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Abstract

High flux reactors (HFRs) are a special type of research reactor aimed at providing a high neutron flux. Compared with power reactors and other research reactors, HFRs have unique technical features in terms of reactor core design, irradiation capability, and operating characteristics. They can be applied to the irradiation tests of nuclear fuels and materials, radioisotope production, neutron science, and experiments. This paper reviews HFRs, including their development history, technical features, and application areas, as well as trends in the development of new and advanced HFRs.

Full Text

Preamble

Review of the Development and Application of High Flux Reactors

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Abstract: High flux reactors (HFRs) are a special type of research reactor designed to provide high neutron flux. Compared with power reactors and other research reactors, HFRs possess unique technical features in reactor core design,

irradiation capability, and operating characteristics. They can be applied to irradiation tests of nuclear fuels and materials, radioisotope production, neutron science, and various experiments. This paper reviews HFRs, including their development history, technical features, application areas, and trends in the development of new and advanced HFRs.

Keywords: high flux reactor, development, design features, application fields, review

1 Introduction

Unlike power reactors that generate electricity, heat, or propulsion, research reactors [1,2] are primarily used for scientific research, engineering tests, or other applications utilizing neutrons, gamma rays, or other radiations [3-5]. Neutron flux represents one of the most important parameters of a research reactor. Research reactors with neutron fluxes of 10^{14}–10^{15} n/(cm^2 • s) or higher are commonly categorized as high flux reactors (HFRs) [6]. Notably, although pulsing reactors can provide these neutron flux values on certain timescales—for instance, IBR-2 can deliver an average fast neutron flux of 2.26$×10^{17}$ n/(cm^2 • s) [7]—they fall outside the scope of this discussion, which focuses on research reactors providing stable neutron fluxes.

Compared with other research reactors, HFRs incorporate specific technical features to achieve substantially higher intensities of fast or thermal neutrons, which play a crucial role in investigations of new fuel elements and materials science, theoretical and applied physics research, and production of rare isotopes. Testing materials for nuclear energy applications, conducting fundamental physics research, and producing industrial and medical isotopes all require high-level neutron fluxes. Driven by these requirements, HFRs with one or more of these functions have been designed and constructed in various countries.

According to statistics from the International Atomic Energy Agency (IAEA) website [8], 840 research reactors are distributed across 70 countries and regions worldwide. As shown in Table 1 , most existing research reactors are being decommissioned or have already been decommissioned, with only 225 research reactors currently operating. Presently, the country with the largest number of operational research reactors (including criticality experimental devices) is Russia (54 reactors), followed by the USA (49 reactors), China (17 reactors), India (5 reactors), Germany (5 reactors), and Canada (4 reactors). Research reactors used worldwide are summarized in Fig. 1 [Figure 1: see original paper]. Among them, 40 reactors (representing 17.8%) have neutron fluxes higher than 10^{14} n/(cm^2 • s), which fall within the scope of HFRs.

Most operational HFRs were built 50 years ago and face problems such as aging and decommissioning. Therefore, new and advanced HFRs must be developed in the near future. This paper reviews HFRs, covering their historical development, technical features, and application areas, while attempting to identify future trends for developing next-generation HFRs.

The remainder of this paper is organized as follows: Section 2 reviews the development history of HFRs. Section 3 analyzes and summarizes the technical features of HFRs, including reactor core design, irradiation capability, and operating characteristics. Section 4 discusses the main applications of HFRs. Finally, Section 5 discusses future trends for HFRs.

2 Historical Development of High Flux Reactors

After the first nuclear reactor, Chicago Pile 1 (CP-1), achieved criticality in 1942, humanity entered a new era of nuclear energy. In 1943, a CP-1 reactor called CP-2 was reconstructed, fueled with natural uranium and moderated by graphite. The normal maximum power of CP-2 was 1 kW, though it could also operate at 5 or 10 kW for short periods in certain experiments [1]. CP-2 is considered the first research reactor, and early experiments performed in this reactor supported the development of subsequent reactors. Early research reactors included X-10, CP-3, LOPO, and HYPO [2]. These reactors were used to conduct extensive experimental programs related to reactor prototype design and operating characteristics of this reactor type. The operating power of these early research reactors typically ranged from kW to MW, with relatively low neutron flux.

With the development of nuclear energy, the demand for higher neutron fluxes for material testing and other applications gradually increased. In 1952, the Material Testing Reactor (MTR) [9] in the United States became critical. This reactor had a power of 40 MW with an average thermal neutron flux of 3$\times$10^{14}$ n/(cm$^2\cdot$s). Based on the neutron flux level achieved by the MTR, this was the first true HFR. In the following decades, multiple HFRs were designed and constructed, including SM [10], High Flux Isotope Reactor (HFIR) [11], Advanced Test Reactor (ATR) [12], High Flux Engineering Test Reactor (HFETR) [13], China Advanced Research Reactor (CARR) [14], and Open Pool Australian Light-water reactor (OPAL) [15]. Based on technical development and advancement levels, the historical development of HFRs can be roughly divided into three stages: the early stage (1940s–1960s), mid-term stage (1960s–2000s), and current stage (from the 2000s to present), as shown in Fig. 2 [Figure 2: see original paper].

Representative HFRs from different stages are summarized in Table 2 [2,8,16-24], which includes their power level, reactor type, status, fuel assembly, neutron flux, first criticality time, and estimated decommissioning time.

2.1 Early Stage

The early stage of HFR development spanned from the 1940s to the 1960s, with typical representatives including the MTR and SM-2. During this period, HFRs underwent significant technological improvements based on typical research reactors to achieve higher neutron fluxes and broader applications, such as the MTR-type fuel assembly and methods for obtaining ultra-high neutron flux in

the reactor core.

The design of MTR began in 1944 at Oak Ridge National Laboratory (ORNL), USA, primarily to satisfy requirements for higher neutron flux in material irradiation tests. MTR achieved its first criticality on March 31, 1952. The reactor's thermal power was 30 MW, and it adopted highly enriched uranium (HEU) fuel. The reactor was cooled and moderated with light water, and beryllium and graphite were used as reflectors. The operating power was increased to 40 MW in 1955, resulting in an average thermal neutron flux of 3$×10^{14}$ n/(cm^2 · s), which maintained the highest neutron flux for many years. Plate fuel assemblies were utilized to permit higher power density and sufficient cooling. This type of fuel consists of an aluminum-uranium mixture with aluminum cladding and is called MTR-type reactor fuel [25]. The MTR-type fuel had a profound impact on the development of research reactor fuel assemblies, and many fuel assemblies used in later HFRs, such as CARR and JRR-3M, are based on this design scheme. A cross-sectional view of the MTR-type fuel assembly is depicted in Fig. 3 [Figure 3: see original paper]. The irradiation application design of MTR was also flexible, with over 100 irradiation positions and six horizontal neutron beam tubes.

The SM-2 reactor [2,22] was the first epithermal neutron spectrum research reactor with water as a moderator. It was a vessel-type HFR in the Soviet Union with a power of 100 MW. SM-2 had 15 vertical channels for radiation resistance testing, four vertical high-temperature channels for corrosion resistance testing, six vertical channels for the accumulation of transuranic elements and radioisotopes, and five horizontal channels. Construction of SM-2 began in January 1956, and it achieved first criticality on January 10, 1961. The power density of SM-2 was extremely high (the estimated average value was 2$×10^{3}$ MW/m^3); therefore, an ultrahigh neutron flux was achieved in the in-core irradiation channels. At that time, the thermal neutron flux in SM-2 was 3.3$×10^{15}$ n/(cm^2 · s) at a thermal power of 50 MW. The construction and successful operation of SM-2 motivated the construction of HFRs in the United States for hard neutron spectrum applications, including the High Flux Beam Reactor (HFBR) and HFIR. The SM-2 reactor was characterized by the following features in its early design: high volumetric inhomogeneity coefficients (~6), deep reactivity losses due to Xe-135 poisoning (>4%), and significant burnup reactivity temperature losses. In 1965, the fuel element of SM-2 was changed from plate fuel to cruciform fuel. In 1974, the thermal neutron flux in the neutron flux trap was improved to 5.0$×10^{15}$ n/(cm^2 · s) when the nominal thermal power was increased to 100 MW. From 1984 to 1987, the horizontal channel of the reactor was "closed." SM-2 was finally inherited by Russia and updated to SM-3 in 1991–1992, as discussed later.

2.2 Mid-term Stage

The mid-term development stage of HFRs refers to the period from the 1960s to the 2000s. During this period, HFR technology matured, and several high

flux research reactors were successively built, including the ATR, HFIR, and HFETR.

Although MTR consistently provided a high neutron flux, the pursuit of even higher neutron flux continued. Based on this background, an improved test reactor design effort began in 1955. The power level was increased to achieve higher neutron flux in irradiation test positions, and experimental loops were installed for fuel irradiation. The new test reactor was called ETR, which was later renamed ATR [12]. The critical device of ATR (ATRC) achieved its first criticality in 1964, and ATR was put into operation in 1967. ATR has a maximum power of 250 MW, with maximum thermal and fast neutron fluxes of 1.0$×10^{15}$ n/(cm^2 · s) (E < 0.625 eV) and 5.0$×10^{14}$ n/(cm^2 · s) (E > 1 MeV), respectively. As shown in Fig. 4 [Figure 4: see original paper], arc-type fuel assemblies fabricated from UAlx fuel meat with HEU (90 wt%) were adopted, and the reactor core comprises 40 fuel assemblies. In contrast to the widely used control rods in other HFRs, ATR adopted rotation control drums, which helped form a relatively uniform axial power distribution. Nine neutron flux traps are enclosed by fuel assemblies in the reactor core, and a total of 77 irradiation channels with diameters of 1.59–12.7 cm are distributed throughout the reactor.

HFIR [27,28] was founded in 1961 and reached its first criticality on August 25, 1965. Full-power operation was achieved in September 1966. The initial motivation for constructing HFIR was to generate significant and weighable quantities of heavy elements (Cm, Bk, Cf, Es, Fm, etc.), particularly ^{252}Cf, to support fundamental research and applications of transplutonium elements. Therefore, a research reactor with an extremely high neutron flux was required, which would accelerate the production efficiency of transplutonium nuclides, enable production of radioisotopes with high specific activity, and facilitate material tests. HFIR is a light-water-cooled and moderated HFR with a rated power of 125 MW. As shown in Fig. 5 [Figure 5: see original paper], the reactor core consists of a series of concentric fuel elements, and the fuel region is divided into inner and outer fuel zones. A flux trap is located at the center of the reactor core, where the maximum total neutron flux reaches 5$×10^{15}$ n/(cm^2 · s), providing basic conditions for transplutonium isotope production. In addition, various irradiation targets can be installed in the beryllium reflector, and four horizontal neutron beams can be used for neutron scattering and imaging.

HFETR [13,28] is a versatile HFR in China, designed as a vessel-type reactor with a design power of 125 MW. The reactor uses U_3Si_2-Al dispersion fuels and is cooled and moderated by light water. HFETR is characterized by high neutron flux, flexible reactor core layout, large irradiation space, and short irradiation periods. The maximum thermal neutron flux is 6.2$×10^{14}$ n/(cm^2 · s) (E < 0.625 eV), and the maximum fast neutron flux is 1.7$×10^{15}$ n/(cm^2 · s) (E > 0.625 eV). Construction of this reactor began in 1971, achieved first criticality in 1979, and started high-power operation in 1980. In 2007, the conversion of HFETR from HEU fuel to low enrichment uranium (LEU) fuel was completed

[29], with ^{235}U enrichment decreasing from 90 wt% to 19.75 wt%. Over the past few decades, HFETR has continuously conducted irradiation research on fuel and materials for power reactors and radioisotope production for industrial and medical applications. This reactor is expected to remain operational until 2028.

SM-2 was reconstructed and updated to SM-3 [22] between 1991 and 1992. The physical startup of SM-3 was conducted in December 1992, and the power startup in April 1993. This reconstruction project set the lifespan at 25 years. SM-3 removed the horizontal channels and added additional vertical experimental channels, including one central neutron flux trap, six channels in the active core, and 30 channels in the reflector. The maximum thermal neutron flux in SM-3 is 5.0$\times$10^{15}$ n/(cm^2 · s) (E $<$ 0.625 eV), which occurs in the central flux trap of the reactor core, and the maximum fast neutron flux is approximately 2.0$\times$10^{15}$ n/(cm^2 · s) (E $>$ 0.1 MeV). This reactor is primarily used for transplutonium nuclide production (10–25 mg ^{252}Cf per year), nuclear fuel production, and material testing. From 2017 to 2020, a modernization update [30] of SM-3 was conducted, including replacement of reactor internal structures and digital control and protection systems, with an expected lifespan extension until 2040.

2.3 Current Stage

Since the beginning of the 21st century, the development of nuclear energy and technology in various countries has increased the demand for HFRs. Several innovative HFRs, such as OPAL and CARR, have been designed and constructed. In addition, several HFRs have been planned and are under construction for multipurpose applications.

CARR [14] is an HFR with satisfactory performance and multiple applications. This reactor reached its first criticality in May 2010 and entered full-power operation in 2012. CARR is a tank-in-pool reactor enclosed by a slightly pressurized aluminum container and submerged in the reactor pool. With this structure, the reactor core would not be exposed even under accident conditions. A cross-sectional view of the reactor core and surrounding reflector is shown in Fig. 6 [Figure 6: see original paper]. The nominal operating power of CARR is 60 MW, and the reactor core is loaded with 21 fuel assemblies using U_3Si_2-Al dispersed fuel plates. The reactor is light-water-cooled and moderated, and a heavy-water tank is used as a reflector. It contains 25 vertical and 9 horizontal irradiation channels, which are almost entirely located in the reflector. Only a few channels are arranged near the boundary of the aluminum container in the reactor core. Applications of CARR include fuel and material irradiation tests, radioisotope production, neutron scattering and imaging, and neutron activation analyses.

OPAL [15] is an open-pool HFR in Australia that achieved its first criticality on August 12, 2006. The nominal power is 20 MW, and it adopts low-enriched U_3Si_2-Al dispersion plate fuel with aluminum cladding. The reactor core is

cooled and moderated using light water and surrounded by a heavy-water reflector. The maximum thermal neutron flux is 3.0$×10^{14}$ n/(cm^2·s), which appears in the irradiation position in the reflector, and the maximum fast neutron flux is 2.0$×10^{14}$ n/(cm^2 · s). The reactor pool is connected to the service pool through a transfer canal. The layout of the reactor core and irradiation channels in OPAL is shown in Fig. 7 [Figure 7: see original paper]. Since its establishment, OPAL has become an important supplier of medical and industrial radioisotopes (such as ^{99}Mo, ^{99}mTc, ^{131}I, ^{153}Sm, ^{51}Cr, etc.), a crucial testing platform for materials science and research, and a service provider for silicon transmutation doping.

The Jules–Horowitz Reactor (JHR) [32,33] is a new HFR under construction in France. The nominal design power of this vessel-in-pool reactor is 100 MW. The reactor is fueled by cylindrical U_3Si_2-Al assemblies. The reactor core is cooled using light water in a slightly pressurized primary circuit, and a beryllium reflector is used. The reactor core and reflector also provide sufficient irradiation positions for fuel and material irradiation tests, offering instrumented and circuit irradiation test capabilities. The expected fast neutron flux in the irradiation position is 5.5$×10^{14}$ n/(cm^2 · s) with energy above 1 MeV, corresponding to a radiation damage of 16 dpa per year. JHR also enables a high thermal neutron flux in the irradiation position, which can be used for radioisotope production. The reactor is planned to operate after 2030 and will enhance irradiation research capabilities for fuel and materials in France and Europe.

To support the development of advanced fast reactors [34] within the scope of fourth-generation nuclear energy systems, the USA, Russia, and China have planned to build new HFRs with fast neutron spectra. Most of these are designed as liquid-metal fast reactors [23]. The Multi-Purpose Fast Research Reactor (MBIR) [35], designed by Russia, is a loop-type versatile high flux fast neutron reactor with an asymmetric active zone layout. The maximum neutron flux of MBIR can reach 5.3$×10^{15}$ n/(cm^2 · s). Three experimental loops, three loop channels, and 14 material science assemblies are installed in the reactor. MBIR is designed to perform irradiation tests with Pb, Pb-Bi, Na, He, and molten salt, which can fulfill the development requirements of sodium-cooled and molten salt reactors. The designed lifespan of MBIR is 50 years, and it is expected to achieve its first criticality and begin operation by 2028. The Versatile Test Reactor (VTR) [24,36] in the USA is another high flux fast reactor with a power of 300 MW and a maximum neutron flux of 4.5$×10^{15}$ n/(cm^2·s). High flux fast neutron reactors typically utilize sodium metal or lead-bismuth alloys as coolants. In China, a concept of ultra-high flux fast neutron reactor (UFFR) [37] has been proposed to achieve a maximum neutron flux at the 10^{16} n/(cm^2 · s) level.

Recently, the Tsinghua High Flux Reactor (THFR) was designed by Tsinghua University, China. THFR is a light-water-cooled reactor with good safety characteristics. Its maximum neutron flux reaches 5.7$×10^{15}$ n/(cm^2 · s), and both its thermal and fast flux can achieve 2.0$×10^{15}$ n/(cm^2 · s), which is

expected to provide a wide range of applications.

3 Design Features of the High Flux Reactor

HFRs possess technical features that distinguish them from power reactors and other reactor types. These features include not only a series of measures adopted to achieve sufficiently intensive neutron fluxes but also special technologies to improve irradiation capability, operational flexibility, and safety. This section analyzes the technical features of HFRs in terms of reactor core design, irradiation capability, and operating characteristics.

3.1.1 Reactor Physics and Thermal-Hydraulic Design

The fundamental design requirement of an HFR is to provide the necessary neutron flux conditions for irradiating samples at the lowest possible power and economic cost. To describe the law governing high neutron flux realization using a homogeneous reactor as an example, the total neutron flux can be described as:

$$\phi = \frac{q_V}{E_f N_f \sigma_f}$$

where q_V is the power density, E_f is the average heat release energy per fission, N_f is the atomic density of nuclear fuel, and σ_f is the effective one-group fission cross section.

Clearly, the neutron flux level can be improved by increasing the power density, reducing the fuel loading, and reducing the one-group fission cross section. Noting that the fission cross section is generally smaller in the fast energy range than in the thermal energy range, the total neutron flux is expected to improve if fission events are dominated by fast neutrons. However, moderated neutrons can contribute to reducing the critical fuel loading. These two contradictory aspects must be considered when designing HFRs.

Several HFRs adopt the design concept of inverse-neutron flux traps [38]. The reactor core is compact and undermoderated, and fast neutrons leak into the surrounding reflector area where they are moderated, resulting in a high thermal neutron flux in the reflector. The determination of the thermal neutron flux level depends on the objective of the study. In the example of ^{244}Cm production through the transmutation of ^{242}Pu, the "bottleneck" for transmutation is the transition from ^{242}Pu to ^{243}Pu. When the characteristic burnup time is set as $1/(\Phi\sigma_c) \leq 0.5$ year, the neutron flux should be $\Phi \geq 1/(\sigma_c \times 0.5 \text{ year}) = 3.4\times10^{15}$ n/(cm^2 · s).

An increase in the power density q_V directly results in a higher neutron flux. For thermal-hydraulic design, the heat released from fuel assemblies represents a burden that significantly increases the cost of loop cooling. The main methods for increasing the allowable q_V are to reduce the coolant temperature at the

core inlet, increase the coolant velocity, and expand the heat exchange surface by using fuel elements with thin shapes, such as plates.

The primary loop pressure of HFRs is significantly lower than that of power reactors. For example, the operating pressure of SM-3 is 4.9 MPa [22]. On one hand, relatively low pressure ensures that experimental setups operate under acceptable conditions; on the other hand, increasing pressure increases the subcooling margin, delays the critical boiling transition, and promotes the growth of q_V. In addition, a lower inlet temperature enables the coolant temperature to remain further away from the melting point of the fuel cladding. The compromise results in a subcooling margin of 70 to 200 °C and a coolant temperature in the primary loop that does not exceed 100 °C.

The coolant velocity is significantly higher than that of power reactors. For example, the maximum velocity in SM-3 is 13.5 m/s [22] and in HFIR is 15.5 m/s [11]. High coolant velocity enhances heat transfer between the coolant and cladding surface; however, it is primarily limited by flow-induced vibrations, thermal stresses on the cladding, and surface corrosion and erosion. The channels between plate-type fuels are generally narrow, and small disturbances during flow produce reciprocal movements at high flow rates. On one hand, this increases the risk of fuel meltdown due to deformation; on the other hand, alternating deformation increases fuel fatigue. Furthermore, increased coolant velocity results in more intensive dissolution of active substances in the coolant toward the surface and tears off part of the corrosion film from the surface, i.e., corrosion and erosion of the fuel cladding. Notably, due to the high heat flux density, the oxide layer on the aluminum cladding dominates the non-negligible temperature margin. The thickness of the oxide layer increases progressively with prolonged operation, limiting the reactor's operating time.

In summary, to determine the maximum q_V of the designed HFR, the following aspects must be considered: (1) fuel element structure and heat transfer parameters; (2) determination of heat transfer conditions and critical heat flux; (3) temperature stresses at high energy densities per volume of the fuel element; (4) stability at high coolant velocities; and (5) limitations imposed by corrosion and erosion on the fuel cladding.

3.1.2 Reactor Body Structure

The reactor body structure refers to the basic configuration of the reactor core, pressure vessel, reactor pool, and other reactor-affiliated facilities. The reactor body structure of an HFR can be roughly divided into three forms: pool, vessel (or tank), and vessel-in-pool (or tank-in-pool). The difference between these structures lies primarily in two aspects: whether the reactor core is enclosed in a pressure vessel (or other pressurized containers), and whether the reactor core vessel is submerged in a reactor pool. The pressurized vessel or tank aids in improving the reactor operating pressure, which enables larger reactor core power density and thus higher neutron flux. A reactor pool filled with water

increases reactor safety and facilitates convenient operation with irradiation targets and other test samples.

The open pool reactor structure is widely used, as seen in MJTR and OPAL. For CARR, based on the pool reactor design scheme, the reactor core is contained in a slightly pressurized tank fabricated from aluminum. ATR and HFETR are vessel-type HFRs, whereas HFIR is a representative vessel-in-pool reactor, with operating pressure typically at 2–3 MPa. The basic structure of a vessel-in-pool reactor improves the neutron flux level with satisfactory safety features, making it preferable for ultra-high-flux reactors. The design concept of inverse-neutron flux traps is typically adopted for pool-type HFRs [38]. The reactor core is compact and undermoderated, and fast neutrons leak into the surrounding reflector area where they are moderated, resulting in a high thermal neutron flux in the reflector.

A pressure vessel is an important device that serves as a second safety barrier to prevent the leakage of radioactive materials. It also provides support and positioning for the internal structure of the reactor. Pressure vessels are typically made of austenitic stainless steel (such as 316LN), which has higher toughness at various temperatures.

3.1.3 Fuel Assembly

HFR systems are simpler than power reactors and typically operate at lower temperatures. The uranium fuel loading of an HFR is significantly lower than that of a power reactor. An HFR typically requires only a few kilograms of nuclear fuel. For example, the total ^{235}U loading in the HFIR core is 9.4 kg.

However, HFR fuel assemblies may require uranium with high enrichment of 20 wt% or higher. Historically, many HFRs used HEU fuels with enrichment higher than 90 wt%, such as HFIR, ATR, and SM-3. With HEU fuels, the absorption by ^{238}U and other reactor core materials can be minimized, resulting in a more compact reactor core structure and longer operating period. In addition, the utilization of HEU can significantly reduce HFR costs, including fuel and construction expenses. Although the unit price of natural uranium is lower than that of HEU (by approximately one-third), reactors using natural uranium require much higher power to achieve the same neutron flux level as reactors using HEU, resulting in much higher fuel burnup. Furthermore, the cost of the first fuel load must be considered. Based on an analysis by Bath [2], the ^{235}U contained in 1 t of natural uranium is about 30 times more expensive than 10 kg of HEU. Moreover, the cost per unit mass of ^{235}U increases significantly when enrichment exceeds 90%. Therefore, the Soviet Union used 90 wt% HEU, whereas the United States used 93 wt% HEU.

Under the Reduced Enrichment for Research and Test Reactors (RERTR) program proposed in the 1970s [39], many HFRs were converted from HEU fuels to LEU fuels. In HFETR, a U_3Si_2-Al dispersion fuel with an enrichment of 20 wt% was used to replace the UAl_4 alloy fuel with an enrichment of 90 wt%, and

the thickness of the fuel meat was adjusted accordingly.

Due to the high burnup of HFRs, the fuel assembly should withstand radiation damage and accommodate fission products effectively. The investigations and wide utilization of dispersion fuels, such as U-Al or U_3Si_2 [40], originate from research reactors including HFRs [2]. Dispersion fuel exhibits good compatibility with the aluminum matrix, high thermal conductivity, satisfactory capability to retain fission gases, and better fabricability.

Fuel cladding made of aluminum or zircaloy is adopted, which has high strength, a small neutron absorption cross-section, and better corrosion and radiation resistance performance. The U_3Si_2 fuel has been used to substitute U-Al fuel under the RERTR project. To compensate for the decrease in ^{235}U enrichment, the uranium density in the fuel assembly must be increased. For innovative LEU fuels [5], such as U-Mo alloys, the uranium density can reach 10 g/cm^3 or higher.

HFRs often have extremely high power densities in the reactor core, up to 1000 MW/m^3 or higher. Plate or casing assemblies are widely used in almost all later HFRs [41] because of their better cooling performance (larger surface area-to-volume ratio), better mechanical and vibration stability (particularly the curved structure), and lower manufacturing difficulty (compared with cruciform fuels). The evolution of the plate fuel assembly in an HFR is shown in Fig. 8 [Figure 8: see original paper]. Fuel plates are typically manufactured using a rolling process, whereas fuel bundles are typically processed using a coextrusion approach.

3.1.4 Coolant and Moderator

Most HFRs use forced circulation cooling, with coolant flowing through the reactor core from top to bottom [42,43]. Commonly used coolants include water and liquid metals, and typical moderators are light water, heavy water, and beryllium.

A large proportion of HFRs use light water as both coolant and moderator. Due to the strong shielding effect of light water on neutrons, the average free path of neutrons in light water is relatively short. When neutrons travel from a fission event to the irradiation channel, a significant proportion of attenuation occurs in the neutron flux. In addition, the water layer in the thermal neutron channel has a strong shielding effect on fast neutrons. The average free path of neutrons in heavy water is longer than that in light water, which potentially contributes to a higher neutron flux.

Liquid sodium or lead-bismuth is often adopted as the coolant in fast-neutron HFRs, such as VTR and MBIR. The satisfactory thermal performance of liquid metal coolant guarantees efficient heat transfer from the fuel assemblies. Sodium-cooled HFRs typically require an intermediate loop, which also increases system complexity. The boiling point of lead-bismuth alloy is 1670 °C at atmo-

spheric pressure, which potentially improves the reactor's inherent safety. The melting point of this alloy is relatively low (125 °C), enabling the reactor to operate at low temperatures and reducing requirements on structural materials. In addition, no significant volume change occurs during the transformation from solid to liquid, which is favorable for frequent startup and shutdown of the reactor. For these reasons, newly proposed fast-neutron HFRs tend to adopt lead-bismuth alloy as a coolant [44]. However, some challenges in lead-bismuth-cooled reactors still exist, such as corrosion of fuel and structural materials.

3.1.5 Reflector

The presence of reflectors reduces the critical fuel mass and increases the neutron flux-to-power ratio. Common reflector materials include water, heavy water, beryllium, beryllium oxide, and graphite. Based on a single-group model for spherical reactors using different moderators and reflectors, Bath et al. [2] identified two configurations that provide the largest ratio of maximum neutron flux to reactor power: reactors using water moderator and beryllium reflector (6.78$\times$10^{10}$ n/(cm^2 $\cdot$ s $\cdot$ kW)), and reactors using heavy water as both moderator and reflector (7.34$\times$10^{10}$ n/(cm^2 $\cdot$ s $\cdot$ kW)).

Therefore, an HFR typically utilizes beryllium or heavy water as a reflector surrounding the reactor core to reduce neutron leakage. The neutron absorption cross-section of beryllium or heavy water is smaller than that of light water, which results in a higher thermal neutron flux and enables irradiation experiments in the HFR. The arrangement of irradiation channels in a heavy-water reflector is relatively convenient; however, adjusting the structure and position of the reflector is difficult. Moreover, the system structure related to heavy water is complex and requires higher maintenance costs, as well as sealing and cooling.

Beryllium also exhibits defects during long-term operations and shutdowns. It is prone to radiation swelling and embrittlement after being employed for decades [45] and experiences beryllium poisoning during shutdowns [46]. To ensure safe reactor operation, radiation supervision and regular replacement of beryllium components are necessary.

3.1.6 Reactivity Control Mechanism

Reactivity control is the basis for reactor startups, shutdowns, and power adjustments. The reactivity control elements of HFRs typically include control rods, control plates, and rotation control drums [47], as shown in Fig. 9 [Figure 9: see original paper]. The main distinctions between the various control elements are their action modes, such as linear or rotational movements. Most HFRs, such as HFIR and HFETR, adopt in-core control rods or control plates, whereas only a few HFRs, such as ATR, use rotational control drums. Some have adopted a control mechanism that combines a control drum and control rod, with the control drum serving as the main approach.

Compared with control rods in the core, control drums installed in the reflector can reduce neutron absorption and flatten the axial power distribution. However, the control worth is typically smaller than that of control rods. The main technical parameters of the control drum include the rotation angle range (typically between 0° and 180°), rotation velocity, single-rotation limit, rotation position accuracy, quick reset time, temperature, pressure, and type of working medium.

A follower fuel assembly is typically adopted as the control element inserted into the reactor core. When the control element is withdrawn from the reactor core, the follower fuel element is inserted into the reactor core, which helps compensate for the reduced reactivity.

For more convenient operation of irradiation devices in the upper space of the reactor, the control drive motors of various control elements are typically located below the reactor core. CARR [14] has four compensation control rods in the reactor core and two safety rods in the heavy-water reflector adjacent to the reactor core. The driving mechanism of the compensation control rod is arranged at the bottom of the reactor core and adopts magnetic driving technology, while the safety rods use hydraulic drive technology with diverse design principles different from those of the compensation control rod, which helps avoid common cause failures and improve reactor safety.

3.1.7 Hydrochemistry

The hydrochemical requirements of HFRs are less complex than those of power reactors due to their lower coolant operating temperatures and shorter fuel lifetimes. An HFR is more concerned with maintaining a low level of radioactivity in the coolant than with scale formation [2]. This radioactivity primarily originates from reactive gases and radioisotopes dissolved in water. In addition to isotopes ^{19}O and ^{41}Ar, fluorine and nitrogen isotopes ^{13}N and ^{16}N also contribute to gas activity. Radioisotopes dissolved in water originate primarily from supplemental water and circuit materials. Sodium and calcium salts in the makeup water are irradiated to produce ^{24}Na and ^{45}Ca. Structural materials and fuel cladding enter the coolant due to corrosion after prolonged irradiation.

In addition, the coolant should be slightly acidic to minimize corrosion of aluminum cladding and beryllium.

According to Vladimirova [48], Russia proposed the following hydrochemical standards for the primary loop of research reactors: pH value at 25 °C, 5.0–6.5, $±$1%; mass concentration of chloride ions, not more than 50.0 μg/kg, $±$20%; mass concentration of aluminum, not more than 50.0 μg/kg, $±$5%; mass concentration of iron, not more than 50.0 μg/kg, $±5×10^{7}$ Bq/L.

3.2.1 Irradiation Facilities

An HFR is primarily used for neutron irradiation. The capabilities and performance considered in irradiation tests primarily include neutron flux, neutron energy spectrum, irradiation space, irradiation time, temperature, pressure, gas environment, and online monitoring. The irradiation facilities [49-51] typically include static irradiation devices, instrumented irradiation devices, irradiation test loops, and rabbit test devices.

A static irradiation device is used to enclose and fix irradiation test specimens, typically in the form of irradiation jars or tanks, frequently in an inert gas or water environment. A small irradiation jar can be arranged in the reactor core or reflector and can be designed with flexibility for insertion and uploading operations. Some samples with low heat generation are suitable for closed irradiation devices, whereas others may require coolant flow channels. Larger irradiation tanks are located outside the reactor core to utilize leaked neutrons.

Working conditions, such as the temperature of the static irradiation device, cannot be monitored during irradiation but only rely on reactor operation. In contrast, the instrumented irradiation device provides the capability to monitor online irradiation parameters such as irradiation temperature, gas composition, coolant temperature, coolant pressure, and coolant velocity. It is equipped with various monitoring devices, including thermocouples, neutron detectors, flow meters, sampling tubes, pressure tubes, gas tubes, and electric heating elements. The temperature of an irradiated sample is the most commonly monitored and controlled parameter. Ensuring that the temperature of the fuel sample does not exceed safety limits is particularly important. In addition, equipment for monitoring neutron fluence is fundamental for irradiation testing of advanced reactor materials [52].

As shown in Fig. 10 [Figure 10: see original paper], the irradiation test loop was designed to simulate the actual operating conditions of test specimens, typically utilized to irradiate nuclear fuel and materials with large heat generation. A typical design is a central neutron flux trap, which is utilized in the SM [22] and HFIR reactors [27]. Fig. 10(b) shows the small irradiation capsule utilized in HFIR for fuel irradiation tests; it is located in the flux trap irradiation position. The aim of designing this trap is to obtain a higher thermal neutron flux than that of the test loop in the active zone. Hence, these traps are often filled with light water [2]. The coolant of the test loop is isolated from the primary coolant, and irradiation parameters, including pressure, temperature, and velocity, are controlled separately by the loop. The design and construction of an irradiation test loop are relatively complex. The Russian MIR.M1 reactor [17] has 11 experimental circuits, including water, steam, and gas test loops, which provide irradiation test environments for various reactors.

The rabbit test device can automatically and flexibly accomplish sample transportation, irradiation, and measurement. The rabbit system is composed of multiple rabbit capsules driven by pneumatic or hydraulic transmission and

controlled by automatic or manual approaches. This test facility enables irradiation samples to be inserted into or removed from the target area during reactor operation, making it suitable for producing radionuclides with short half-lives, neutron activation analysis (NAA), and nuclear data measurement.

3.2.2 Post Irradiation Examination

The facilities for post-irradiation examination of irradiated nuclear fuel and materials are primarily used for transportation and temporary storage, cutting and dismantling, non-destructive testing of irradiation devices and samples, and post-irradiation inspection of spent fuel and materials. These include appearance and size analysis, weight measurement, burnup analysis, composition and microstructure analysis of irradiated samples, accident condition simulation, study of mechanical and thermal performance, and special research performed according to user requirements. The post-irradiation facility [53,54] primarily includes a hot cell and radioisotope processing device.

The cluster of hot cells is composed of heavyweight concrete hot cells, lead-shielded hot cells, and shielded glove boxes. The hot cell is often adjacent to the HFR, with transportation channels and waterways connected to the reactor. An interface device is used to transport irradiated fuel or material from an external transportation container to a temporary storage room in a hot cell. Special lifting facilities, master-slave robots, and power robots are used to conduct post-irradiation inspections of different types and structures of fuel elements and structural materials.

Post-processing for radioisotope production involves irradiated target dissolution, radiochemical separation and purification, and radioactive waste transportation. Radioisotope processing facilities include hot cell lines and several glove boxes. Highly radioactive isotopes need to be processed in the hot cell, while relatively less radioactive isotopes can be handled in glove boxes.

3.3 Operating Characteristics

In an HFR, the operating power and period change frequently according to the requirements of specific experimental missions, leading to different operating characteristics and safety standards [52].

The physical startup or first criticality is an important milestone in HFR construction. Physical startup experiments can verify the theoretical design of the reactor and obtain basic physical parameters, such as control rod worth and reactivity temperature coefficient, for subsequent operation. For instance, ATR has a critical testing device, ATRC, which is a 1:1 replicate of the reactor core. With the development of reactor physics analysis methods, the startup of an HFR can be accurately predicted using numerical simulations, which may substitute for the construction of critical experimental devices. The physical startup of CARR was entirely based on theoretical results from physics calculation codes [56].

Beryllium blocks can produce high-energy neutrons through the (γ,n) reaction [57]. The strong background generated by the photoinduced neutron effect of beryllium is effective in overcoming blind spots when the HFR operates at high power for a period without requiring an additional neutron source to restart. However, the presence of photoexcited neutrons also increases the difficulty of extrapolating fuel elements during the initial fuel-loading procedure for criticality. In addition, the effects of beryllium poisoning [46] must also be considered. ^{9}Be produces ^{6}Li and ^{3}He with strong thermal neutron absorption cross sections in fission reactions with fast neutrons. ^{3}T from ^{6}Li decays to ^{3}He during reactor shutdowns, enabling large accumulation of ^{3}He. The longer the reactor has been in operation and the longer the shutdown, the larger the negative reactivity and the shorter the allowable shutdown time [58]. The beryllium status must be monitored prior to startup.

In an HFR, the surface heat flux of the fuel assembly is large. As mentioned previously, the operating pressure and temperature of the coolant are relatively low, but the coolant flow speed is considerably high to ensure sufficient cooling capability. Irradiation test components or targets affect the reactivity and power distribution of the HFR core [59] and cause significant heat generation. Therefore, additional requirements exist for cooling the experimental equipment [60]. Because the coolant channel is narrow, blockage accidents in the coolant channel must be prevented during operation [61,62].

Under high- or full-power operating conditions, the coolant of an HFR flows from top to bottom to cool the reactor core, driven by the primary pump. During low-power or shutdown operation, the reactor is cooled by natural circulation, and the coolant flows from bottom to top. This means that the coolant flow direction reverses, which results in zero coolant velocity during reversal, causing the convective heat transfer coefficient to decrease and resulting in deterioration of heat transfer. The flow reversal effect [43] should be considered during reactor shutdown.

Special attention should be given to various operations and experiments that may cause reactivity changes during operation. The reactivity disturbance value and rate should be accurately estimated. Irradiation test components should be considered part of the reactor, and their reactivities should be evaluated individually. Notably, when a large number of irradiated samples are placed in the irradiation channel, the neutron flux is significantly reduced due to large absorption, resulting in failure of the irradiation channel. The operation of large reactivity components should be performed during shutdown cooling periods, whereas the manipulation of small reactivity components can be performed without reactor shutdown.

The lifespan of a vessel-type HFR depends primarily on the life of its pressure vessel, which is determined by the irradiation effect of fast neutrons (energy typically higher than 0.1 MeV). Early designed HFRs opted for pressure vessel replacement, such as HFIR. The SM-3 reactor was constructed with a new pressure vessel inside the old one [22]. Therefore, monitoring the fast neutron

fluence in pressure vessels is necessary during the lifespan of HFRs. HFETR uses SUS321 stainless-steel rods instead of aluminum rods in the outermost reflector to extend the life of the pressure vessel.

4 Applications of High Flux Reactors

According to statistical data from the IAEA website [8], the applications of operational research reactors are summarized in Table 3 . Due to its stronger irradiation capability and more complete experimental facilities, the HFR typically has significant advantages over other research reactors in various application areas. As shown in Fig. 11 [Figure 11: see original paper], based on the demand and importance of irradiation missions, the HFR is primarily applied in nuclear fuel and material tests, radioisotope production for medical and industrial use, and neutron science research.

4.1.1 Fuel Irradiation Tests

To further satisfy requirements for improving the efficiency, reliability, and safety of nuclear power plants, innovative fuel assemblies are continuously being developed to increase fuel burnup, extend refueling cycles, and enhance safety margins and reliability.

The technical parameters considered in nuclear fuel irradiation primarily involve neutron flux [63,64], neutron energy spectrum, channel dimension, gas environment, online monitoring, and fuel failure rate. Fuel irradiation tests [65] are primarily conducted in irradiation loops, which are completely sealed and isolated from the reactor core to prevent radiation contamination even if the tested fuel assembly is damaged. Simulation of nuclear fuel behavior under transient and accident conditions can also be conducted in specific irradiation loops. During irradiation, fission power of the fuel assemblies and gamma radiation increase the reactor core temperature. Fuel irradiation samples containing more fissionable materials require higher cooling rates and larger experimental volumes, which should also receive more attention.

Existing HFRs used for fuel tests typically utilize thermal neutrons. Rod-bundle test fuel assemblies are adopted for irradiation tests of pressurized water-cooled reactor fuels. A 4$\times$4 test assembly contains four guide tubes and 12 test fuel rods with different fuel densities, enrichments, and other parameters. The actual operating conditions of PWR fuel assemblies are simulated during irradiation tests. From 2012 to 2014, HTR-PM fuel pebbles were irradiated in HFRs for qualification tests, with a total irradiation time of 355 EFPD [66]. Five fuel pebbles were fixed in the irradiation capsule, which was placed in the sweep loop irradiation test facility, and the central pebble temperature was maintained at 1050 $\pm$ 50 °C. Post-irradiation examination showed satisfactory performance of the HTR-PM fuel pebbles, with no particle failure. Micro fuel testing has also become an important application, such as that performed in HFIR [67]. The micro fuel sample can be encapsulated in a sealed target and placed in a

basket through which primary coolant flows without requiring an independent test loop.

With the development of advanced nuclear reactors, the demand for fast reactor fuel tests is increasing, e.g., U-Zr alloy, U-Pu-Zr alloy, UPuN, and MOX fuels. Therefore, an irradiation testing circuit suitable for fast reactor fuel irradiation should be constructed to satisfy requirements for special working fluids, neutron fluence, and radiation damage dose.

4.1.2 Material Irradiation Tests

To achieve better technical specifications and safety, advanced nuclear energy systems typically use innovative materials with better radiation or corrosion resistance and the ability to withstand higher operating temperatures [68-70]. The irradiation temperatures and radiation damage required for different advanced nuclear energy systems [71] are shown in Fig. 12 [Figure 12: see original paper].

The irradiation temperatures required for advanced nuclear reactors, particularly VHTR (650–1050 °C), GFR (550–900 °C), MSR (550–700 °C), and fusion reactor (300–1000 °C), are generally higher than those of conventional fission reactors. The required radiation damage doses are also much higher, such as those in fusion reactors (150–200 dpa), MSR (100–180 dpa), SFR (90–160 dpa), and LFR (50–130 dpa). To fulfill the irradiation requirements of materials used in these innovative reactors, both the temperature and fast neutron fluence of the HFR should be improved.

For example, ATR is primarily used for fuel and material irradiation tests, and multiple material irradiation tests have been conducted [72]. Instrumented lead experiments are used to perform irradiation tests on structural materials, cladding, and fuel pins. Six pressurized water loops installed in the flux traps can be used for irradiation of structural materials, cladding, tubing, and fuel assemblies. Materials and fuels for naval reactors, high-temperature gas-cooled reactors, and Magnox reactors have been irradiated using ATR [72]. The fuel assemblies used in the Soviet Union's nuclear thermal propulsion were tested in the IVG.1M and IGR reactors [73].

4.2 Radioisotope Production

Radioisotopes [74] have wide applications in industry, medicine, agriculture, and related fields. Most industrial and medical radioisotopes, particularly neutron-rich radioisotopes with high specific activities, are produced by HFRs worldwide. Medical radioisotopes [75] form an important foundation of nuclear medicine, with applications primarily in diagnostics (medical imaging) and therapy (radiation used to kill cancer cells or lesions). Some transplutonium isotopes such as ^{238}Pu, ^{241}Am, ^{249}Bk, ^{252}Cf, etc., play an irreplaceable role in industry, nondestructive detection, aerospace heat sources, reactor startups, and scientific

research. Several isotope-based radioactive sources are required in industrial and agricultural areas, including ^{60}Co, ^{137}Cs, and ^{191}Ir.

Radioisotopes are primarily produced through neutron-induced reactions (such as (n,γ), (n,α), (n,p), and (n,f)) occurring in irradiation targets. Most reactions involve radiative capture and fission [74]. In the radiative capture method, the product and target nuclides belong to the same element; therefore, chemical separation of the product nuclide from the target is frequently disabled, which reduces the specific activity of the product to some extent. Multiple types of radioisotopes can be obtained using the fission method, which facilitates acquisition of carrier-free radioisotopes with high specific activity.

The preparation of radioisotopes involves several continuous processes [74], including appropriate selection of target materials, target fabrication and encapsulation, irradiation in the reactor, transportation to the hot cell, target disassembly, radioisotope separation and purification, processing and source encapsulation, quality control, product packaging, and shipping. During the procedure of loading irradiation targets in the reactor core, irradiation positions and periods are flexibly chosen according to requirements for producing different types of radioisotopes based on neutron fluxes and spectra. Radioisotope preparation requires radiochemical post-processing of irradiation targets, and radiochemical processing must be conducted in hot cells with corresponding radiation protection requirements. Radioisotope products should also satisfy quality control requirements, and specific activity, chemical purity, and radiochemical purity are the three main parameters for assessing radioisotope product quality. For medical radioisotopes, the production process requires establishment of a QA/QC system and good manufacturing practices (GMP) requirements [76].

4.2.1 Rare Isotopes Production Transplutonium elements (such as Pu, Am, Cm, Bk, Cf, Es, and Fm) include plutonium and its subsequent homologous elements in the periodic table. These nuclides are all prepared through artificial nuclear reactions due to their limited production amounts and rather difficult production processes; they are also referred to as rare isotopes.

The radioisotopes produced in an HFR are closely related to the neutron flux level. The production of transplutonium nuclides [77-80], such as ^{249}Bk, ^{252}Cf, and ^{253}Es, requires ultra-high thermal or resonant neutron flux. Industrial radioisotopes with long half-lives typically require long irradiation periods.

The production of transplutonium nuclides such as ^{252}Cf is complex and technically challenging [81]. The conversion chain of ^{252}Cf from ^{242}Pu, ^{241}Am, ^{244}Cm, or other target nuclides involves a series of more than 10 neutron capture reactions. Intermediate nuclides such as ^{242}Am, ^{245}Cm, and ^{247}Cm have large fission cross-sections, and the thermal neutron absorption cross-sections of ^{246}Cm and ^{248}Cm are relatively small, which results in a very low yield of ^{252}Cf. Therefore, ^{252}Cf production requires higher thermal neutron flux (the average thermal neutron flux is typically larger than 1.5$\times10^{15}$ n/(cm^2 $\cdot$ s)), and fission losses

during irradiation should be controlled as low as possible. Currently, only the USA and Russia can produce transplutonium nuclides on an industrial scale. The maximum thermal neutron fluxes of HFIR and SM-3 are both larger than 5.0$×10^{15}$ n/(cm^2·s), and the irradiation targets are located in the central neutron flux trap in the reactor core. ^{252}Cf production in the USA began in 1952 by irradiating ^{239}Pu in MTR, and large-scale production was initiated in 1966 after the establishment of HFIR and REDC at ORNL. A total of 78 production campaigns for transplutonium nuclides were performed until 2019, with accumulated production of ^{252}Cf reaching 10.2 g while preparing ^{249}Bk (1.2 g), ^{253}Es (39 mg), ^{257}Fm (15 pg; 1 pg = 10^{-12} g) and other nuclides [79]. SM-3 was used for ^{252}Cf production, adopting actinide oxide aluminum metal ceramic targets.

The preparation of transplutonium targets is one of the most important issues in transplutonium production. The flowchart is shown in Fig. 13 [Figure 13: see original paper]. Irradiation targets are typically aluminum-based materials (plutonium, americium, and curium) containing transplutonium oxides. This type of target aids in improving thermal conductivity and preventing sintering of transplutonium oxide ceramics. The main approach for large-scale ^{252}Cf production depends on irradiating ^{242}Pu or mixed americium/curium targets. Due to the large cross-sections of many target nuclei (such as ^{239}Pu, ^{242}Pu, ^{242}Am, ^{244}Cm, etc.), the target material density should be reduced to decrease the self-shielding effect of the target nucleus and heat released in the target during irradiation. The quality and safety of the fabrication and encapsulation process of the transplutonium target should be well controlled, which involves high-temperature and radiation-resistant target preparation technology and high-sealing welding technology for irradiation targets.

By analyzing the cross-sectional energy spectrum distribution of intermediate nuclides in the conversion chain of transplutonium nuclides, the neutron capture cross-sections of major nuclides such as americium/curium are relatively large in the resonance energy region, which can increase the probability and yield of neutron absorption by transplutonium nuclides. This means that transplutonium production amounts can be further optimized by adjusting the neutron spectrum of the irradiation target to increase the capture-to-fission ratio [81-83].

Transplutonium targets typically operate continuously in the reactor for nearly six to eight months. The irradiated targets are uploaded from the reactor core and transported to hot cells for radiochemical reprocessing. The post-processing primarily includes target dissolution, co-decontamination of transplutonium and lanthanide elements, separation of transplutonium and lanthanide elements, and transplutonium separation.

4.2.2 Medical Isotopes Production Nuclear medicine [84] is one of the most important applications of radiation and nuclear technology. In contrast to external radiation therapy, radioactive materials are transported into organs to be examined or treated based on the patient's metabolism. Radioisotopes for

medical applications (such as ^{99}Mo and ^{131}I) form the basis of nuclear medicine and healthcare. Due to the short half-life of radioisotopes, nuclides are difficult to store over long terms.

High or ultra-high neutron flux increases the efficiency of producing medical radioisotopes with high specific activity in shorter times. The production of medical radioisotopes (such as ^{60}Co, ^{63}Ni, ^{89}Sr, ^{90}Y, and ^{177}Lu) on an industrial scale typically requires a neutron flux larger than 10^{14} n/(cm^2 · s), and higher neutron flux contributes to achieving higher specific activities. Short-lived medical radioisotopes frequently require online processing of irradiation targets. A broader neutron energy spectrum provides more flexible selection for irradiating a radioisotope target with an appropriate neutron flux. The production of radioisotopes that are fission products typically involves two approaches: the fission-based method and the radiative capture method (or activation method). OPAL was one of the earliest HFRs to use an LEU target for ^{99}Mo irradiation. The fission method facilitates acquisition of carrier-free medical radioisotopes with high specific activity. In addition, the radiative capture method is more sensitive to the neutron flux level; thus, HFRs have potential advantages for increasing specific activity through the activation method.

The HFRs used for medical isotope production and supply include HFR (Netherlands), BR2 (Belgium), SAFARI-1 (South Africa), and OPAL (Australia). The main radioisotope products are ^{99}Mo/^{99}mTc, ^{177}Lu, ^{89}Sr, and ^{131}I. In the coming years, several major medical radioisotope production reactors worldwide will encounter issues such as aging, shutdown, and decommissioning. After 2030, only OPAL and FRM-II will be able to supply medical isotopes on a large scale. The production capacity gap for medical radioisotopes remains significant, with global shortages of ^{99}Mo and ^{177}Lu exceeding 10,000 Ci/week and 50,000 Ci/year, respectively. The global supply-demand contradiction will further intensify, and important medical radioisotopes will face shortage risks. To satisfy demands for radioisotope production, the Dutch government approved construction of a novel HFR, PALLAS [85], in 2012 to replace the operating HFR in Petten. The PALLAS reactor will have a thermal power of 55 MW with a design lifespan of 40 years and will be primarily used for producing medical radioisotopes. Construction has already begun.

The irradiation periods of several radioisotopes with short half-lives are shorter than the refueling period, such as ^{99}Mo, whose production reaches an equilibrium value after an irradiation period of 5–7 days. Excess irradiation will not increase production amount and will increase the concentration of radioisotopes with long half-lives and high-level radioactivity. Therefore, online processing of the irradiation target is required, which involves pressure boundary sealing issues caused by the top opening of the pressure vessel. The quality control limitations of radioisotope targets include the maximum reactivity disturbance limit, cooling flow limit, and gamma heat release rate of the material.

4.3.1 Neutron Scattering

Neutron scattering technology [86] is based on measuring and analyzing changes in momentum and energy after interaction between thermal neutrons (or cold neutrons) and materials, and can be used to study the microstructure and dynamics of materials. Cold neutrons are neutrons with energy levels of meV or lower that are suitable for neutron scattering, neutron imaging, and other applications. Neutron scattering involves neutron diffraction, large-scale structural scattering, inelastic scattering, and other effective means [87,88]. Typical neutron scattering spectrometers include small-angle neutron scattering, time-of-flight polarized neutron reflection, and cold-neutron triple-axis spectrometers.

The quality of the neutron beam emitted from the reactor core is related to the position and angle of the neutron beam channel, which should be determined during HFR design. A neutron scattering spectrometer is selected based on the characteristics of the reactor core design. HFIR has four horizontal neutron beam tubes and 15 neutron scattering spectrometers [11].

Thermal neutron experimental spectrometers are typically arranged around the reactor core and utilize neutrons extracted from horizontal neutron channels. Thermal neutron scattering spectrometers include neutron stress analysis, thermal neutron triaxial, and neutron diffraction spectrometers [89], etc. The moderating effect of thermal neutrons increases the proportion of cold neutrons in the neutron energy spectrum. Cold neutrons with longer wavelengths are suitable for structural testing in the nanometer to submicron range, as well as for inelastic scattering measurements in the energy range below 10 meV. A mirror-structured guide tube can be used to guide neutrons over long distances to suitable spectrometers at appropriate positions. However, thermal neutrons cannot be released through a mirror-structured guide tube, which results in significant losses along the path. Ordinary cold neutron scattering spectrometers typically include small-angle neutron scattering spectrometers, time-of-flight polarized neutron spectrometers, and cold neutron triaxial spectrometers.

4.3.2 Neutron Imaging

For neutron imaging [90,91], the attenuation of intensity of a neutron beam passing through an object is used to perform perspective imaging of the measured object. Therefore, microstructure, spatial distribution, density, multiple defects, and related information on sample materials can be presented at a certain resolution.

Neutron imaging devices can be divided into fast neutron [92], thermal neutron [93], and cold neutron imaging devices [94]. Fast neutron imaging is suitable for testing large samples of various materials. The thermal neutron imaging device is located near the reactor core and has a high neutron flux, which is suitable for real-time imaging and large-scale sample testing. By selecting different filters and intercepting neutrons in different energy spectra, thermal neutron, epithermal neutron, and fast neutron imaging can be achieved. The cold neutron

imaging facility in the cold neutron experiment hall has a low background and is suitable for application in high-resolution, symmetrical, and polarized neutron imaging. The non-destructive detection approach has significant technical advantages compared with X-rays and other traditional radiography technologies, making it suitable for imaging turbine blades, high-speed rail wheels, and nuclear fuel assemblies. In recent years, the combination of neutron imaging with digital technology and artificial intelligence has helped improve imaging effects and achieve a wider range of applications [87].

4.3.3 Neutron Activation Analysis

NAA [95,96] is a non-destructive nuclear analysis method that uses a neutron beam with certain energy and current intensity to bombard a sample, resulting in activation of the measured element into a radioactive nuclide and measurement of the characteristic gamma-ray energy and intensity released by the generated nucleus. NAA technology has wide applications in physics, chemistry, materials, and energy. NAA can analyze multiple elements with high sensitivity, high accuracy, and low pollution, and is suitable for detecting samples in a wide range of sizes over shorter periods.

Compared with accelerator neutron sources and radioisotope neutron sources, the HFR neutron source has high neutron fluence, large activation cross-section for most elements, satisfactory spatial uniformity of neutron flux, and simple nuclear reaction pathway, which results in lower detection limits and higher sensitivity and accuracy. The reactor contains an NAA laboratory that analyzes samples irradiated in large pneumatic transport irradiation tubes for only a few minutes. They arrive at the laboratory within seconds from the reactor, and activation products with very short half-lives can be analyzed.

4.4 Other Applications

In addition to the major application fields described above, HFRs have extensive applications in other areas such as neutrino detection, silicon transmutation doping, and neutron therapy.

Neutrinos [97] are among the most fundamental particles in nature. They participate only in weak and gravitational interactions, have minimal interactions with matter, and exhibit extremely strong penetrating abilities. Neutrino research has always been at the forefront of particle physics research, which can help us understand the origin of matter and the universe and reveal the physical principles of the internal structure and evolution of celestial bodies, such as the sun and supernovae. The HFR has a compact reactor core with intensive neutrons, which is suitable for detecting ultrashort baseline neutrino oscillations and accurately measuring reactor-based antineutrino spectra while providing support for measurement of neutrino mass sequence [98-100]. In addition, performing basic physics research on neutrinos helps in understanding the nuclear reaction process inside fission reactors. PROSPECT [99] is a neutrino experiment facility

installed in HFIR that is used to accurately measure the antineutrino spectrum of highly enriched uranium-fueled reactors and detect sterile neutrinos at an energy level of eV by searching for neutrino oscillations on a few-meter-long baseline.

Silicon transmutation doping [101-103] is widely used to dope silicon with phosphorus through the neutron capture reaction of ^{30}Si(n,γ)^{31}Si with subsequent beta decay to ^{31}P. Irradiated silicon is used to produce high-quality semiconductors. Silicon doping primarily utilizes the thermal neutron flux, and the fast neutron and gamma fluxes should be as low as possible. Silicon doping does not have very high requirements for neutron flux levels, and the irradiation facility is simpler; however, a larger irradiation space is required to accommodate a silicon ingot with a diameter of 8–12 inches. Therefore, this type of irradiation is suitable for pool-type HFRs, and a silicon ingot can be placed in the reflector surrounding the reactor core. Furthermore, the uniformity of irradiation and neutron spectrum screens should be considered in the design of silicon-doping schemes.

Reactor-based neutron therapy [104] is an important medical treatment approach, and the physical basis is neutron absorption reactions, such as ^{10}B(n,α)^{7}Li, ^{6}Li(n,α)^{3}H, or ^{157}Gd(n,γ)^{158}Gd. The radiation released through these reactions is typically in the MeV range and results in high linear energy transfer (LET). The resulting biological effects are concentrated in the treated tissues. Boron neutron capture therapy (BNCT) [105] utilizes a thermal neutron beam to treat shallow tumors. Such facilities are typically located near hospitals. For the HFR, building a comprehensive therapy base for neutron therapy is appropriate. However, radiation protection and more flexible arrangement should be considered.

5 Future Trends

To satisfy future research and development requirements for advanced nuclear power systems, newly designed HFRs are pursuing better performance in the following aspects:

1. **Higher Technical Parameters**
   The design of a novel HFR frequently requires higher technical parameters, including higher neutron flux, wider energy spectrum range, and better irradiation performance. For fast neutron spectrum irradiation, the fast neutron flux should typically lie in the range of 10^{12} to 10^{15} n/(cm^2 · s) with a radiation damage of 20–30 dpa per year. To achieve higher neutron flux, the power density of the reactor core should be increased as much as possible at an appropriate power level, typically adopting a compact reactor core structure. Additionally, the structural scheme of the reactor body, fuel assembly scheme, control approach, and coolant system should be determined. A broader neutron spectrum range is beneficial for various experiments such as radioisotope production and material irradiation tests

[106]. The neutron spectrum of the irradiation device could be optimized by arranging neutron flux traps in the reactor core, selecting irradiation channel structures, and reasonably absorbing materials to improve neutron utilization in irradiation experiments. Newly built HFRs are typically equipped with multiple irradiation test loops with different irradiation environments for material tests and improved online information collection capability of the irradiation device with accurate detection information on temperature, pressure, and fission gas concentration to further enhance HFR irradiation capability.

2. **Higher Nuclear Safety Characteristics**
While pursuing higher technical specifications, the safety goals for building new HFRs are constantly improving, and higher nuclear safety standards must be satisfied to ensure reactor safety under normal operating and accident conditions. The reactor should be designed with satisfactory inherent safety, which typically presents as a large negative reactivity temperature coefficient and strong self-protection capability. Innovative HFRs typically adopt passive safety systems and engineered safety facilities (primary pressure relief, safety injection, boron injection, containment isolation, and residual heat removal systems) to further improve reactor safety and mitigate accident consequences. The automation level of newly built HFRs should be appropriately improved to minimize reliance on operators and avoid the impact of human factors on HFR safety.

3. **Comprehensive Versatility**
The comprehensive use of irradiation resources is an important challenge for the application of new HFRs and is also an optimal way to fully utilize HFR irradiation resources. HFRs often prioritize one or more functions when considering other applications. For example, in HFRs dedicated to radioisotope production, targets are always arranged in irradiation channels with higher thermal neutron fluxes. The application of material irradiation tests and neutron beam extraction can also be considered as supplementary schemes. This design approach is beneficial for improving neutron utilization efficiency. The design of an innovative HFR is typically recommended to satisfy requirements for comprehensive versatility.

4. **Application of Innovative Technology**
The design and construction of an HFR is a complex system engineering project with high technical difficulty and a relatively long development cycle, involving a combination of multiple disciplines such as nuclear physics, fluid mechanics, thermodynamics, structural mechanics, and control technology. The use of several new technologies, such as digital technology, can improve the efficiency of design and engineering construction [38]. Digital systems adopt technologies such as digital twins and model-based systems engineering (MBSE) to build a digital design platform, digital engineering construction and debugging platform, digital delivery platform, and intelligent operation platform, providing efficient digital support for

HFR development.

The following suggestions are proposed for future development, design, and application of HFRs:

1. The main challenge in developing HFRs is improving neutron flux while ensuring safety. A multipurpose HFR with comprehensive utilization of irradiation resources is one of the development directions. The simultaneous development of various HFR types is recommended. For example, a water-cooled high flux thermal neutron reactor is suitable for producing radioisotopes, particularly rare nuclides, and can achieve ultra-high thermal neutron flux with a mature nuclear engineering foundation. To address increasing demands for radiation damage to nuclear materials, a high flux fast-spectrum reactor is required, such as a sodium-cooled or lead-bismuth-cooled reactor.

2. In HFR design, the relationship between reactor core design and primary technical parameters (such as neutron flux, radiation damage, and operation period) should be considered. The design procedure depends on application requirements, which is suitable for establishing a goal-oriented design system. Reactor design should achieve optimal parameters for specific applications. A high utilization rate in HFR operation is also recommended.

3. To satisfy irradiation requirements of advanced nuclear fuel and materials, newly built systems should fulfill special irradiation parameter requirements (such as high neutron flux, sufficient irradiation volume, and sufficient irradiation damage) with specialized irradiation devices. The irradiation test facility is recommended to operate with special media such as liquid metal, molten salt, and supercritical water. The irradiation experiment should be capable of online monitoring of irradiation test parameters with high reliability. The HFR should also be equipped with advanced post-processing facilities to produce radioisotope products or perform fuel and material post-examinations. Irradiation test technology should match the reactor structure and specific irradiation test forms, including specimen partition layout, irradiation device design, irradiation parameter monitoring and control, and comprehensive irradiation environment control technologies. The irradiation test design should fully satisfy irradiation index requirements of specimens and ensure safety of irradiation tests and reactor operation. Due to demands for new irradiation tests, development of irradiation test technologies with a wider range of applications, more measurement parameters, and higher precision indicator control capabilities should be accelerated.

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Note: Figure translations are in progress. See original paper for figures.