemical reactivity, a high boiling point, and excellent thermal expansion properties. From a chemical perspective, the chemical reactivity of lead is significantly lower than that of sodium; it does not readily undergo violent chemical reactions when it comes into contact with water or air at room temperature. This feature theoretically eliminates potential sodium fire hazards in sodium-cooled systems, thereby significantly enhancing reactor operational safety. In terms of thermal-hydraulic performance, lead has a significantly higher boiling point than sodium. This advantage not only avoids core uncovering issues caused by coolant boiling but also effectively mitigates the risk of core void insertion accidents that may occur in sodium-cooled fast reactors. Additionally, the higher coefficient of thermal expansion of Pb enhances the natural circulation driving force in the primary circuit of the reactor. This natural circulation capability, based on thermal expansion effects, endows the reactor with superior passive safety characteristics, enabling more reliable heat removal under passive operating conditions.

The positive reactivity void coefficient refers to the phenomenon in which coolant vaporization increases the core temperature and triggers positive power feedback, which is a recognized technical challenge in fast-neutron-spectrum reactor design [68,69]. Sodium-cooled fast reactors have a lower boiling point for their coolant, making significant positive feedback more likely under overheating conditions. In contrast, lead-cooled fast reactors using LBE coolant exhibit nearly no void effect under normal operating conditions, although local phase change risks may still exist in extreme accidents. Lead has weak neutron moderation capability and a low absorption cross-section, resulting in an absolute void coefficient value smaller than that of sodium. During severe accidents, the low melting point and fluidity of sodium may exacerbate the risk of molten fuel migration, while the high density of lead can promote passive dispersion of fuel, reducing the probability of recriticality. SMRs mitigate risks through a triple mechanism: a compact core design that enhances neutron leakage to weaken positive feedback, a modular design that keeps fuel loading below critical thresholds, and passive systems that suppress temperature transients. Lead-cooled SMRs demonstrate outstanding advantages in terms of chemical stability and thermal safety; however, the recriticality mechanisms of large commercial reactors during molten fuel migration phases require in-depth study. In the future, it will be necessary to establish a dedicated accident analysis framework for lead-cooled reactors, focusing on multi-physics field coupling simulations and experimental validation of molten fuel-coolant interactions to improve safety evaluation systems.

The transient kinetic characteristics of liquid-metal-cooled fast reactors are closely related to the coolant type [70]. For reactors using lead-based coolants (such as lead or lead-bismuth eutectic alloys) and sodium-based coolants (such as NaK or pure sodium), the differences

primarily manifest in two key parameters: the Doppler coefficient and neutron lifetime. The Doppler coefficient characterizes the feedback capability of fuel temperature changes on reactivity as the fuel temperature reactivity coefficient. Because sodium has an atomic mass of 23, which is significantly smaller than lead's 207, the neutron energy spectrum in sodium-based reactors is relatively softened with a higher proportion of epithermal neutrons, enhancing the resonance absorption effect of uranium/plutonium isotopes in fuels like UO_2 and MOX. Therefore, the absolute value of the Doppler coefficient in sodium-based reactors is typically -0.8 to -1.2 pcm/K, which is larger than that in lead-based reactors (-0.3 to -0.5 pcm/K). This implies that during sudden power surges, sodium-based reactors can suppress reactivity disturbances more rapidly through stronger negative feedback. In contrast, lead-based reactors use high-enrichment fuels like Pu-239 and closed fuel cycle designs, resulting in relatively weaker Doppler effects. They must rely on passive mechanisms, such as coolant thermal expansion or core geometric deformation, to compensate for transient safety requirements.

As the average neutron generation time, the neutron lifetime directly affects the dynamic speed of the transient response [71,72]. In lead-based reactors, the high-density lead hardly moderates neutrons, maintaining an extremely hard, fast neutron energy spectrum with an extremely short neutron lifetime (approximately 1×10^{-6} s), causing a surge in power changes in milliseconds. This imposes stringent requirements on the response speed of control systems and the timeliness of the feedback mechanisms. In sodium-based reactors, due to the slight moderating effect of sodium, the neutron energy spectrum is slightly softer with a slightly longer neutron lifetime (approximately 3×10^{-6} s), which slows the transient development rate and provides more reaction time for mechanisms like Doppler feedback. This difference is particularly significant for loss-of-flow accidents. Sodium-based reactors may experience positive void reactivity due to coolant loss; however, their stronger Doppler feedback and slightly longer transient window can partially offset the risk of sudden power surges. Although lead-based reactors exhibit negative void effects due to the high density of lead, their weaker fuel temperature feedback and extremely short neutron lifetime require core designs to enhance leakage feedback through compact geometric configurations and other means to ensure safety margins.

From a design trade-off perspective, sodium-based reactors theoretically excel in transient self-stability due to their superior Doppler feedback and neutron lifetime matching [73]. However, they must address the engineering challenges arising from the violent reactivity of sodium with water and air. Conversely, lead-based reactors simplify safety system design through inert coolant characteristics, making them more suitable for long-cycle high-power operation, although their transient safety relies more on collaborative optimization of multi-physics coupling feedback. Both reactor types must integrate non-Doppler mechanisms, such as coolant density effects and fuel expansion feedback, to construct multi-dimensional transient safety barriers. Future research should further quantify the nonlinear effects of neutron spectrum hardening on fuel temperature feedback and explore collaborative optimization pathways between the control strategies and material performance.

3.2. Technical Problems Related to Lead-Based Coolants and the Progress of Solutions

As the core heat transfer working medium of fourth-generation nuclear reactors, the engineering application of lead-based coolants faces multiple technical challenges [74].

In the field of corrosion and protection of structural materials, ferritic steel T91 exhibits selective dissolution-deposition behavior of Fe, Cr, and Ni under working conditions of 500 – 700 °C [74,75]. Austenitic stainless steel 316 L [74] shows a significant reduction in fracture toughness under the coupled action of stress and a liquid lead-based eutectic. Surface modification technologies have demonstrated remarkable protective effects in response to such material failure problems. Laser cladding of metal coatings can effectively

reduce the corrosion rate of materials, and the resistance of martensitic steel subjected to nanocrystallization treatment to liquid-metal corrosion is significantly improved. In addition, an oxygen concentration regulation strategy based on precise control technology can promote the formation of a dense oxide film on the material surface, effectively inhibiting the corrosion process [76].

The stability of the oxygen control system is the key technical bottleneck restricting the engineering applications of lead-based reactors. The oxygen solubility in liquid lead-based alloys is significantly temperature-sensitive, and even slight temperature fluctuations can lead to significant changes in the oxygen concentration. In addition, compounds formed by the combination of radioactive isotopes and oxygen can cause sensor signal drift. Innovative achievements have been made in coolant oxygen control in recent years. The new solid-state oxygen pump technology enables the linear adjustment of oxygen flux [77], and multi-parameter coupling control technology has significantly improved the accuracy of dynamic regulation [78].

In terms of radionuclide management and control, the diffusion of the radioactive isotope ^{210}Po and the deposition of activation products pose the main risks. There are two main targeted protection strategies: multi-stage molecular sieve adsorption technology and electromagnetic separation technology, which can achieve the efficient removal of radioactive substances.

These innovative achievements have significantly enhanced the reliability and safety of lead-based coolant systems, laying a solid foundation for the commercialization of fourth-generation nuclear energy systems. Future research should focus on optimizing material properties, reducing operation and maintenance costs, and collaborating with advanced nuclear energy technologies. This aims to break through bottlenecks, such as the low utilization rate of traditional nuclear power resources and the difficulty of nuclear waste disposal, and contribute to the sustainable development of a clean energy system.

4. Selection of Other Materials

In addition to the nuclear fuel and coolant materials, the main materials involved in the core of a lead-cooled fast reactor include fuel cladding, core structural materials, control materials, absorbing materials, reflecting materials, and shielding materials. This section analyzes the selection and characteristics of these materials.

4.1. Fuel Cladding and Core Structural Materials

In the selection of structural materials for lead-cooled fast reactors, ferritic/martensitic steels, austenitic steels, and ceramic materials are the main candidate materials, each of which has unique performance characteristics. Table 4 lists their advantages, limitations, and applicable scenarios [79–82].

Table 4. Properties of the lead-based coolant.

Material Type	Advantages	Disadvantages	Applicable Scenarios
Ferritic/Martensitic Steel	Excellent resistance to irradiation swelling, good toughness, and stable thermophysical properties.	The problem of liquid metal corrosion is significant.	Medium-high temperature ($\geq 450\text{ }^{\circ}\text{C}$), intense irradiation environment.
Austenitic steel	It has good corrosion resistance, excellent cold-working performance, and good high-temperature stability.	The dissolution corrosion is severe, and the liquid metal embrittlement phenomenon is prominent at low temperatures.	Medium temperature ($450\text{--}600\text{ }^{\circ}\text{C}$).
Ceramic material	It has excellent high-temperature stability, stable chemical properties, high strength, and good wear and corrosion resistance.	It has poor toughness and high processing difficulty.	High-temperature ($\geq 600\text{ }^{\circ}\text{C}$), strong-corrosion environment.

Ferritic/martensitic steel, austenitic steel, and ceramic materials each have unique performance characteristics and applicable scenarios. Ferritic/martensitic steel, with its excellent resistance to irradiation swelling, good toughness, and thermal physical stability, has become the preferred material for medium-high temperature and strong-irradiation environments. Typical applications include structural materials for nuclear reactors and high-temperature steam pipelines. However, the problem of liquid metal corrosion of ferritic/martensitic steel needs to be addressed using anti-corrosion technologies. Austenitic steel has advantages in the medium-temperature field. Its corrosion resistance, cold working performance, and high-temperature stability make it widely used in heat exchangers. However, high-temperature dissolution corrosion and low-temperature metal embrittlement limit its use under extreme conditions. Ceramic materials, with the highest service temperature, chemical inertness, and ultra-high hardness, are ideal for extreme working conditions and are suitable for nuclear fuel cladding. However, their intrinsic brittleness and processing difficulties must be optimized using composite toughening technologies. From a comprehensive performance comparison, ceramic materials perform the best in terms of temperature adaptability and corrosion resistance, austenitic steel has an advantage in mechanical properties, and ferritic/martensitic steel is irreplaceable in irradiation environments. In engineering practice, ferritic/martensitic steel is preferentially selected for high-temperature and strong irradiation scenarios, austenitic steel is recommended for medium-temperature and corrosion-resistant environments, and ceramic matrix composites are essential for ultra-high-temperature/strong corrosion working conditions.

4.2. Control Materials and Absorbing Materials

The materials currently selected as control/absorber materials are mainly Gd_2O_3 , B_4C , HfO_2 , Dy_2O_3 , and liquid Li.

Gd_2O_3 is widely used as a burnable poison in traditional pressurized water reactors. However, its fast neutron absorption cross-section is relatively small; therefore, in fast neutron reactors, it is only used as a burnable poison for initial reactivity control. B_4C is a commonly used absorbing material in fast reactors and can also be used as a shielding material. In the control bodies controlled by control drums, the absorbing material on the surface of the drum usually uses B_4C . However, B_4C expands after being irradiated, and its service life is only a few effective full-power years. A mixture of HfO_2 and Dy_2O_3 can also be used as an absorption material. Compared with B_4C , this neutron absorber does not generate gas, has a high density, long service life, strong neutron absorption ability, can withstand a high temperature of 2600 °C, and has excellent irradiation stability and compatibility with the lead environment. However, due to the scarcity of resources, it is only suitable for specific scenarios.

In the conceptual design of the core of the SPARK, series lead-cooled fast reactors [80], highly enriched liquid metal Li is used as an absorbing material. The melting and boiling points of lithium are 180.5 °C and 1330 °C, respectively, which are compatible with the operating temperature range of the lead-bismuth eutectic (LBE) used as the core coolant. However, using liquid-metal Li as the absorber can reduce the height of the core. When a solid control rod is completely withdrawn, an additional length equivalent to that of one fuel assembly must be reserved above the active zone of the core. However, when the liquid control material is completely pressed out of the assembly, there is no need to reserve an assembly height above the core. This is because when the volume of liquid Li is constant, the length can be reduced by increasing the cross-sectional area of the space for storing liquid Li. However, the reaction of $6Li$ with neutrons generates tritium, and the technology for tritium treatment is not yet mature. In addition, when liquid-metal Li is

used as the absorbing material, the drive mechanism is complex, and the technology is not yet mature.

4.3. Reflective Material

In the engineering design of fast-neutron reactors, the selection of reflector materials has a crucial impact on the neutron economy and core life. The current candidate material systems mainly include austenitic stainless steel, beryllium (Be), lead (Pb), and magnesium oxide (MgO).

The thermal neutron absorption capacity of austenitic stainless steel is relatively low, and the neutron reflection effect is limited. In small reactors, neutron leakage is a prominent problem. It is necessary to compensate for the insufficient reflection efficiency by increasing the thickness of the shielding layer, which will increase the volume of the core. Beryllium, with its low absorption cross-section and high scattering characteristics, can achieve a relatively high neutron reflection efficiency. However, this material has the technical bottleneck of uneven power distribution, which can be effectively improved by optimizing the geometric parameters of the reflector layer. As a new type of ceramic reflector material, magnesium oxide has both good neutron reflection ability and low-density characteristics, which can significantly extend the service life of the core. This material remains stable in high-temperature environments and exhibits excellent radiation resistance. Lead, with its high density, can achieve efficient neutron reflection and effectively shield high-energy radiation. However, the mechanical properties of lead degrade in a low-temperature irradiation environment, and its radiation resistance must be improved through material modification.

A comprehensive comparison shows that MgO stands out in terms of neutron reflection efficiency and structural lightweighting. Beryllium has the best neutron-moderation performance. Pb has significant advantages in radiation shielding, while stainless steel is still competitive in terms of engineering maturity.

4.4. Shielding Material

The application of shielding materials is relatively flexible and mainly includes B₄C, T91, Pb, and LBE. The characteristics of these materials are described in detail above. In some current design schemes, a reflector layer is directly arranged on the outermost periphery of the core, and a shielding layer is no longer required [83].

5. Design of Assembly Geometric Structure

The core of a lead-cooled fast reactor mainly comprises the following types of assemblies: fuel, control, support, shielding, and reflector assemblies. The fuel assembly is a key component of the core and is the main source of energy for the reactor. The control assembly plays a crucial role in lead-cooled fast reactors and is a key component in ensuring the safe and stable operation of the reactor. The support assembly is a key component for maintaining the structural stability of the core in lead-cooled fast reactors. It undertakes the important task of supporting core assemblies, such as the fuel and control assemblies, ensuring that these assemblies maintain the correct position and spacing within the core. The shielding and reflector assemblies play vital roles in radiation protection. They are mainly used to shield or reflect neutrons and shield gamma rays to protect personnel and equipment around the reactor from radiation hazards. The structures of the support, shielding, and reflector assemblies are relatively simple, consisting of structural materials enclosing support, shielding, or reflector materials. Therefore, this section focuses only on the geometric structure design of the fuel and control assemblies.

5.1. Geometric Structure Design of Fuel Assembly

5.1.1. Radial Geometric Structure Design of Fuel Assembly

In recent years, in the conceptual design schemes of the cores of small modular lead-cooled fast reactors, in addition to the use of traditional box-type fuel assembly [84], an open-type fuel assembly scheme has gradually attracted attention, and its geometric structure is shown in Figure 1b [85]. This assembly has no peripheral assembly box structure but is replaced by several support and positioning rods. The fuel assembly is arranged in an open-type square assembly mode, which can reduce the loading number of structural materials in the active zone of the core, make the core arrangement more compact, and effectively improve the neutron economy of the core. However, the open square assembly can reduce the flow resistance and increase the flow area, thereby further improving the natural circulation ability.

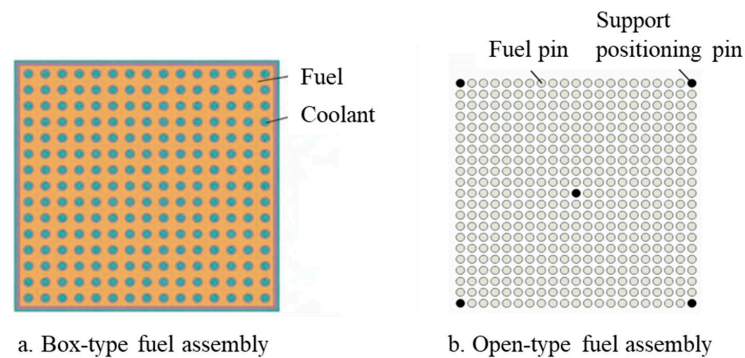


Figure 1. Geometric structures of box-type and open-type fuel assemblies [84,85].

According to the different radial structures of the fuel rods, the geometric structures of the fuel assembly can be divided into four types: rod bundle fuel assembly, annular fuel assembly [86], honeycomb-type fuel assembly [87], and spiral-cross fuel assembly [88]. The geometric structures are illustrated in Figure 2.

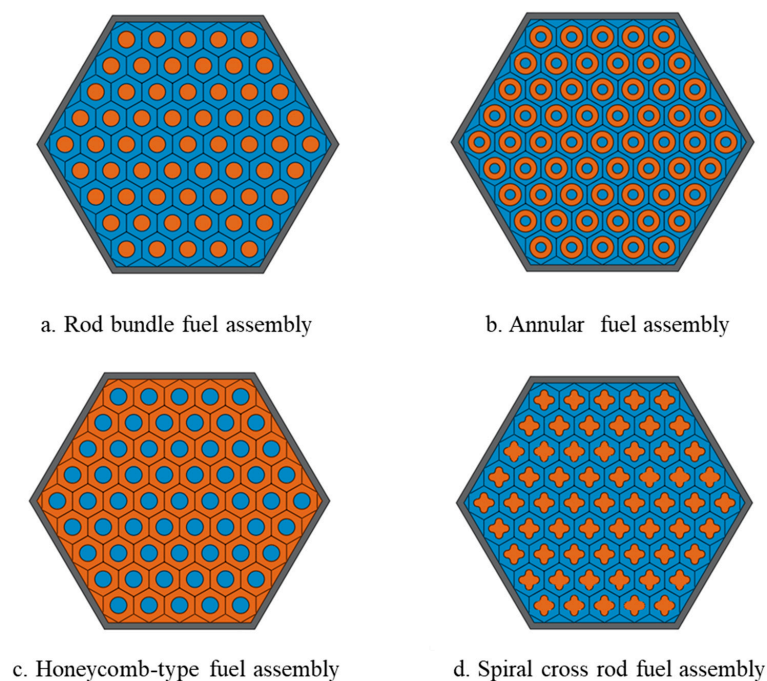


Figure 2. Geometric structures of the cross-sections of the four types of fuel assemblies.

Rod-bundle-type fuel assemblies are widely used in pressurized water reactors and liquid-metal-cooled fast reactors, with mature technology and rich operational experience. The design of a hollow annular fuel assembly can effectively reduce the central temperature of the fuel pellets, accommodate the expansion of the fuel pellets caused by neutron irradiation and heat release, and alleviate the mechanical interaction between the pellets and cladding. The honeycomb-type fuel assembly changes the positions of the fuel and coolant, increasing the volume fraction of the fuel in the assembly, which is beneficial for increasing the nuclear fuel loading and reducing the core size. Compared with the rod-bundle type and annular fuel assemblies, the honeycomb-shaped fuel assembly has better steady-state neutronic characteristics. Using this assembly can reduce the coolant flow area to increase the initial keff of the core and the refueling cycle. The honeycomb-type fuel assembly can also reduce the pressure drop in the core and improve natural circulation. Therefore, the honeycomb-type assembly is conducive to the miniaturization and lightweighting of lead-bismuth reactors. A spiral cross- fuel assembly is proposed in response to the need for the fuel rods of the rod bundle-type fuel assembly to rely on wire wraps for positioning. Its spiral structure can be regarded as a variation of the wire wrap. The heat conduction of the spiral structure is better than that of the wire wrap, and the spiral structure does not form eddy currents. The spiral structure has a strong mixing effect on the coolant, weakening local hotspots, and the temperature and flow velocity fields show symmetric periodic changes along the winding direction of the spiral structure.

In the assembly, some fuel rods are arranged in a quadrilateral shape, as shown in Figure 1, and others are arranged in a triangular shape, as shown in Figure 2. The fuel assembly with a quadrilateral arrangement has a loose structure, which can restrain the flow velocity of the coolant, thereby slowing down the corrosion or erosion of the structural materials by the coolant. The fuel assembly with a triangular arrangement has a compact structure, which is beneficial for breeding fuel.

5.1.2. Axial Geometric Structure of Fuel Assembly

The general axial structure of the fuel assembly is shown in Figure 3 [80]. It is mainly composed of the upper and lower heads, upper and lower reflector layers, fuel active zone, and gas cavity for accommodating fission gases. The coolant flow channel runs through the entire assembly.

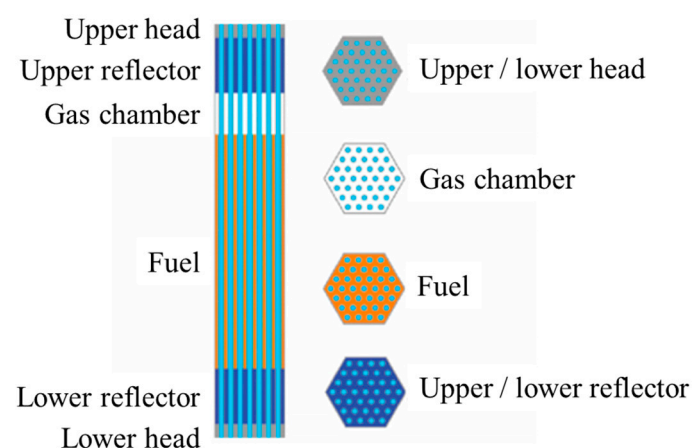


Figure 3. Geometric structure of the axial cross-section of the fuel assembly [80].

The core loading method designed based on the traveling wave burnup theory can achieve high-efficiency in-situ breeding-burnup of nuclear fuel obtain a relatively long burnup lifetime, and the reactivity fluctuation of the core is small. In this design, the fuel active zone comprises two parts: the ignition and breeding zones. The active zone uses

highly enriched fuel, and the breeding zone uses depleted or natural uranium to react with neutrons scattered from the ignition zone. Its burnup process is similar to “smoking”, and the ignition zone burns towards the breeding zone. Figure 4 shows an axial schematic of this fuel element [85].

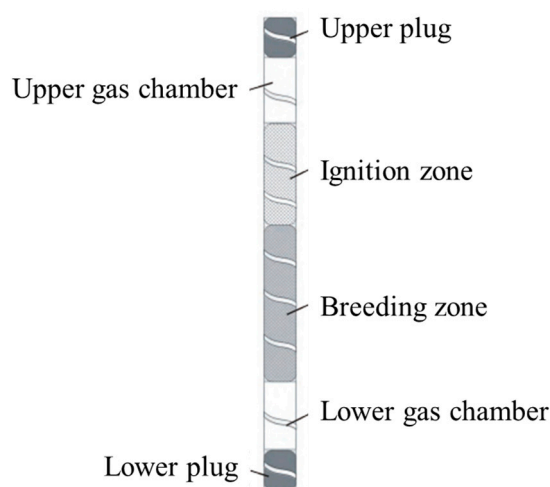


Figure 4. Structure of the fuel element with an axial arrangement in the active zone [85].

5.2. Geometric Structure of the Absorber/Control Assembly

Under normal circumstances, the control volume occupies a separate assembly space. Control volume assemblies can be divided into two types according to their different functions: burnup regulation assembly and emergency shutdown assembly. The former is used for the regulation and compensation of reactivity, while the latter is used for reactor shutdown in emergency situations. The materials of these two types of control assemblies are somewhat different, and the materials used in emergency shutdown assemblies have a stronger neutron absorption capacity.

The geometric structures of the control volume assemblies can be divided into three categories: solid control assembly, liquid control assembly, and control drum. The geometric structure of the solid control assembly is the same as that of the fuel assembly.

The structure of the liquid control assembly is illustrated in Figure 5 [89]. When the control assembly is in the state of being pushed out of the core, the liquid 6Li absorber is stored in the absorber retention area above the active zone of the core and is separated from the liquid 7Li driving liquid with an enrichment of 99.995% by a movable piston. At this time, the liquid 6Li absorber is located at the upper part of the active zone of the core, and the outer pipeline with an axial height corresponding to that of the active zone is filled with the liquid 7Li driver liquid. When the control assembly is pushed into the core, the movement of the piston in the center of the assembly pushes the liquid 6Li absorber into the outer pipeline, and its axial position is at the height of the active zone, thus realizing the control function.

The structure of the control drum is illustrated in Figure 6. Its main body is a cylinder that can rotate around the central axis, and a certain angle of the side surface of the cylinder is covered with an absorbing material. The control drums are often arranged on the periphery of the fuel assemblies, and the core is controlled by rotating the drums. When the absorbing materials are completely facing away from the center of the core, it is equivalent to all the solid control assemblies being withdrawn; similarly, when the absorbing materials are directly facing the center of the core, it is equivalent to all the solid control assemblies being inserted. The control drum can meet different control requirements by rotating at different angles. Since there is no rod withdrawal or rod insertion operation, the use of the control drum can reduce the required height in the axial direction of the core.

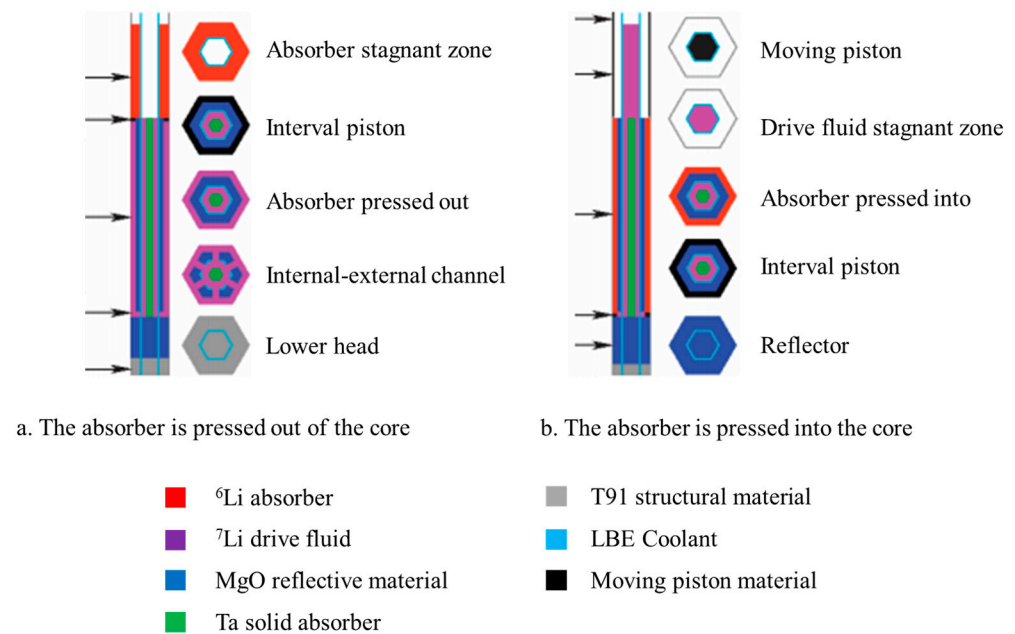


Figure 5. Structure of liquid control assembly [89].

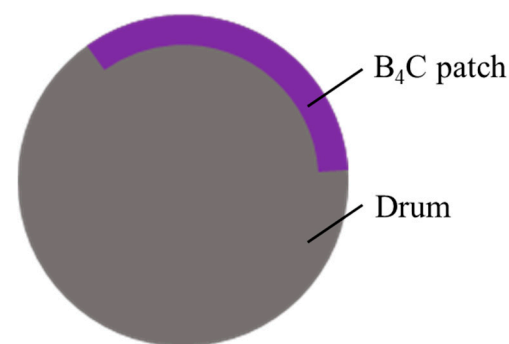


Figure 6. Cross-sectional structure of control drum.

6. Core Geometric Structure

6.1. Radial Cross-Section Geometric Structure of the Core

The core design under normal circumstances is shown in Figure 7 [90]. It is primarily composed of fuel assemblies, control assemblies, reflector layers, and shielding layers. Generally, the fuel assemblies are concentrated in the central position of the core, and the control assemblies are evenly distributed among them. A reflector layer is arranged around the fuel assemblies to scatter the neutrons flying outward and reduce the neutron leakage. A shielding layer is arranged around the reflector layer to shield high-energy rays and play a protective role.

In recent years, it has been proposed to arrange the control assemblies in the reflector layer area surrounding the fuel assemblies, as shown in Figure 8 [85]. When the control assemblies are arranged in the reflector layer area, the arrangement method and functional grouping are more flexible, and there are more positions where the control rod assemblies can be arranged. This does not affect the reactivity control capability of the core and can significantly reduce the technical difficulty of the core refueling process, reducing the influence or interference of the control rod assemblies on the refueling process. In addition, the control assemblies are removed from the core active zone, which can significantly reduce the structural material loading in the core active zone and make the core layout more compact.

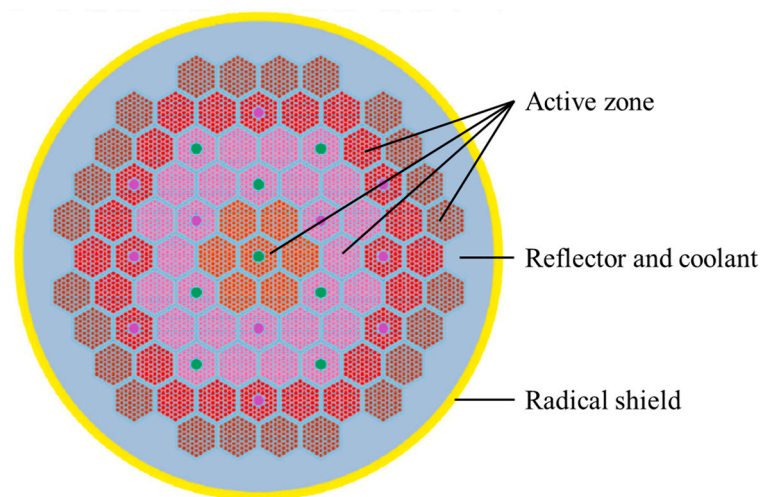


Figure 7. Radial cross-sectional structure of the core [90].

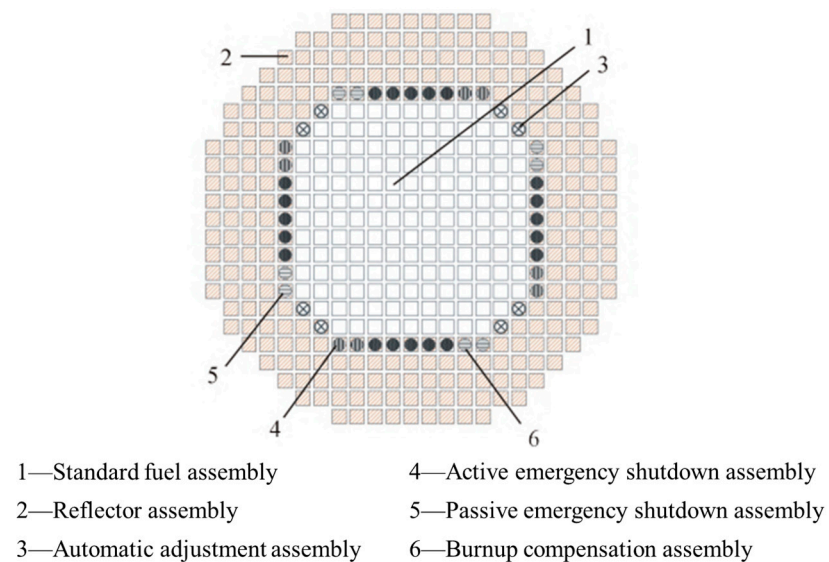


Figure 8. The control assemblies are arranged on the periphery of the fuel assemblies [85].

The control drums are arranged on the periphery of the fuel assemblies, as shown in Figure 9 [91]. Control drums do not occupy much space, have a compact structure, and cause little power disturbance; therefore, they are often used for the control of small reactors.

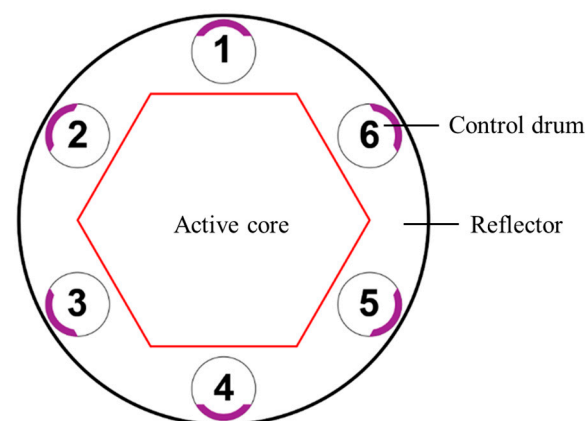


Figure 9. The radial structure of the core controlled by the control drums [91].

Not all conceptual design schemes of lead-cooled fast reactor cores will have both reflector and shielding layers simultaneously. In these designs, the two assemblies are combined into one and set as a reflector layer, as shown in Figures 8 and 9. In addition, in some designs, the coolant is directly used as a reflector or shielding layer. Lead (Pb) has a small neutron absorption cross-section. When used as the core reflector layer, it can not only improve the neutron economy of the core but also effectively shield high-energy γ rays [92].

The fuel assemblies in the core are typically arranged in zones to reduce the power peaking factor. Assuming that all the fuel assemblies in the core are the same, it is evident that the power peak in the central part of the core will be excessively high. To avoid this situation, two methods are commonly used. One is to reduce the enrichment of the fuel in the middle of the core, and the further away from the center, the higher the enrichment of the fuel in the area is. The other is to reduce the diameter of the fuel rods in the middle of the core, and the further away from the core, the larger the diameter of the fuel rods in the area. The first method is more widely used than the second method. The idea behind both methods is to reduce the heat generation in the middle of the core or to remove excessive heat using more coolant.

6.2. Geometric Structure of the Axial Cross-Section of the Core

The axial cross-sectional structure of the core was the same as that of the assembly, as shown in Figure 10 [39,52].

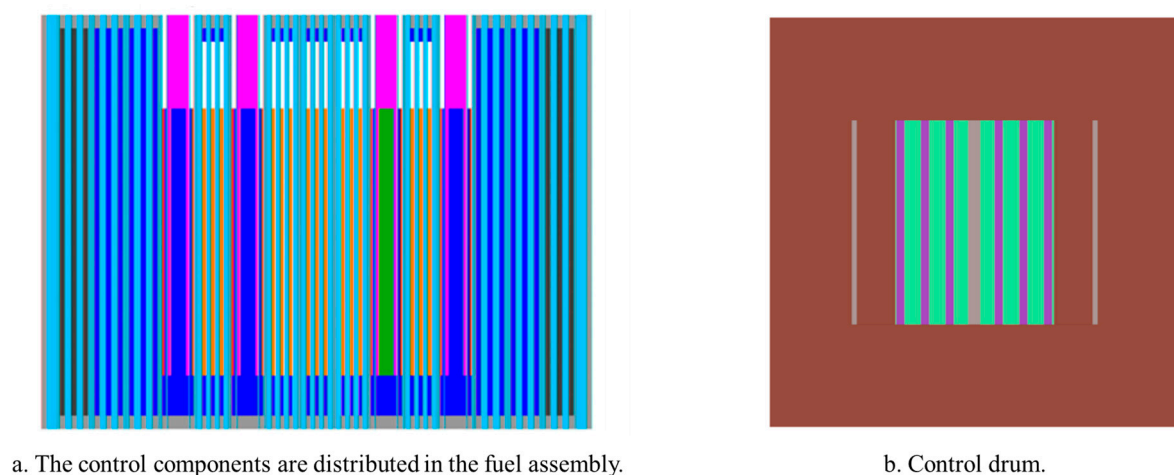


Figure 10. Axial cross-sectional structure of the core [80,93].

In the section on the geometric structure of the fuel assembly, an assembly design scheme based on the traveling wave burnup theory was mentioned. The fuel active zone is stratified axially. Then, considering the influence of the fuel being arranged radially in zones in the core, a new fuel distribution scheme can be formed, which is called the “onion-type” core. The axial cross-sectional structure is shown in Figure 11. Nguyen et al. [53] showed that the “onion” structure can flatten the power and extend the core life.

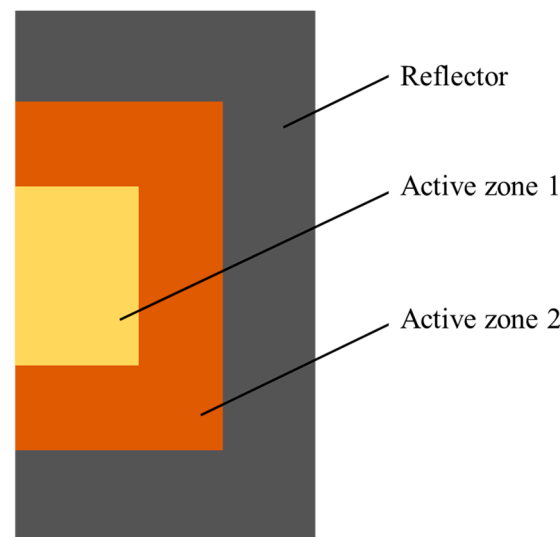


Figure 11. Axial cross-section of the “onion-type” core structure [94].

7. Summary and Prospect

As the core reactor type of the fourth-generation nuclear energy system, the lead-cooled fast reactor has made remarkable progress in the field of core design in recent years, further highlighting its inherent safety, efficient nuclear fuel transmutation capability, and economic benefits. In terms of nuclear fuel innovation, nitride fuels have become an ideal choice for small modular reactors due to their high thermal conductivity, high melting point, and neutron economy. The “onion-type” core design under the traveling wave burnup theory significantly extends the core lifespan and optimizes the power distribution through an in-situ breeding-burnup mechanism. Regarding coolant optimization, there is a trend of transitioning from lead-bismuth eutectics to pure lead. In the future, it is necessary to focus on solving the problems of the stability of the oxygen control system and the management and control of radioactive ^{210}Po . In the field of materials, ferritic/martensitic steels perform excellently in medium- and high-temperature irradiation environments, and ceramic matrix composites show potential under extreme working conditions. Combining surface modification technologies with oxygen concentration regulation strategies provides new ideas for solving the corrosion resistance problem. In terms of assembly and core design, innovative designs, such as open-type and honeycomb-type fuel assemblies, consider both neutron economy and natural circulation ability. The control drum technology greatly simplifies the core structure through non-intrusive control.

Despite significant technological advancements, the commercialization of lead-cooled fast reactors still faces multiple challenges. In materials science, it is necessary to overcome the technical bottlenecks of radiation resistance and liquid metal corrosion. Developing nanocrystalline steel ceramic-matrix composites and optimizing manufacturing processes to reduce costs are crucial. In the field of thermal safety, it is essential to further verify the dynamic oxygen control technology for liquid metals and the ^{210}Po protection system and establish a thermal-hydraulic model for all operating conditions to enhance the robustness of passive safety systems. Regarding core design, the compatibility of thorium-based fuels with the closed fuel cycle must be explored, and multi-physics-field coupling design tools must be developed to achieve a balance between performance and safety margins. At the international level, it is necessary to accumulate operating experience through transnational demonstration reactor projects and formulate unified design standards and safety criteria to accelerate technological iterations. In the future, lead-cooled fast reactors are expected to become a key carrier for the low-carbon energy transition in fields such as

base-load power supply, high-temperature hydrogen production, and ship power. They are also expected to provide clean energy solutions for carbon neutrality goals through technological breakthroughs and reshape the global nuclear energy technology landscape.

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