THE PRESENT STATUS AND FUTURE POTENTIAL APPLICATIONS OF RRS IN CIAE

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1. BRIEF INTRODUCTION TO RRs IN CIAE AND THEIR UTILIZATION

China Institute of Atomic Energy (CIAE), as the comprehensive nuclear research basis of China, was founded in 1950 as the birthplace of Chinese nuclear science and technology. CIAE made great contributions for the establishment and development of nuclear science the technology in China. CIAE is situated southwest of Beijing and 40 km away from the center of Beijing City. Currently, it has 3200 staff members, including 700 senior scientists.

The general information of 18 research reactors (RRs) in China is registered on the IAEA Research Reactor Database. The name, thermal power, current status and first criticality date of CIAE's RRs are listed in Table 1.

TABLE 1. GENERAL INFORMATION OF RRs IN CHINA

Facility name	Thermal power (kW)	Status	First criticality date
HWRR-II	15 000	OPER	1958/9/1*
SPR IAE	3 500	OPER	1964/12/20
ZERO POWER REACTOR	0	SHUT	1966/1/1
ZPR FAST	0.05	OPER	1970/6/29
MNSR IAE	27	OPER	1984/3/10
CEFR	65 000	OPER	2010/7/21
CARR	60 000	OPER	2010/5/13**

*Initial HWRR criticality, has since been upgraded
** Its first criticality

In Table 1, except that the HWRR-II is temporarily out of service and the Zero Power Reactor is shutdown, all reactors are under operation and normal utilization. The main information and brief utilizations of RRs in CIAE is introduced below, except the CARR reactor, which is introduced in the section 2.

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 an upgrade during the years of 1988 to 1991, and its maximum thermal neutron flux is 2.4×10^{14} $cm^{-2}s^{-1}$. It is suitable for thermal neutron physical experiment, radioisotope production, etc.

The reactor has the advantages of a high ratio of thermal-neutron-flux-to-power, large irradiation space and low gamma ray background. Its main technical parameters are listed in Table II. The top view and main control room of HWRR-II are shown in Figures 1 and 2.

Fig. 1. Top view of HWRR-II.

Fig. 2. Main control room of HWRR-II.

SPR IAE (Swimming Pool Reactor) is a research reactor moderated and cooled by light water. Its rated power is 3.5 MW and reinforced power is 5.0 MW. Construction of this reactor started in 1959, and it approached its first criticality on 20 Dec., 1964. It was mainly used for fuel element tests and material irradiations in the initial period. Now it has been improved into a multipurpose and comprehensive utilization reactor that is mainly used for the radioisotope production, NTD silicon, material irradiation tests, 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 Figure 3 and Figure 4.

ZPR FAST was initially made critical on 29 June, 1970. It was a fast neutron zero power reactor, built for the mastering of fast reactor technology. 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 Figure 5.

Fig. 3. Main Control Room of SPR IAE.

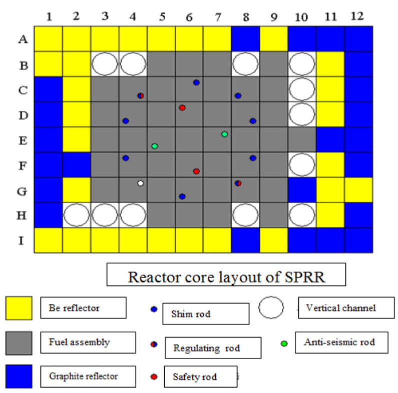

Fig. 4. The core layout of SPR IAE.

Fig. 5. The side view of ZPR FAST.

MNSR IAE, with a power of 30 kW, uses light water as both moderator and coolant, beryllium metal as reflector, and natural circulation as the cooling method. This reactor has high inherent safety and better radwaste containment ability so that it could be built inside the city. It is mainly used for NAA, short-lived radioisotope production and training.

Since 1984, nine Miniature Neutron Source Reactors (MNSRs) have been constructed domestically and abroad. Domestically four MNSRs are located in Beijing, Shenzhen, Jinan and Shanghai respectively. Another five MNSRs are located in Pakistan, Iran, Ghana, Syria and Nigeria respectively. Until now, it has accumulated 100 reactor years of safe operation. The top view of MNSR IAE is shown in Figure 6.

The conversion from high enrichment uranium (HEU) to low enrichment uranium (LEU, ^{235}U enrichment < 20%) could be upgraded only through replacment of one fuel assembly. The main technical parameters of the upgraded MNSR (MNSR-I) are listed in Table 2, and its core configuration is shown in Figure 7.

The fast reactor is one candidate for Generation IV nuclear energy systems with the characteristic of resource friendliness and environment friendliness, and advantages of improved utilization of uranium and the capability to burn radioactive waste. China Experimental Fast Reactor (CEFR), used for experiments and electricity production, is being built in China, and is estimated to reach initial criticality in 2010 and be connected to the grid in 2011. The reactor complex and outside view are shown in Figure 8 and Figure 9.

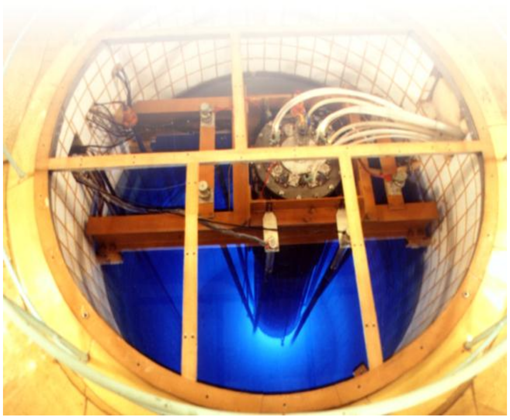

Fig. 6. The top view of MNSR.

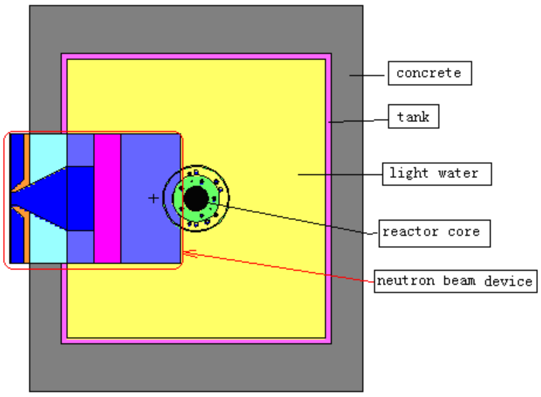

Fig. 7. The core configuration of MNSR-I.

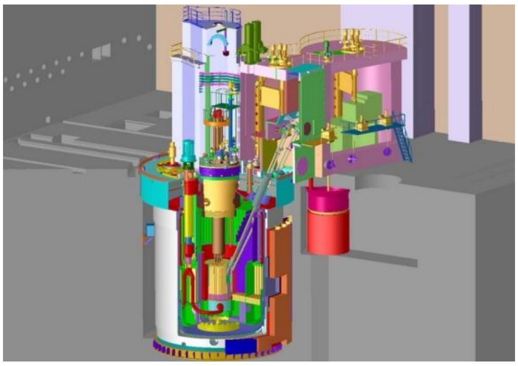

Fig. 8. The Reactor complex of CEFR.

Fig. 9. The outside view of CEFR.

TABLE 2. MAIN TECHNICAL PARAMETERS OF TYPICAL REACTORS

Name	MNSR-I	SPR IAE	HWRR	CARR	CEFR
Fuel	UO_2 LEU 12.5%	UO_2–Mg LEU 10%	UO_2 LEU 3.0%	U_3Si_2 LEU 19.75%	UO_2 HEU 64.4%
Clad.	Zr-4	Al	Zr-2	Al	S.S
^{235}U, kg*	1.12	5.6	7.68	11.0	~66
Control Rods**	1 SR 1 RR 1 AUR	4 SR 2 RR 7 SHR	4 SR 2 RR 8 SHR	2 SR 1 RR 3 SHR	3 SR 2 RR 3 SHR
Vertical Channels	4	20	33	26	——
Φ_{th}, $cm^{-2}\cdot s^{-1}$ ***	1×10^{12}	5.2×10^{13}	2.4×10^{14}	8×10^{14}	3.5×10^{15}

* Initial loading
** SR-Safety Rod, RR-Regulation Rod, SHR-Shim Rod, AUR-auxiliary control rod
*** Maximum unperturbed neutron flux in vertical channels used for utilization

2. BRIEF INTRODUCTION TO CARR

In general, CARR is in accordance with the development tendency of RRs, such as multipurpose, high performance and high safety capabilities along with non-proliferation concerns of nuclear technology. In the design stage, the advanced utilization methods are considered according to the utilization development tendency of RRs.

CARR is an inverse neutron trap, multipurpose and high performance RR which was designed and built independently by China. Its rated nuclear power is 60 MW. The plate type fuel was adopted with U_3Si_2Al dispersion as the fuel pellet and aluminium alloy as cladding material.

The large proportion fast neutrons could escape from the compact core to the surrounded heavy water reflector and generate a higher thermal neutron flux and larger utilization space in the reflector. The unperturbed neutron flux is as high as $8\times10^{14}\,cm^{-2}s^{-1}$. These main technical parameters and performance will reach or approach the level of advanced RRs constructed currently in the world. There are many innovative designs that are beneficial to improving the main technical parameters and overall performance, as well as improving advancement, safety and reliability, and reducing radioactivity dose levels and effects on personnel and environment.

It has 21 vertical channels and 9 horizontal channels. It provides strong neutron beams for neutron scattering, NAA, neutron radiography, etc., as well as a good neutron flux and sufficient irradiation space for radioisotope 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 Figure 10 and Figure 11.

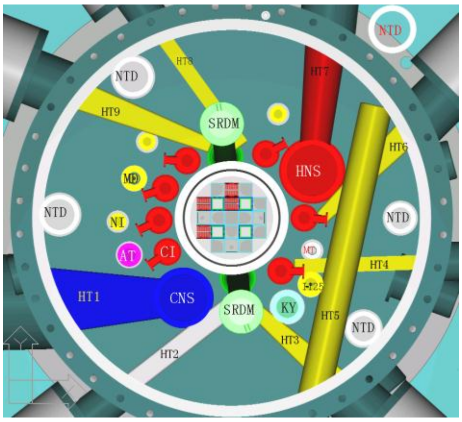

Fig. 10. The Core layout of CARR.

Fig. 11. The exterior view of CARR.

3. PLANNED UTILIZATIONS OF CARR

3.1. Development tendency of RR utilizations in the world

RRs have played an important role from the aspect of the application of nuclear technology. The utilization tendency has developed with more extensive. The following items are the main utilizations.

3.1.1. Nuclear engineering technology

The irradiation testing of various new fuel materials or configurations are undertaken according to different needs, in addition to the existing comprehensive performance test. The important aspects are the research and development of fuel elements, assemblies, components and others construction materials used in NPPs and RRs.

3.1.2. Fundamental research

Fundamental research always includes research on reactor physics characteristics, experimental measurements for the validation of nuclear data, and neutron scattering experiments with special neutron sources such as a thermal neutron source, cold neutron source and hot neutron source.

3.1.3. Applications of nuclear technology

(i) Radioisotope production and applications

The number of newly constructed RRs in the world is decreasing given the expensive costs for their operation and maintenance, and old RRs are aging, with a large proportion nearing shutdown. RR resources are precious, and necessary applications like radioisotope production will be vital for existing RRs. For example, ^{99}Mo, ^{192}Ir, etc., as well as new developed radioisotopes, are the important isotopes irradiated by RRs.

Since newly constructed RRs always are advanced RRs with high neutron fluxes, some radioisotopes with very small absorption cross-sections and very long half-lives, could be irradiated by advanced RRs.

(ii) NTD silicon production

NTD silicon production in reactors began in the 1970s in China. NTD silicon has a better homogeneity than that of silicon from conventional doping methods. NTD silicon is edging out conventional zone doping silicon rapidly as used in large power, high current electric devices. Many China's RRs with vertical irradiated channels produced NTD silicon for the large requirements of China's market.

NTD silicon promotes the cost-reduction effects of the insulation gate bipolar transistor (IGBT) that is used effectively for power devices such as hybrid cars. Therefore, the size requirement of NTD silicon has gradually increased with output demand growing. Application fields are growing wider. It is estimated that the large diameter, as large as 10 inches, even 12 inches, will be strongly needed in the future.

(iii) NAA

Reactor NAA (RENAA) is main utilization method of NAA and widely used in many fields on most RRs. Along with RENAA, PGNAA and NDP will be widely utilized with the cold neutron source (CNS). NAA, including PGNAA and NDP, will be utilized for much more fields.

NAA can be used for analyzing microelement content in samples, and can be involved in nearly all scientific areas, namely, geology, earth chemistry, environmental science, life science, meteorology, food science, archaeology, medicine, agriculture and industry. Solid, liquid and gas samples are available for irradiation.

(iv) Neutron radiography

Neutron radiography will find extensive uses in the fields of industry application, geology, agriculture, archaeology, art history, etc. For example, industrial applications include the nuclear industry, medicine, material science, civil engineering, biology, auto industry, electrics and electrical engineering, air and space industry, oil and gas exploration and fuel cells.

Furthermore, neutron radiography will be performed using especially the high neutron fluxes of RRs. Along with the RRs developed with high neutron fluxes, neutron radiography could be used for low absorption cross-section samples and online real time radiography for flow samples. So it could be used in the investigation of flow conditions inside an opaque pipe like liquid sodium metal in stainless steel piping, the combustion states in engine, and so on. By the related software, the concrete configuration inside the opaque shell could be visualized.

(v) Neutron capture therapy

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 tumours has reached an unprecedented record of 33.3%. BNCT has some advantages such as accurate localization ability and remarkable curative effect, as compared with other current therapy methods.

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

3.2. Planned utilizations of CARR

3.2.1. Nuclear engineering technology

(i) Nuclear fuel research

The irradiation testing of fuel or fuel assemblies including comprehensive performance tests, safety experiments to simulate accidental situations, and enhanced burn up studies, are planned on CARR.

The High Pressure High Temperature Loop (HPHTL) is planned for construction on CARR. One vertical channel is designed with an inner diameter of 7 cm, and the unperturbed neutron flux is about 4×10^{14} $cm^{-2}s^{-1}$. The relative auxiliary systems and equipment will be constructed in the near future. It could be used as the fuel burnup test and enhanced burnup test. The design pressure is about 15 MPa and the temperature 290°C. The name of designated vertical channel is KY. The alternative way for fuel irradiation testing is to use capsules in which the fuel element is inserted into a medium material such as Al. The available channels are CI and MT.

An He-3 auxiliary system is also planned to add on the HPHT loop, and it is also under conceptual design. Since the pressure of helium gas is adjusted easily and quickly, the nuclear density of He-3 could be adjusted easily and quickly, as well as the macro absorption cross-section. At last, power transients of testing fuel could be simulated on CARR. The other auxiliary systems for the HPHT loop are used to research the interaction between pellets and cladding, the temperature distribution and the releasing action of gas fission production under the condition of anticipated transients.

The estimated irradiation samples include the current fuel rods of PWRs, MOX and thorium fuel elements.

(ii) Materials irradiation property research

In addition to the HPHTL, there are 4 vertical channels inside the core vessel. They could be used for irradiated material to simulate irradiation damage with a large fast neutron flux of about 2×10^{14} $cm^{-2}s^{-1}$. The diameter of these 4 vertical channels is as small as 3 cm.

An alternate location is provided at the central position of CARR by withdrawing the central fuel assembly. According to the design, the central fuel assembly could be removed and a special irradiation rig installed for fast neutron irradiation damage simulation. Normally, the central fuel assembly is cooled by light water. If it is removed and replaced by the irradiation rig, the necessary method to ensure enough fast neutrons is to cool the material sample with helium or nitrogen gas. The maximum fast neutron flux is about 8×10^{14} $cm^{-2}s^{-1}$ following replacement with a gas cooled irradiation rig.

The components of the reactor such as the fuel assemblies, control rods, guide tubes, reactor pressure vessel, shielding blanket, reflector, nuclear I&C, etc., are needed to bear high doses of radiation from the reactor. For example, A508-3 steels used for the pressure vessel, fuel cladding materials and grid assembly materials and LT-21 aluminium alloys were irradiated in HWRR, SPR IAE, HFETR, etc. Similar applications could be irradiated in CARR.

Dismantling, testing and analysis for properties are carried out in hot cells after irradiation. One hot cell is designed and constructed near the reactor pool inside the reactor building. It could be used for the examination of irradiation samples and fuel assemblies. The dismantling of large samples or fuel assemblies couldn't be conducted inside this hot cell. According to the plan, the sample or assembly will be dismantled in another hot cell outside of the CARR building but inside CIAE. The distance from the CARR building to the comprehensive hot cell groups is less than about 300 meters.

3.2.2. Fundamental research

(i) Neutron scattering and applications

Neutron scattering experiments are 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 for the research of magnetic properties in solid matter, micro-dynamics and large biomolecule structure.

A CNS at CARR has been designed in which the liquid hydrogen or the liquid deuterium is used to cool neutrons. The cryogenic thermo-siphon loop with nature circulation is designed in the CNS vertical channel. The cold neutrons will be guided to the CNS horizontal channel face to the vertical channel and then to the two beam tubes and four guide tubes. The design neutron scattering experiment building is about 36×60 meters near CARR.

There is also a plan to install a hot neutron source (HNS) at CARR. A vertical channel with a diameter of 28 cm is designed near the reactor core. It is estimated that hot graphite will be used and the design temperature is about 2000K, so the relative Maxwell neutron spectrum could be formed with higher neutron energy than the normal thermal neutron at the normal temperature.

It is scheduled that many apparatus are being installed or will be installed on the CARR, such as a 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 and small angle neutron spectrometers.

(ii) Nuclear physics

Nuclear data measurement in RRs is a most important method, since RRs could provide a wider neutron energy range and a higher neutron flux than accelerators. There are several horizontal channels on CARR. When the graphite block is installed on the beam of the horizontal channel, a broad Maxwell thermal neutron spectrum could be formed.

(iii) Reactor physics and shielding research

In addition to normal reactor physics experiments, a shielding experiment is planned using the combination of several shielding materials and elaborated configurations. The out-pile design and relative equipment are dependent on which neutrons or gamma rays are needed. Some horizontal channels could be used for this utilization.

3.2.3. Applications of nuclear technology

(i) Radioisotope production and applications

Radioisotopes have significant application value in many fields such as industry, agriculture, medicine and science research, etc. For instance, a ^{60}Co source has been widely used for irradiations in industrial applications including sterilization, seeds, property alteration, etc. Radioisotopes like ^{60}Co, ^{192}Ir, ^{169}Yb are used in the fields of industry radiography and irradiation detection. Radioisotopes 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.

By irradiating normal solid targets, fission targets and gas targets in RRs, hundreds of radioisotopes, such as ^{131}I, ^{153}Sm, ^{99}Mo, ^{125}I, etc., can be produced in CARR. The irradiated infrastructure in the heavy water tank of CARR includes 3 vertical channels with a diameter of 50 mm, 1 vertical channel of 70 mm especially for ^{125}I, and 7 channels of 70 mm with a forced cooling loop. Isotopes ^{131}I, ^{32}P, ^{131}Ba, ^{153}Sm, ^{113}Sn, ^{192}Ir, ^{89}Sr, ^{166}Ho, ^{188}W, among others, are planned to be produced in CARR. ^{125}I production will be adopted in the interruption circulation mode. The conceptual design of irradiated capsules and the associated activities are estimated with the planned operation time. There is a plan to evaluate the requirements from the world's market and balance the irradiation resource and suitable operation plan in the future.

(ii) NTD silicon production

There are 5 vertical channels especially for NTD silicon designed at CARR. The diameters of 5 channels are one 3 inches, one 4 inches, one 5 inches and two 6 inches. Four channels are located at the edge of the heavy water tank, and one channel is located outside of the heavy water tank. Since the current tendency of silicon diameter is enlarging, the backup vertical channel is the HNS channel in order to irradiate large diameter silicon. The inner diameter of the HNS channel is 280 mm, but the thermal neutron flux is so high, the cooling system and irradiated period should be designed carefully. In order to approach good uniformity and accuracy, the newest advanced designed method should be adopted.

(iii) NAA

There is a vertical channel (AT) designated for ReNAA by using the rabbit system. For PGNAA the cold neutron beam port marked as HT1 and thermal neutron beam port HT9 will be adopted. The relative systems, such as the sample preparation, irradiation, measurement, automatic sample changer as well as computer software, will be upgraded. Due to the high neutron flux, higher sensitivity could be achieved.

(iv) Neutron radiography

A high resolution static neutron radiography system and a high frame rate neutron radiography system will be developed at CARR, and 3D material distribution image software will be utilized to set up the detailed configuration.

4. CONCLUSIONS

CIAE, as the earliest nuclear research centre and the current comprehensive research organization in China, had good experiences of RR utilizations and contributions to society. Along with the construction of CARR, which is the multipurpose, high performance, high safety research reactor in China, the utilization perspective is well planned. On the basis of many vertical channels and horizontal channels on CARR, many utilization fields, such as nuclear fuel and material irradiation research, neutron scattering experiments, nuclear physics, reactor physics, shielding research, radioisotope production, neutron transmutation doping, NAA, neutron radiography and training and education have been put forward.

The next step for the highly effective utilization of CARR is to conduct the balance of utilization, in order for the programming and design of the infrastructure with the parameters as advanced as possible.