Current status and technology development tendency of research reactors in China

Ke Guotu, Shen Feng, Zhao Shouzhi, Zhang Weiguo, Yuan Luzheng
(China Institute of Atomic Energy, Beijing 102413, China)

Abstract: The current status and development history of domestic and abroad research reactors (RRs) are mentioned. The representative RRs and their respective technology characteristics are introduced. The utilizations of China's RRs, mainly included as nuclear engineering technology, basic research applications of nuclear technology, teaching and personnel training, are explained.
Key words: current status; research reactor; nuclear technology development tendency; nuclear technology utilization

1 Introduction

Since the beginning of last century, nuclear technologies have made great progress in the world. Nuclear reactor is one of the important facilities which effectively promote the developments of nuclear science and technology and have a great effect on human being. Research reactors (RRs), as basic establishments providing neutron and gamma rays for multi-fields applications, are important facilities which were built and put into utilization in the early time and are still developed and improved with the progress of the nuclear technology and its extension sciences and technologies.

According to RRDB (RR DataBase) of IAEA in Apr., 2009, there are overall 665 RRs world wide. Among them, 237 RRs are still in operation, 9 temporary shutdowns, 5 still under construction, and 237 already shutdown without being decommissioned, 176 decommissioned and 1 planned. Among the operational RRs, there are 40 critical assemblies (usually zero power), 58 pool RRs, 25 tank-in-pool RRs, 29 TRIGA RRs, 12 fast RRs, 9 heavy water RRs, 9 MNSRs, 6 Canada SlowPoke RRs, 4 Subcritical Facilities, 4 ARGONAUT RRs and other 12 RRs. The general statistics show in the Fig. 1. The power distribution of operational RRs is summarized in Fig. 2.

The comprehensive abilities, such as regulations and standard system and quality assurance system, design, construction, operation and maintenance, decommission, training, etc., have been established and well developed in China until now. The information of main RRs in China and their related technical characteristics as well as utilizations are introduced in this paper.

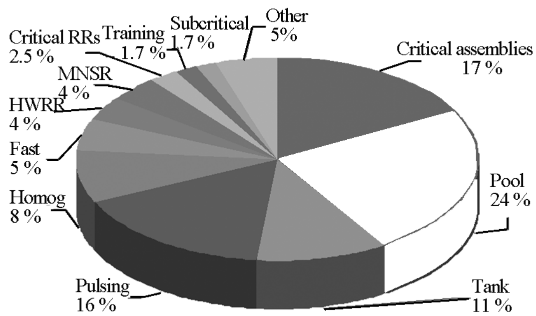

Fig. 1 RRs classification information

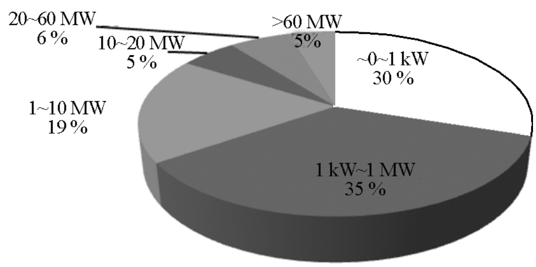

Fig. 2 Power distribution of the operational RRs

2 Current status of China's RRs and utilizations

2.1 General information and development history

The name, thermal power, current status and first criticality date of China's RRs are listed in Table 1.

Received 30 *September* 2009

Table 1 General information of RR in China

Facility name	Thermal power/kW	Status	First criticality date
HWRR-II①	15 000	OPER	1958/9/1
TSINGHUA UNIV.	1 000	OPER	1964/10/1
SPR IAE	3 500	OPER	1964/12/20
ZERO POWER REACTOR	0	SHUT	1966/1/1
ZPR FAST	0.05	OPER	1970/6/29
HFETR CRITICAL	0	OPER	1979/6/20
SPRR-300	3 000	OPER	1979/6/28
HFETR	125 000	OPER	1979/12/27
MNSR IAE	27	OPER	1984/3/10
MNSR-SZ	30	OPER	1988/11/1
MNSR-SD	33	OPER	1989/5/1
NHR-5	5 000	OPER	1989/11/3
PPR PULSING	1 000	OPER	1990/8/1
MJTR	5 000	OPER	1991/3/2
MNSR-SH	30	OPER	1991/12/18
HTR-10	10 000	OPER	2000/12/21
CFER	65 000	CONS	
CARR	60 000	CONS	

Note: ① II means upgraded

The development history of RRs in China can be summarized and divided into three stages.

1) Starting (1950s) HWRR, with the power of 10 MW, is the first reactor in China. With the method of import, China rapidly mastered related technology, setup related science fields and trained large number of specialists. It becomes the start point of flourish of China's nuclear Science and Technology (S&T).

2) Local R&D and forming scale (1960s to the early 1990s) Several reactors had been constructed by China through local R&D. For example, several swimming pool research reactors, HFETR, several MNSRs (5 for export, 4 for domestic) and PPR Pulsing, etc. In this period, HWRR was upgraded with higher thermal power and thermal neutron flux, larger irradiation space, more utilization fields, etc.

The characteristics of this period are mastering RRs technology, forming the large scale utilizations of RRs, driving and supporting the foundation and development of nuclear S&T industrial system in China.

3) Innovation and development (1990s to present) The advanced RR, which is coincidental with world's tendency, is developed by China. China Advanced Research Reactor (CARR) is a typical example. This kind of RR has the characteristics of high performance, multipurpose, high safety and reliability. It could meet the requirements of nuclear engineering technology, basic research and nuclear technology applications. Among the similar RRs, the comprehensive performance of CARR is ranked as No. 1 in Asia and No. 3 in the world.

In order to develop the advanced nuclear energy system, China constructed China Experiment Fast Reactor (CEFR) and High Temperature Reactor (HTR). Simultaneously, the nuclear desalinization facility, RI production reactor and Accelerator Driving Subcritical (ADS) System are researched and developed in China.

2.2 Main RRs and technology characteristic

2.2.1 SPR IAE

SPR IAE is a research reactor moderated and cooled by light water. Its rated power is 3.5 MW and reinforced power is 5.0 MW. It was built from 1959 and approached first criticality on Dec. 20, 1964. It was mainly used for fuel element test and material irradiation test in the early time. Now it has been improved into a multipurpose and comprehensive utilization reactor that is mainly used for the RIs production, NTD silicon, material irradiation test, topaz irradiation colorization, medicine irradiation, and in-pile measurement technology, etc.

The reactor has the characteristics of high inherent safety, simple configuration and flexible arrangement. Its main technical parameters are listed in Table 2. Its main control room and core layout are shown in Fig. 3 and Fig. 4.

Table 2 The main technical parameters of typical reactors

Name	MNSR-I	SPR IAE	HFETR	HWRR	CARR	PPR-PULSING	NHR5	HTR10	CEFR
Power/MW	0.03	3.5	125	15	60	1	5	10	65
Fuel	UO_2 LEU 12.5 %	UO_2-Mg LEU 10 %	UAl_x HEU 90 %	UO_2 LEU 3.0 %	U_3Si_2 LEU 19.75 %	$UZrH_{1.6}$ LEU	UO_2 LEU	UO_2 LEU	UO_2 HEU 64.4 %
Clad.	Zr-4	Al	Zr-2	Zr-2	Al	S. S	Zr-4	Graphite	S. S
^{235}U, kg①	1.12	5.6	13	7.68	11.0	——	24.6	16.10	367
Control rods②	1SR 1RR 1AUR	4SR 2RR 7SHR	2SR 14RR 2SHR 4	4 SR 2 RR 8SHR	2SR 1RR 3SHR	1SR 1RR 1SHR 1PR	1SR 2RR 10SHR	10CR	3SR 2RR 3SHR
Vert. channels	4	20	11	33	26	——	No	No	——
Φ_{th}/ $cm^{-2}\cdot s^{-1}$③	1×10^{12}	5.2×10^{13}	1.2×10^{15}	2.4×10^{14}	8×10^{14}	——	Not useful	Not useful	3.5×10^{15}

Note: ① Initial loading; ② SR-Safety Rod, RR-Regulation Rod, SHR-Shim Rod, AUR-auxiliary control rod, PR-Pulsing Rod; ③ Maximum unperturbed neutron flux in vertical channels used for utilization

Fig. 3 Main Control Room of SPR IAE

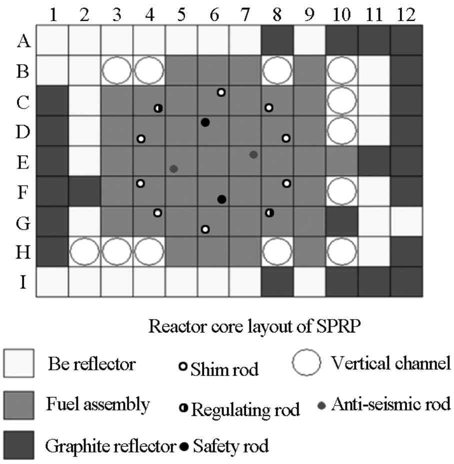

Fig. 4 The core layout of SPR IAE

2.2.2 HFETR

HFETR, rated power of 125 MW, is a pressurized water reactor which is moderated and cooled by light water, adopting by U–Al metal fuel in multilayer tube with High Enrichment Uranium (HEU), and reflected by Beryllium. It is initially critical on Dec. 27, 1980. It is mainly used for long term fuel irradiation test and material irradiation test and damage research, and for RIs and NTD silicon production, NAA, etc.

The reactor has the characteristics of high power and neutron flux, large irradiation space. Its main technical parameters are listed in Table 2. The top view of HFETR is shown in Fig. 5.

2.2.3 HWRR-II

HWRR-II is a tank type reactor with heavy water as coolant and moderator, Zr-2 alloy as cladding and graphite as reflector. Its rated power is 15 MW after upgrade and maximum thermal neutron flux 2.4×10^{14} $cm^{-2} \cdot s^{-1}$. It is suitable for thermal neutron physical experiment, RIs production, etc.

The reactor has the advantages of high ratio of thermal neutron flux to power, large irradiation space and low gamma ray background. Its main technical parameters are listed in Table 2. The top view and main

Fig. 5 The top view of HFETR

control room of HWRR-II and bird's view of ES-SALAM (HWRR type) in Algeria (imported from China) are shown in Fig. 6 to Fig. 8.

Fig. 6 Top view of HWRR-II

Fig. 7 Main control room of HWRR-II

2.2.4 Test reactor

In order to master the related engineering technology of specific reactor, some test reactors were built in China, for example, CEFR, High Temperature Gas cooled Reactor (HTGR), low temperature Nuclear Heating Reactor (NHR).

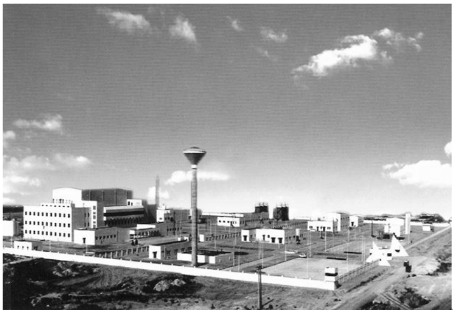

Fig. 8　Bird's view of ES-SALAM in Algeria

Fast reactor is one candidate of generation IV nuclear energy system with the characteristic of resource-friendly and environment-friendly, and possesses advantages of improving utilization of uranium and burning radioactive waste. CEFR, used for experiment and electricity production, is being built in China, and will be of initial criticality recently and be connected to the grid in 2010. The reactor complex and outside view are shown in Fig. 9 and Fig. 10.

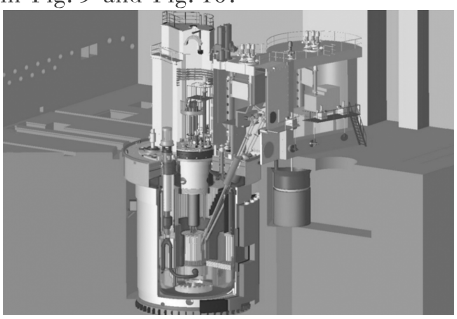

Fig. 9　The Reactor complex of CEFR

Fig. 10　The outside view of CEFR

HTGR, started its full power operation at the end of 2002, is a kind of advanced nuclear reactor with high electricity production efficiency and better safety features. The top view of HTR is shown in Fig. 11.

The NHR, with power of 5 MW, was built completely in 1989. This reactor has several advanced technical features such as integrated configuration, passive residual heat removal, etc. The exterior view and main control room of NHR is shown in Fig. 12.

Their main technical parameters are listed in

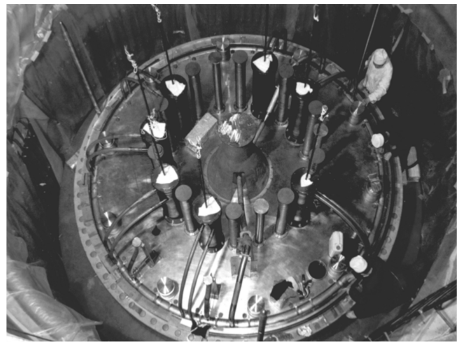

Fig. 11　The top view of HTR-10

Fig. 12　The exterior view and main control room of NHR

Table 2.

2.2.5　Others

Besides the RRs mentioned above, China has also built several zero power facilities, MNSRs and PPR Pulsing reactor.

1) FAST Zero Power Reactor (ZPR FAST) ZPR FAST is initially critical on June 29, 1970. Many research activities were carried out such as nuclear data assessment, calculation method verification and engineering physics simulation, etc. Some fast reactor measurement technologies and experiment methods were developed. The side view of ZPR FAST is shown in Fig. 13.

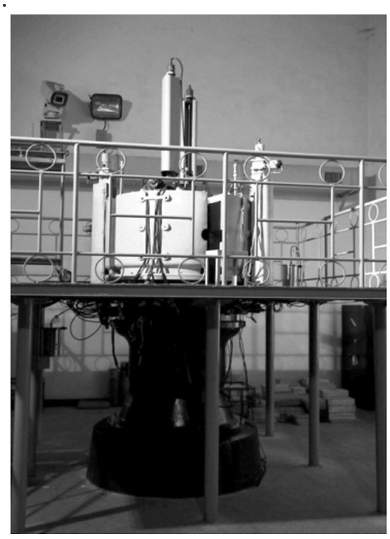

Fig. 13　The side view of ZPR FAST

2) Uranium Solution Zero Power Facility

(USZPF) It was June, 2002 when USZPF was initially critical. It adopted uranium solution as fuel and is used for nuclear critical safety research of key equipments in the fuel cycle. The top view of USZPF is shown in Fig. 14.

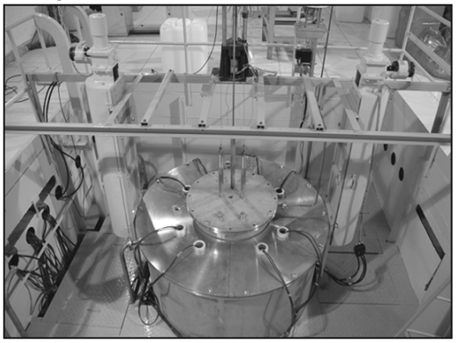

Fig. 14 The top view of USZPF

3) MNSR MNSR, with the power of 30 kW, uses light water as both moderator and coolant, beryllium metal as reflector, and natural circulation as cooling method. This reactor has high inherent safety and better radiowaste containing ability, so it could be built in the city. It is mainly used for NAA, short-lived RIs production and training.

Since 1984, 9 MNSRs had been constructed in domestic and abroad. Domestic 4 MNSRs are located in Beijing, Shenzhen, Jinan and Shanghai respectively. Other 5 MNSRs are located in Pakistan, Iran, Ghana, Syria and Nigeria respectively. Until now, it has accumulated 100 safe operation reactor years of MNSRs. The top view of MNSR is shown in Fig. 15.

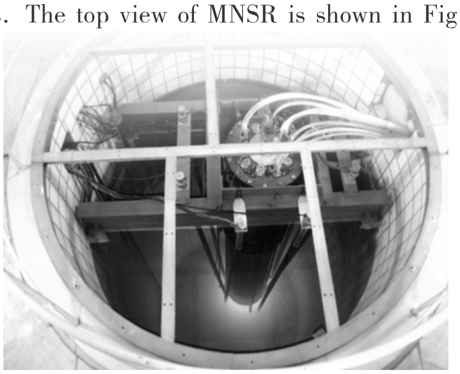

Fig. 15 The top view of MNSR

The conversion from High Enrichment Uranium (HEU) to Low Enrichment Uranium (LEU, ^{235}U enrichment < 20 %) could be upgraded only through replacing of one fuel assembly. The main technical parameters of upgraded MNSR (MNSR-I) are listed in Table 2 and its core configuration is shown in Fig. 16.

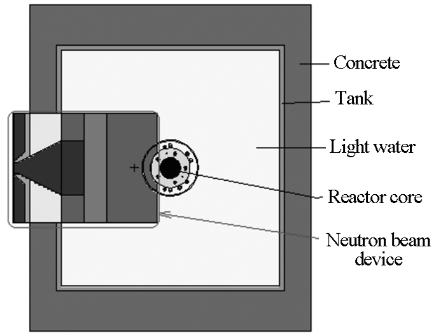

Fig. 16 The core configuration of MNSR-I

4) PPR pulsing reactor PPR pulsing reactor, designed and constructed by China, is a pool-type RR with $UZrH_{1.6}$ as fuel-moderator element. It approached first criticality on July 22, 1990. The top view of PPR pulsing is shown in Fig. 17.

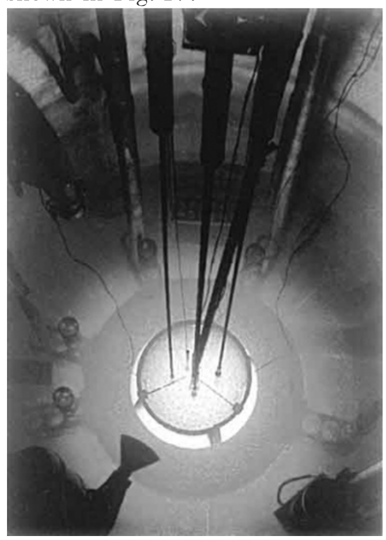

Fig. 17 The top view of PPR pulsing

2.3 RR utilizations

2.3.1 Nuclear engineering technology

1) Nuclear fuel research The irradiation test of fuel or fuel assembly, which include comprehensive performance test, safety experiment under accidental situation, further burnup, is conducted through the utilization of RRs.

The comprehensive performance test is used to validate the fuel design and manufacture processing. The safety experiment is used to research the interaction between pellet and cladding, the temperature distribution and the releasing action of gas fission production under the condition of anticipated transient.

The fuel irradiation test always needs a specific in-pile circulation loop and a hot cell for processing.

2) Materials irradiation properties research The components of reactor, such as fuel assembly, control rods, guide tubes, reactor pressurized vessels, shielding blanket, reflector, nuclear I&C, etc., are nee-

ded to bear high dose irradiation in reactor. For example, A508-3 steels used for RPV, fuel cladding materials, grid assembly materials and LT-21 aluminum alloys were irradiated in HWRR, SPR IAE, HFETR, etc.

Irradiation capsule and special circulation loop are normally adopted to irradiate materials in RRs. Dismantling, test and analysis for properties are carried out in hot cell after irradiation.

3) Nuclear measurements and detection technology RRs can provide effective platforms for R&D and test of the nuclear detectors, such as ionization chamber, counter, scintillation detector, semiconductor detector and Self Power Neutron Detector (SPND), etc., and equipments for thermal-hydraulic parameters measurement.

The radioactive source produced by RRs can be used for non-destructive detection, tracing and exploring mines.

2.3.2 Fundamental research

1) Nuclear physics Nuclear data measurement in RR is the most important method, since RR could provide a wider neutron energy range and a higher neutron flux.

2) NSE and applications Neutron Scattering Experiment (NSE) is the most important tool to research matter structure and is widely used in many fields such as condensed matter physics, biology physics, material science, etc., and is regarded as the best probe to the research of magnetic in solid matter, micro-dynamics and large bio-molecule structure.

The beam lines with different neutron energy could be guided out-pile for NSE. Besides of thermal neutron from thermal reactors, the Cold Neutron Source (CNS) and Hot Neutron Source (HNS) facilities could be installed in thermal RRs and guided out-pile for NSE.

3) Reactor physics research Many kinds of reactor physics experiment and research could be carried out in RRs, including neutron flux measurement, neutron spectrum measurement, reactivity measurement, dynamic parameter measurement, shielding experiment, verification of reactor physics design and program, nuclear criticality safety research, etc.

2.3.3 Applications of nuclear technology

1) RIs production and applications The R&D and production of Radio-Isotopes (RIs) are important applications of RR. By irradiating normal solid targets, fission targets and gas targets in RR, hundreds of RIs, such as ^{131}I, ^{153}Sm, ^{99}Mo, ^{125}I, etc., can be produced.

RIs have significant application value in many fields such as industry, agriculture, medicine and science research, etc. For instance, ^{60}Co source was widely used for irradiation industry including sterilization, seeds, property alteration, etc. The RI sources like ^{60}Co, ^{192}Ir, ^{169}Yb are used in the fields of industry radiography and irradiation detection. The RI sources like ^{99}Mo–^{99m}Tc, ^{131}I, ^{32}P, $^{12}5I$, ^{153}Sm, are used for nuclear medical and ^{32}P, ^{14}C, ^{3}H for tracing research.

2) NTD silicon production and application Neutron Transmutation Doping (NTD) silicon production in reactors began in 1970s in China. The NTD silicon has a better homogeneity than that of silicon with convention doping method. NTD silicon is edging out conventional zone doping silicon rapidly when it is used in large power high current electric device market. Many RRs with vertical irradiated channels in China produced NTD silicon for large requirements of China's market.

3) NAA Neutron Activation Analysis (NAA) is one of the most important applications of RRs. Thermal and cold neutron are mainly used in NAA for Reactor NAA (ReNAA), Prompt Gamma NAA (PGNAA) and Neutron Depth Profile (NDP), etc.

The NAA can be used for analyzing microelement content in the sample, and involved in nearly all scientific areas as geology, earth chemistry, environmental science, life science, meteorology, food science, archaeology, medicine, agriculture, industry, etc. Solid, liquid and gas samples are available to irradiate.

4) NRG Neutron Radiography (NRG) is one of the non-destructive detection imaging technologies, and could provide complementary information in comparison with X-ray or gamma images. 3D material distribution image can be generated with NRG. A strong and well collimated neutron beam on the RR is the prime prerequisite for a high performance NRG station.

5) Property change by irradiation Topaz, with the color of transparent yellow or light yellow, is relative cheap. After irradiation, the topaz can be changed to a gem with homogeneous bright or light blue. Consequently, the quality and aesthetic feeling of the irradiated topaz have been increased. This application usually can be carried out in light water RR.

2.3.4 Teaching and personnel training

Being different from long-term steady operation of NPP, RRs have advantages of convenient, frequent operation and simple operation, which are suitable for teaching and practical training of operators or employees engaged in physics experiment. A training combined with NPP simulator could have remarkable effects.

Various sorts of reactor physics experiments could be carried out in RRs to improve the staff's practice level and enhance their understanding of phenomena in the reactor. The feasible experiments mainly include neutron flux measurement, static measurement of nuclear parameters, dynamical reactivity measurement, etc.

3 Development tendency of RRs and their utilizations

3.1 Development tendency of RRs

At present, the development tendencies of RR are to improve reactor operation parameters, to expand the utilizations fields and functions, to amend the safety performance, and to reduce the operation costs. The general rules could be summarized as following several items.

3.1.1 Depending on main requirements

Which kind of reactor, that means fast reactor or thermal reactor, large power or small power, will be built depends on the main purpose and the technology. The RRs could be mostly classified into following several kinds according to the purposes.

1) Teaching They are mainly used for the mastery of the basic phenomenon in reactor, the physical experiment and training. They are generally zero power facilities and low power reactors.

2) Material irradiation test They are mainly used for irradiation test of fuel and material, and also reasonably for RIs production, NTD silicon production and NAA, etc.

3) Neutron beam application They are mainly used for NSE, which are for matter structure research and also reasonably for fuel irradiation test, NAA, NRG, NTD silicon and RIs production, etc.

3.1.2 High performance

With the in-depth research of RR and the improvement of research and design methods, the new-built RRs are more advanced. Under the precondition of designated application, the higher ratio of neutron flux to power, the better. A high ratio shows a high income with the same investment.

In order to have lager space for testing and irradiating specimens, the new-built RRs have generally larger space for irradiation. Normally, the RRs need different neutron spectrum for various irradiations. For example, the materials irradiation damage needs harder neutron spectrum, however, most RIs production, NAA, the application of thermal column and NSE need softer thermal neutron spectrum, so the RRs with the different neutron spectrum is relatively popular. Among the new-built or improved RRs, CARR, JRR-3M, OPAL, FRM-II, HANARO are considered as the RR with high performance.

3.1.3 Multipurpose

Because of the costs of construction and operation of the RR and human resource, most new-built RRs are multipurpose. The large power RR is mainly use for RIs and NTD production, NAA, NSE, fuel and material irradiation test, NRG and training. Other utilizations include Neutron Capture Therapy (NCT), nuclear pumped laser system, gemstone irradiation colorization, etc. Normally, NSE is the main utilization for the neutron beam reactor, and fuel and material irradiation test is accessorial utilization. It is vice versa for the materials test reactor.

3.1.4 High safety

The safety is constantly improved with the improvement of S&T. The nuclear and radiation safety of staff and public around the nuclear facilities is substantially improved by reducing the nuclear radiation risk through optimized design, adding safety features and sealing the building. The detailed methods include improving the automatic level, setting abundant shutdown systems, possessing high inherent safety, reasonably adopting passive safety system, etc.

3.1.5 Non-proliferation of nuclear

Normally, LEU fuel is adopted in the most new-built RRs in the world, in order to satisfy the requirements of Non-Proliferation of Nuclear. The LEU fuel alteration of operational RRs is gradually carried out at the same time.

3.2 Development tendency of RRs utilizations

RRs had played an important role on the aspect of the application of nuclear technology. The utilizations tendency is developed with more extensive fields but through the existing principle except for the existing utilizations.

3.2.1 Nuclear engineering technology

The various new fuel materials or configuration, such as U-Mo alloy, MOX fuel and annulus fuel element, have been proposed and will be undertaken the irradiation test according to the different needs, except for the existing comprehensive performance test. The important aspects are the research and development of fuel element, assembly, components and others construction materials used in NPPs on the background of rapid development in China. It is estimated that more material irradiation properties researches, nuclear measurements and detection technology researches will be flourished in the near future.

3.2.2 Fundamental research

Along with some advanced research reactor established in China and S&T development requirements from economics continuously increasing, the fundamental research on RRs is developing to large scale gradually. Especially like NSE on CARR, which has 9 horizontal channels with high thermal neutron flux and excellent cold neutron flux, it is the highest neutron flux in current Asia RRs and one of the highest neutron flux in the world, compared with the parameters of advanced research reactors as FRM-II in German and HFR in France.

It is scheduled that many apparatus are installing or will be installed on the CARR, such as high resolution powder diffractometer, high intensity powder diffractometer, residual stress diffractometer, texture neutron powder diffractometer, time of flight spectrometer, triple axis spectrometer, four circle diffractometer, neutron reflectometer, cold neutron triple axis spectrometer, neutron interferometer, neutron spin echo, small angle neutron spectrometers, etc. These apparatus will provide the good platforms for NSE in many fields, such as nuclear physics, life science, material science, chemistry detection, biology, food production technology, industry, agriculture, criminal investigation, material irradiation, nuclear astronomy, nuclear archaeology, nuclear medicine, etc.

3.2.3 Applications of nuclear technology

1) RIs production and applications The number of newly constructed RRs in the world is decreasing since the expansive cost for their operation and maintenance, and the old RRs are aging and large proportion of them is near shutdown. The RRs resources are precious and the necessary applications like RIs production will be hard works for existing RRs. For example, ^{99}Mo, ^{60}Co, ^{192}Ir, etc., as well as new developed RIs, are the important RIs irradiated by RRs.

Since the newly constructed RRs always are advanced RRs with high neutron flux, some RIs with very little absorption cross-section and very short life, could be irradiated by advanced RRs. For example, the ^{210}Po, ^{63}Ni, etc, could be irradiated by the RRs.

2) NTD silicon production and application NTD silicon promotes cost-reduction effect of an Insulation Gate Bipolar Transistor (IGBT) that is used effectively for power devices, such as hybrid cars. Therefore, the size requirement of the NTD silicon is gradually increased, output demand growing. And application fields are more and more wide. It is estimated that the large diameter, as large as 12 inches, will be strongly needed in the future.

3) NAA ReNAA is main utilization method of NAA and widely used in many fields in most RRs of China. Except the ReNAA, PGNAA and NDP will be widely utilized along with the CNS developed and put into operation in CARR in the future. The NAA, included PGNAA and NDP, will be utilized for much more fields.

4) NRG NRG will find extensive uses in the fields of industry application, geology, agriculture, archaeology, work of art, etc. For example, industry applications includes nuclear industry, medicine, material science, civil engineering, biology, auto industry, electrics and electrical engineering, air and space industry, oil and gas exploration, fuel cells, etc.

Furthermore, NRG will be well performed especially for the high neutron flux in RRs as CARR. Low neutron flux is used for static sample normally. Along with the RRs developed with high neutron flux, NRG could be used for the low absorption cross-section samples and as the online real-time radiograph for the flow samples. So, it could be used in the investigation the flow condition inside the opaque pipe like liquid sodium metal in S. S pipe, and the combustion states in engine, and so on. By the related software, the concrete configuration inside the opaque shell could be gotten.

5) NCT Boron Neutron Capture Therapy (BNCT) is considered to be one of the most effective therapy methods for curing cancer. The 5-year survival rate of shallow head tumor cured reaches an unprecedented record up to 33.3 %. BNCT has some advantages of accurate localization ability and remarkable curative effect, compared with other current therapy methods.

The neutron beam can be induced from the horizontal channels in RR and can be used for NCT with necessary medical equipments after well collimated. The neutron flux in most RRs is enough for this utilization in the condition of available irradiated time.

4 The R&D of new conceptual RRs

The new conceptual RRs always had their own research objective. The objective may be for RIs production, minor actinides depletion, high electricity production efficiency, more safe and lower operation cost, etc. Here are some examples underdeveloped.

4.1 Sub-critical reactor in ADS

Accelerator Driven Sub-critical System (ADS) is a promising and clean nuclear power system based on its advantage and benefit in respects of criticality safety, waste transmutation and fuel breeding, and non-proliferation of nuclear. Waste transmutation for minor actinides is the most important utilization for ADS.

The first ADS experimental platform—Venus 1# has been constructed in CIAE, China. It is a coupling core of the fast neutron spectrum zone and thermal neutron spectrum zone driven by pulsed neutron source.

The inner fast neutron zone provide fast neutron spectrum and the thermal neutron zone is a fission zone and gives energy amplification. This platform reached advanced level and made good effect on the world.

An accelerator driven swimming pool thermal reactor, adopted with CARR spent fuel assemblies, is designed with two operation modes, i. e., operating at subcritical mode driven by accelerator and operating at critical mode with obvious nuclear power. This is the nearest research objective of ADS subcritical reactor.

An accelerator driven sodium cooled fast reactor is designed with power level as high as China Commercial Demonstrated Fast Reactor (CDFR). The depletion of minor actinides is the main task as well as its electricity production.

4.2 Super-critical water cooled reactor (SCWR)

Super-critical water cooled technology is well developed in the conventional coal power plant. Its obvious advantage is higher electricity efficiency (> 40 %) than that (30 % ~35 %) of normal high pressure high temperature (non super-critical) water. Currently, this technology is unavailable to use in nuclear power plant directly. The material corrosion, thermal-hydraulics, heat conductivity and more other engineer problems are appeared when super-critical water is adopted in NPPs. Except the higher efficiency, SCWR also have several advantages, such as systems simplified, equipments miniaturized, cost reduced possibly, some technology induced easily from conventional fossil power plant, and the flexibility for neutron spectrum selection (thermal, epithermal or fast reactor), etc, compared with conventional Pressurized Water Reactor (PWR).

Before demonstrated or commercial SCWR NPP constructed, the prototype RR will be constructed firstly, in order to verify the every separated technology and integration.

5 The brief introduction to China advanced research reactor (CARR)

In general, CARR is accord with the development tendency of research reactors for its very high performance. In the design stage, the advanced utilizations are considered according to the utilization development tendency of RRs. The first criticality is estimated in 2009.

CARR is an inverse neutron trap, multipurpose and high performance research reactor which is designed and built independently by China. Its rated nuclear power is 60 MW. The plate-type fuel is adopted with U_3Si_2-Al dispersion as fuel pellet and aluminum alloy as cladding material.

The large proportion fast neutron could escape from the compact core to the surrounding heavy water reflector, and form the higher thermal neutron flux and larger utilization space in the reflector. The unperturbed neutron flux is as high as 8×10^{14} $cm^{-2}s^{-1}$, near to the limit of RRs. This main technical parameters and performance will reach or approach the level of advanced RR constructed currently in the world. There are many innovative designs, which are beneficial to improving main technical parameters and overall performance, and to improving advances, safety and reliability, and to reducing radioactivity dose level and effect on personnel and environment.

It has 21 vertical channels and 9 horizontal channels. It provides strong neutron beams for NSE, NAA, NRG, etc., as well as has good neutron flux and sufficient irradiation space for RIs production, fuel and material irradiation test, etc.

Its main technical parameters are listed in Table 2. The cross section view and exterior view are shown in Fig. 18 and Fig. 19.

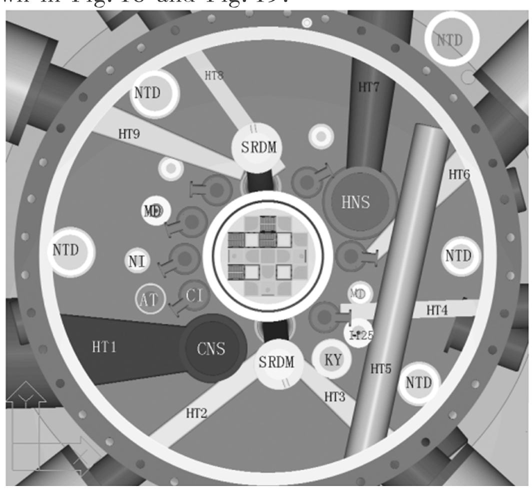

Fig. 18 The core layout of CARR

Fig. 19 The exterior view of CARR

(cont. on p. 100)

Every irradiation channel is equipped with a SPND to monitor neutron fluence.

5) Monitoring computer and under water monitor, etc.

CARR is expected to irradiate 30 t Si ingots per year. The radial and axial heterogeneity should be controlled below 5 %, and the detail value will be obtained in reactor operating practice.

Acknowledgments

We are indebted to Liu Fenglin in NPIC and Li Zhaomin in CAEP for their help in providing information on NTD practice at research reactors, we are grateful to Gao Jijin for his help in offering very valuable references.

Author

Qiao Chenyang, male, was born in 1968. He graduated from Shanghai Jiaotong University majoring in nuclear reactor engineering. He is a senior engineer now. He can be reached by E-mail: qiaochy@126.com

Sun Zhiyong, male, was born in 1977 and graduated from Xi'an Jiaotong University in 1977, majoring in nuclear energy and thermal energy.

(cont. from p. 94)

6 Discussion

From the first RR constructed in China, other several nuclear facilities had been constructed in short term. The tremendous achievements in nuclear field had been made and large number of nuclear specialists trained. RRs of China had made the great contributions to the starting and safe operation of China NPPs. The utilizations of RRs had made gigantic effect on many S&T fields. Generally, the RRs in China have made great contributions to many fields, such as society, economy, defense, agriculture, industrial, etc.

Looking back to the last several decades, the rapid development of RRs and their utilizations is benefited from the emphasis by the nuclear industrial field and from the national developments.

Along with China's rapid development in many fields and the requirement of creative S&T, the bright future of RRs and their utilizations could be anticipated.

Author

Ke Guotu, male, was born in 1965 and graduated from Tsinghua University in 1989. He is now the director of the Department of Reactor Research and Design (DRERD) and also a professor and doctoral supervisor.