Design Status and Prospects of Small Multipurpose Pool-Type Research Reactors

Authors: Han Peng, Chen Xiaoliang, Zhu Jiyin, Zhu Jiachen, Xiaoliang Chen

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Abstract

Pool-type research reactors currently constitute a key reactor type among global multipurpose research reactors, having attracted considerable attention due to their outstanding performance in safety characteristics, versatility, and operation and maintenance. Among pool-type reactors, small research reactor designs with thermal power ranging from 1–10 MW are the most mature and enjoy the widest range of applications. Distinguished by fuel type, key cases of global small pool-type research reactors under construction and in operation that have implemented the RERTR (Reduced Enrichment Research and Test Reactor) low-enrichment program and undergone core redesign are introduced, specifically focusing on five fuel types: uranium oxide, uranium-aluminum, uranium-silicon, uranium-molybdenum alloy, and UZrH. Through comparative analysis and investigation, it is concluded that the future development trajectory for small pool-type research reactors will embrace compact core designs fueled by high-density low-enriched uranium, predicated on compact and transportable small cores, and centered on large-pool neutron source application facilities as the principal architecture.

Full Text

Preamble

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Design and Prospects of Small Multifunctional Pool-Type Research Reactors

HAN Peng, CHEN Xiaoliang, ZHU Jiyin, ZHU Jiachen

(Institute of Reactor Engineering and Technology, China Institute of Atomic Energy, Beijing 102413)

Abstract

Pool-type research reactors represent a key category among multi-purpose research reactors worldwide, attracting significant attention due to their outstanding safety characteristics, versatility, and operational maintainability. Among pool-type reactors, small research reactors with thermal power of 1–10 MW feature the most mature design approaches and the broadest range of applications. Based on the RERTR (Reduced Enrichment Research and Test Reactor) program and associated core redesign efforts, this paper categorizes global small pool-type research reactors according to five fuel types: U_3Si_2, UMo alloy, UZrH, UAl , and U_3O_8. Representative cases of small pool-type research reactors under construction or in operation worldwide are presented for each fuel type. Through horizontal comparative analysis, the study concludes that future small pool-type research reactors will adopt compact core designs utilizing high-density low-enriched uranium fuel, with development focused on compact, movable small cores as the foundation and large-pool neutron source application facilities as the primary architecture.

Keywords: Multifunctional; Pool-type research reactor; Compact reactor core; Dispersion fuel; UMo alloy

1. Current Status of Fuel Design for Small Pool-Type Research Reactors

Since the 1950s, global research reactors have experienced rapid development driven by advances in fuel technology and experimental research demands. Numerous high-enriched uranium (HEU) fuel reactors were constructed with neutron trap-type core designs, and reactor power increased to the megawatt level. Thermal neutron flux densities reached 10^{14}–10^{15} n/cm^2·s, primarily for transplutonium production, material testing, and various experimental studies, such as the Omega West Reactor (OWR) in the United States and China' s heavy water reactor [1]. Between 1978 and 1980, the International Nuclear Fuel Cycle Evaluation Conference mandated reducing fuel enrichment to 20% and initiated the Reduced Enrichment Research and Test Reactor (RERTR) program. Since its inception, 36 reactors have converted from HEU to low-enriched uranium (LEU) fuel. To enable widespread conversion without significantly reducing research capabilities, performance, or increasing operational costs—or requiring major component modifications—new LEU fuels must achieve higher densities [3]. Consequently, high-density LEU dispersion fuels such as U_3O_8-Al, UZrH, U_3Si_2-Al, and UMo-Al were subsequently developed and deployed. During conversion, reactor thermal power was increased and core structures and fuels were redesigned. This paper focuses on investigating and analyzing low-enrichment research reactors that underwent core redesign following the RERTR program' s launch in the 1980s, as summarized in Table 1 , to explore future development directions for small pool-type research reactors.

As shown in Table 1, current global 1–10 MW small pool-type research reactors are primarily categorized by moderator type into water-moderated pool reactors and TRIGA (Training, Research, Isotopes, General Atomic) reactors using zirconium hydride as moderator. Dispersion fuel elements exhibit excellent performance characteristics including high thermal conductivity, good rigidity, safety, high burnup, and long service life. Plate-type fuel elements offer good thermal conductivity with low operating temperatures, high specific power and power density, deep burnup, and low operating costs [32]. Therefore, water-moderated pool-type research reactors predominantly employ plate-type dispersion fuels.

1.1. Dispersion Fuel Types

Dispersion fuel consists of fissile material particles uniformly dispersed in a metal, ceramic, or graphite matrix with good thermal conductivity, mechanical properties, and low thermal neutron absorption cross-section. The continuous matrix isolates fuel particles, preventing most of the matrix from being damaged by fission products and ensuring good mechanical performance throughout the fuel element’ s service life. The matrix also surrounds and constrains fuel particles, maintaining good thermal conductivity between fuel particles and cladding, enabling higher burnup compared to bulk fuel [32].

The international RERTR program has been ongoing for 46 years. To achieve research reactor low-enrichment conversion without compromising comprehensive performance, high-density dispersion LEU fuels including U_3O_8, UAl , and U_3Si_2 have been developed and continuously applied. UAl fuel achieves densities of 2.3 gU/cm^3, while U_3Si_2 fuel reaches maximum densities of 4.8 gU/cm^3. With enrichment at 19.75% and density of 4.8 gU/cm^3, U_3Si_2-Al has become the most widely used fuel globally as reactors undergo low-enrichment conversion. Currently, countries are developing high-density U-Mo alloy fuel.

1.1.1. U_3O_8 Dispersion Fuel

NUR (Nuclear Uranium Reactor) is a 1 MW pool-type research reactor that first achieved criticality in 1989. Its core structure is shown in Figure 1 [Figure 1: see original paper]. The reactor uses U_3O_8-Al fuel with 19.7% enrichment and 2.96 gU/cm^3 density in plate-type fuel elements. The core contains 17 fuel assemblies (12 standard and 5 control assemblies), with cross-sections shown in Figure 2 [Figure 2: see original paper]. NUR uses light water for cooling and moderation with graphite reflectors and features multiple vertical and horizontal irradiation channels. The reactivity control system consists of five Ag-In-Cd absorber rods clad in 316L stainless steel (four control rods and one regulating rod) [33,34].

NUR has four vertical channels (two in-core, two in reflector), four radial horizontal channels, one tangential horizontal channel, two rapid pneumatic transfer systems, one hot cell, and one transfer chamber. The arrangement of internal horizontal channels and thermal columns is shown in Figure 3 [Figure 3: see original paper]. The maximum thermal neutron flux density is 1.4$\times10^{13}$ n/cm^2·s, and the maximum fast neutron flux density is 2.5$\times10^{13}$ n/cm^2·s. NUR is primarily used for personnel training, neutron activation analysis, nuclear data analysis, neutron radiography, small-angle neutron scattering, and production of radioisotopes and radiopharmaceuticals. Future plans include increasing power to 3.5 MW [34,36].

1.1.2. Uranium-Aluminum Alloy Dispersion Fuel IRR-1 (Israeli Research Reactor-1) is a 5 MW open pool-type light water reactor that first achieved criticality in 1960. It uses UAl -Al dispersion plate fuel with 93% enrichment and 0.68 gU/cm^3 density. Light water serves as coolant and moderator, with two rows of graphite reflectors around the active core to reduce neutron loss. The core structure is shown in Figure 4 [Figure 4: see original paper], containing 23 standard fuel assemblies and 5 control assemblies. Each standard assembly comprises 23 parallel fuel plates clad in 6061 aluminum plates, while control assemblies consist of 17 fuel plates with rectangular channels at both ends for control rod movement. Control plates are made of Ag-In-Cd material. The maximum thermal neutron flux density in-core is 2.5×10^{13} n/cm$^2\cdot$s, and 1.0×10^{13} n/cm$^2\cdot$s in the reflector [37,38].

The Soreq Nuclear Research Center in Israel conducted extensive studies on IRR-1 low-enrichment conversion. While maintaining the original core layout, various LEU fuels with 20% enrichment and different densities were analyzed. Due to manufacturing challenges for IRR-1 fuel compacts, UAl -Al dispersion plate fuel with 20% enrichment and 2.3 gU/cm^3 density was selected, with fuel plate thickness of 0.51 mm. After low-enrichment conversion, the maximum fast neutron flux density remained unchanged, while the maximum thermal neutron flux density decreased by 3% to 2.4×10^{13} n/cm$^2\cdot$s. IRR-1 features eight horizontal channels for research and training in nuclear engineering, neutron radiography and diffraction, activation analysis, and gemstone coloration [39].

1.1.3. Uranium-Silicon Dispersion Fuel U_3Si_2-Al dispersion fuel is used in research reactors worldwide with thermal power ranging from 0.7 MW to 135 MW, demonstrating its ability to withstand various harsh reactor conditions. Among the more than 260 operating research reactors globally, the majority of low-power-density reactors have successfully implemented low-enrichment conversion using this fuel, including IEA-R1 (Brazil), RA-6 (Argentina), RECH-1 (Chile), JRTR (Jordan), HOR (Netherlands), PARR-1 (Pakistan), RP-10 (Peru), RINSC (USA), and UMLRR (USA).

IEA-R1 is a 5 MW open pool-type research reactor that first achieved criticality in 1957, initially using 93% enriched U-Al fuel. To support the RERTR program, low-enrichment conversion began in the early 1980s, achieving full-core LEU operation at 5 MW in 1997. The converted IEA-R1 uses U_3Si_2-Al fuel with 19.9% enrichment and 3.0 gU/cm^3 density. Each standard fuel assembly contains 18 fuel plates, with the structural framework shown in Figure 6 [Figure 6: see original paper] [40]. Light water serves as moderator and coolant. The core consists of 30 MTR-type fuel assemblies and graphite reflectors arranged in an 8×10 grid plate [41,42].

IEA-R1 includes 144 irradiation positions, two short-term pneumatic irradiation positions, one large-sample irradiation position, and a pneumatic transfer system to the radiopharmaceutical center. Ten horizontal beam channels (eight radial, two tangential) provide neutron beams for nuclear physics experiments. The maximum thermal neutron flux density at the central channel is 5.5×10^{13} n/cm^2 · s, 1.5×10^{13} n/cm^2 · s at reflector channels, and 1.0×10^{13} n/cm^2 · s at horizontal channels. The maximum fast neutron flux density is 1.2×10^{14} n/cm^2 · s [44].

IEA-R1 is used for thermal and epithermal neutron activation analysis (NAA), high-resolution neutron diffraction, neutron radiography, geochronology, nuclear data measurement, instrument development, and boron neutron capture therapy (BNCT) research. For isotope production, it manufactures ^{131}I, ^{153}Sm, and ^{192}Ir for medical applications; ^{40}Ar, ^{79}Kr, ^{82}Br, and ^{203}Hg for industrial uses; and performs neutron transmutation doping for semiconductor manufacturing and production of calibration standards and reference materials. Future plans include digital console installation, beryllium neutron channel irradiation devices, research on ^{99} Tc production via neutron capture, and irradiation systems for gaseous radioisotope production [45].

1.1.4. Uranium-Molybdenum Fuel The theoretical maximum densities of U_3Si_2-Al and U_3Si_2-Al dispersion fuels are 4.3–4.8 gU/cm^3 and 5.0 gU/cm^3, respectively. While uranium-silicon dispersion fuel demonstrates good irradiation performance at temperatures around 110°C for small research reactors operating at 1–10 MW, it cannot meet the requirements of high-performance, high-power research reactors. Additionally, silicon' s thermal conductivity is significantly lower than other metals, and silicon reprocessing in uranium-silicon fuel presents challenges [46].

Since the late 1990s, countries have pursued U-Mo fuel research, focusing on two types: dispersion and monolithic alloy. Dispersion U-Mo fuel can leverage mature U_3Si_2 fuel manufacturing processes but suffers from swelling and fuel-matrix chemical reaction issues, while failing to solve low-enrichment conversion for all high-performance research reactors. Monolithic U-Mo fuel can meet performance requirements for any high-performance research reactor for the foreseeable future, but low production rates and high costs have limited its widespread application. With maturing U-Mo fuel technology, the United States, South Korea, Russia, and Europe have completed irradiation tests for medium-flux research reactors, with South Korea and the United States currently constructing research reactors using dispersion and monolithic U-Mo fuels, respectively (MURR and KJRR).

U-Mo alloy fuel offers significantly higher uranium density and thermal conductivity than traditional UO_2 and uranium silicide fuels used in research reactors, enabling high neutron flux with low-enriched uranium. The alloy exhibits excellent irradiation performance with a theoretical maximum density of 16.0 gU/cm^3. For spent fuel reprocessing, the melt-and-dilute method with aluminum addition is more mature and straightforward. Current U-Mo fuels are primarily UMo-Al dispersion and UMo monolithic types. Dispersion U-Mo fuel, typically in plate or rod form, is expected to achieve densities of 8.0–9.0 gU/cm^3. South Korean dispersion fuel uses an aluminum-silicon matrix with maximum uranium density of 8 gU/cm^3, while Russian dispersion fuel uses an aluminum matrix with maximum density of 9.0 gU/cm^3. French UMo alloy fuel can achieve densities up to 9.0 gU/cm^3.

MURR (Missouri University Research Reactor) is a compact core design light water tank reactor that achieved criticality in 1966, with power increased from 5 MW to 10 MW in 1974. The fuel assembly is shown in Figure 7 [Figure 7: see original paper], with each assembly containing 24 curved plates at 45° angles. The fuel is uranium aluminide (primarily U_3Al) with 93% enrichment and 1.43 gU/cm^3 density. Light water serves as moderator and coolant. Reactivity is controlled by four boron plates and one stainless steel regulating plate, with beryllium and graphite reflectors. The MURR core consists of eight fuel assemblies of identical physical dimensions arranged vertically in the annular space between two cylindrical aluminum reactor vessels. The core cross-section is shown in Figure 8 [Figure 8: see original paper]. MURR includes 19 vertical channels (three in-core, 16 in reflector) and six horizontal channels, with maximum unperturbed thermal neutron flux density of 4.0$×10^{14}$ n/cm^2·s and maximum fast neutron flux density of 1.0$×10^{14}$ n/cm^2·s [46,47].

MURR began low-enrichment conversion in 2006, completing feasibility verification in 2009. The LEU-converted MURR uses U-10Mo fuel with 15.3 gU/cm^3 density, increasing power from 10 MW to 12 MW. The LEU fuel assembly shape remains unchanged, but the number of fuel plates is reduced to 23 per assembly, each 64.77 cm long with 60.96 cm active fuel length. The fuel uses zirconium as an interlayer and Al6061 as cladding, with average assembly burnup of 180 MWd. Preliminary fuel element design, performance calculations, and safety analyses under steady-state and transient/accident conditions have been completed [48,50]. The LEU fuel elements still use boron as control material. Post-conversion, neutron flux levels at in-core irradiation channels, rabbit systems, single-crystal silicon irradiation channels, and horizontal beam outlets decreased by approximately 34% above the core center plane but increased below the core center plane, with overall core neutron flux levels slightly higher than the original HEU core [48,50].

The MURR cross-section is shown in Figure 9 [Figure 9: see original paper], featuring central irradiation channels, a pneumatic tube system, irradiation channels in the graphite reflector region, a large-capacity water pool, six horizontal beam ports, and a thermal column. The first four facilities provide sample carrier placement locations in different core regions for silicon transmutation doping, radiopharmaceutical development, life sciences research, isotope production, and neutron activation analysis. Six beam ports direct neutron beams from the core to experimental equipment, primarily for neutron scattering experiments and boron neutron capture therapy. MURR also conducts research in archaeology, anthropology, and geology [51,52].

1.2. UZrH Fuel Type

TRIGA reactors are small pool-type reactors that can operate without stringent safety containment, typically used for education, training, scientific research, and isotope production. TRIGA reactors use UZrH nuclear fuel, whose reaction rate decreases with increasing temperature, making them extremely safe with virtually no possibility of nuclear accidents. Early TRIGA reactors used high-enriched uranium fuel but have gradually transitioned to low-enriched uranium through the RERTR program.

Low-enriched UZrH fuel elements consist of a mixture of uranium, zirconium, hydrogen, and erbium, with nominal U-235 enrichment of 20%. Zirconium hydride provides neutron moderation and imparts a large negative temperature coefficient. Erbium serves as a burnable poison to offset the large excess reactivity from the substantial uranium content in initial fuel loading. Erbium' s large epithermal resonance also increases the instantaneous negative temperature coefficient, enhancing reactor safety. The fuel element design is shown in Figure 10 [Figure 10: see original paper]. TRIGA fuel assemblies feature two graphite axial neutron reflectors, a zirconium rod in the center of the fuel mixture, a molybdenum disk supporting the fuel mixture, and 304 stainless steel cladding [53].

MA-R1 (Morocco nuclear research reactor) is a 2 MW TRIGA MARK II reactor using water and ZrH as moderator, light water cooling, and graphite and water as reflectors. It uses homogeneous UZrH fuel with 19.75% enrichment and 5.90 gU/cm^3 density, controlled by five ^4B_4C control rods. The core structure is shown in Figure 11 [Figure 11: see original paper]. MA-R1 has four in-core vertical channels and one reflector vertical channel, primarily for medical isotope production, with maximum thermal neutron flux density of 2.0$×10^{13}$ n/cm$^2\cdot$s. Five horizontal channels (three radial, two tangential) with maximum neutron flux density of 1.0$×10^{13}$ n/cm$^2\cdot$s are used for neutron scattering and radiography, with a thermal column located outside the core [54,55].

MA-R1 is equipped with various irradiation facilities providing high neutron flux levels for basic nuclear research, training, and radioisotope production. Facilities include pneumatic transfer systems for short-lived radionuclide neutron activation analysis, three irradiation channels in the high-flux core region for radioisotope production, a rotating sample rack at the active zone edge inside the graphite reflector for longer-duration sample irradiation (hours), a graphite thermal column for thermal neutron activation analysis, and four horizontal beam channels through the tank for ^{131}I production [56].

1.3. Summary of Fuel Types

Based on characteristics of fuels used in domestic and international small pool-type research reactors, the advantages, disadvantages, and applications of each fuel type are summarized in Table 2 . U_3O_8-Al and UAl -Al dispersion plate fuels, developed since the 1960s, have relatively low uranium density and show no clear advantages over U_3O_8-Al fuel for future low-power-density small research reactors. Additionally, these fuels have low burnup and are unsuitable for high-performance research reactors. Given the mature development and application of uranium-silicon fuels, U_3Si_2-Al will continue to play an important role in low-power-density small research reactors (1–10 MW) for some time. For high-power-density, high-performance research reactors, U-Mo fuel will be the future focus to ensure high burnup, long cycle length, and excellent thermal performance. The United States will use monolithic U-Mo fuel for MURR' s 12 MW low-enrichment conversion, South Korea is constructing the 15 MW KJRR reactor using dispersion U-Mo fuel, and Russia and Europe are conducting irradiation tests of U-Mo fuel for medium- and high-flux research reactors.

2. Core and Fuel Element Structure Design

2.1. Core Structure Design

As neutron scattering experimental technology plays an increasingly important role in energy, materials, information, and life sciences, research reactors worldwide have begun adopting high-density LEU fuel to expand neutron beam applications outside the active core region. To avoid performance degradation, cores often employ compact designs, making compact anti-neutron-trap pool-type research reactors favored by many countries. A compact core minimizes core volume by reducing the number of fuel assemblies or lattice pitch at a given reactor power, thereby increasing fission density to obtain high fast neutron flux density [57].

Current international small pool-type research reactors generally use compact core designs to increase maximum neutron flux density while achieving core neutron flux zoning. These reactors use high-density low-enrichment fuel with light water as moderator and coolant, and typically employ solid reflectors such as graphite, beryllium, or beryllium oxide to enable free core movement. Horizontal and vertical irradiation devices are arranged in the reactor pool, fully demonstrating the multi-purpose, strong neutron source characteristics of small pool-type reactors.

Compact core designs yield high quality factors (defined as the ratio of maximum thermal neutron flux density to thermal power [58]), as shown in Table 3 . Small compact pool-type research reactors achieve higher quality factors with the same enrichment and fuel type, and their neutron flux can satisfy numerous neutron source applications. Compact cores can create large-volume high-flux regions, achieve extremely high fast neutron spectral purity in-core, and obtain high thermal neutron spectral purity in the reflector region. Based on production requirements and safety conditions, in-core fast neutron irradiation channels can be converted to thermal neutron channels for isotope production, enabling multi-purpose utilization. Compact cores provide high-flux-density thermal neutrons in the external reflector region for thermal/epithermal neutron applications such as neutron scattering experiments, neutron activation analysis, isotope production, and BNCT.

However, compact core designs have certain limitations: (1) Compact cores have small volumes with less fuel mass and smaller lattice pitch, resulting in lower core excess reactivity and shorter cycle lengths. Future improvements require fuel zoning and reloading to increase fuel discharge burnup and reduce operating costs. (2) Small lattice pitch creates high core heat flux density, challenging fuel and coolant heat transfer performance and making high-power operation difficult. Control rod configurations are also constrained by small pitch—follower-type control rods have high differential worth, while in-assembly control plates create large power peaking factors, both impacting safe operation. (3) Compact cores require high-performance reflectors to reduce neutron leakage. Reflected thermal neutrons create high flux peaks at the active zone boundary, forming high thermal neutron flux in the peripheral reflector region. Additionally, low-enriched uranium generates significant gamma heating in reflector regions, and Type II pool reactors typically use graphite or beryllium reflectors, imposing high demands on solid reflector high-temperature radiation resistance.

2.2. Fuel Element Structure Design

In compact cores with high fission density, fuel element maximum thermal load and irradiation performance become primary design constraints. Fuel element structural design can increase heat transfer area with coolant, balance core power distribution, avoid excessive power peaking factors, and effectively improve core heat transfer capability.

Since the RERTR program' s implementation, compact anti-neutron-trap core designs have been gradually adopted to maintain reactor performance without significant reduction. To increase fuel density and mass per unit volume while ensuring high fuel element surface-area-to-volume ratio, various plate-type, curved-plate, involute-plate, and annular fuel elements have emerged, as shown in Figures 12 [Figure 12: see original paper]–15 [Figure 15: see original paper]. (1) With identical fuel enrichment and structural materials, involute and curved plate assemblies require less structural material mass and volume per unit mass of U-235 than flat plate assemblies, enabling more compact reactor cores that achieve higher in-core fast neutron flux density and higher out-of-core thermal neutron flux density. (2) For heat transfer area, involute assemblies enable dual-sided heat transfer with larger surface area. The equal-width flow channels between involute plates provide better flow stability, higher critical velocity, and higher heat transfer efficiency per unit volume, effectively increasing reactor operating thermal power and performance. (3) For irradiation channel arrangement, a single involute fuel assembly forms the entire core, preventing internal vertical irradiation channel placement. Curved plate assembly internal channels are limited to the cylindrical region formed by the assembly, restricting channel size and number. Flat plate assemblies offer flexible structure, allowing numerous experimental channels in-core and supporting neutron beam traps for diverse irradiation applications. (4) For fuel discharge burnup, involute assemblies use whole-assembly replacement with shallow average burnup. Curved plate assemblies enable batch replacement, slightly increasing burnup. Flat plate assemblies, being smaller, allow zoned batch replacement, achieving high fuel discharge burnup, improving fuel utilization economics, and reducing operating costs, while also offering manufacturing advantages [61]. Annular fuel elements have two cooling surfaces with large surface-area-to-volume ratio, reduced heat conduction path, and significantly lower peak fuel temperature, enabling effective power density increases and improved economics while maintaining adequate safety margins. However, annular fuel development faces challenges including flow and heat matching between inner and outer channels, inner tube welding and inspection, and special safety issues from dual channels. Currently, no Type II pool-type research reactor uses annular fuel elements [62].

In summary, involute assemblies are optimal for high-flux neutron beam applications, while flat plate assemblies offer greater advantages in operational cost, economics, and multi-purpose applications, with curved plate assemblies occupying a middle ground.

2.3. Summary of Structural Types

Based on domestic and international research reactors constructed after low-enrichment conversion, the advantages and disadvantages of overall core structures and fuel element designs are summarized in Table 4 . The primary development direction for future research reactors is constructing sufficient irradiation facilities and fully utilizing limited neutrons to expand application scenarios. Anti-neutron-trap core designs provide high in-core and out-of-core neutron flux density and enable neutron energy zoning, significantly enhancing operational value compared to traditional neutron trap designs. Using new high-density fuels such as U_3Si_2-Al and U-Mo ensures adequate core excess reactivity, increases fuel discharge burnup, and reduces operating costs. For future low-power-density small research reactors, plate-type fuel elements can improve irradiation experiment flexibility and efficiency, leveraging advantages of low-temperature irradiation and low-cost operation to achieve complementary high-, medium-, and low-power research reactor configurations. For high-power, high-performance research reactors, fuel element structures with excellent heat transfer performance are preferred. Annular fuel elements offer the best heat transfer performance, and despite current safety challenges, future combination with U-Mo fuel represents an important option for high-performance research reactor construction.

3. Prospects for Small Pool-Type Research Reactors

As global research reactor construction slows and many aging reactors retire, existing facilities cannot meet demands for high-performance neutron sources.

High-power, high-flux research reactors require substantial investment, high operating costs, and long construction periods, making them unable to quickly satisfy various neutron source applications. In contrast, small open pool-type research reactors offer short construction periods. Currently, 5 MW compact core designs using uranium-silicon fuel can achieve maximum fast and thermal neutron flux levels exceeding 10^{14} n/cm$^2 \cdot$ s, sufficient for numerous neutron source applications including isotope production, neutron activation analysis, and neutron scattering. Compared to high-power research reactors, small compact pool-type reactors have lower power, operating costs, and simple, flexible structures with convenient maintenance. With the entire core submerged at the pool bottom, safety is enhanced. Future development of small pool-type research reactors and their application systems should focus on improving comprehensive versatility while maintaining adequate neutron flux levels.

1) **Reactor Performance**: Fuel type and core structure (fuel element structure) are decisive factors for future small pool-type research reactor performance. High-density U-Mo alloy ensures adequate core excess reactivity, significantly increasing neutron flux density and extending cycle length to meet design requirements for any high-performance reactor for at least the next half-century, while offering clear advantages in fuel reprocessing. Compact core design increases maximum neutron flux density, enables core neutron flux zoning, and creates large-volume high-flux regions. Annular, involute, and plate-type structures all provide large surface-area-to-volume ratios, effectively enhancing core heat transfer and reactor safety, with appropriate element structures selectable based on application objectives to improve comprehensive capabilities.

2) **Reactor Application Capabilities**: Applications and performance requirements for research reactors over the past decade are summarized in Table 5 . Future small pool-type research reactors will use in-core vertical channels for radioisotope production and material testing, pool vertical channels for silicon neutron transmutation doping (NTD), and horizontal channels for neutron activation analysis, neutron radiography, and neutron scattering. With compact, small-diameter cores and limited internal channels, large reactor pools with internal neutron application facilities will be established to expand overall application scenarios. Cores will use solid reflectors and be movable as a whole, allowing flexible position changes based on primary irradiation objectives to simultaneously conduct various neutron applications, improving economics and capabilities.

Future advanced research reactors will develop toward improved performance, expanded scope and functionality, and enhanced economics. New designs must satisfy comprehensive versatility and adequate neutron flux levels while ensuring safety. Core structure design, fuel element structure innovation, and development of new high-density LEU fuels are essential paths to improving performance. Based on decades of international pool-type research reactor development, future Chinese small pool-type research reactor design should emphasize structural design and new fuel development.

1) **Structure**: Compact core design enables reactor miniaturization, solid reflectors enable free core movement, and large pools with numerous irradiation facilities enable expanded application scenarios. This combination maximizes neutron utilization efficiency and defines the development direction: compact movable cores as the foundation, with large-pool application facilities as the main architecture.

2) **Fuel**: Developing high-density U-Mo alloy fuel can meet requirements for high-performance research reactors with neutron flux of 10^{15} n/cm^2·s. Using plate-type, annular, cross-spiral, and other fuel element structures can effectively enhance core heat transfer and achieve high-power, high-flux design goals. U-Mo alloy fuel elements in plate and annular configurations can support both low-enrichment conversion projects and performance upgrades for existing and new reactors using U_3Si_2-Al fuel, while facilitating standardized fuel types and simplified reprocessing.

Future small pool-type research reactor development will continue to focus on performance improvement, scope expansion, cost reduction, and safety enhancement to strengthen China' s overall capabilities in research reactor design and neutron source applications.

Author Contributions

HAN Peng: Project planning and manuscript writing. CHEN Xiaoliang: Overall concept and argumentation. ZHU Jiyin: Manuscript review. ZHU Jiachen: Manuscript revision and editing.

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