2.21 Status of Research Reactors in China: Their Utilization and Safety Upgrading

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Abstract

The main research reactors in China basically consist of several old reactors including HWRR, HFETR, SPR, MJTR and MNSR. Except the last one, all the other reactors operate at a high power density and represent themselves as main tools in China for engineering testing, radioactive isotope production, and neutron scattering research.

The research and production activities by these reactors are briefed. Main equipment and research topics for neutron scattering are described. The production of radioisotope is summarized.

Safety upgrading activities in recent years taken by these old reactors are described, which make the safety feature of each reactor significantly improved and on the whole more close to (even not completely consistent) with the targets set by the modern safety regulation.

Since a new multi-purpose research reactor CARR is expected available around the year of 2005, a schedule about the construction of new reactor, reforming or decommissioning of old reactors and smoothly transition of research and production activities from old to new reactor during the coming years has been under careful planning.

A suggestion of potential international cooperation items has been preliminarily given.

Key words

Research reactor  Utilization  Safety  Neutron scattering  Radioactive isotope production
New reactor design  CARR
1 Introduction

Main research reactors in China are listed in Table 1 below. They can be categorized into several groups.

In the first group is the reactor named High Flux Engineering Testing Reactor or HFETR in short. It's of tank type with a primary pressure of about 2MPa and a rated power of 125000 kW. The core is loaded with maximum 13 kg U-235 of 90% enriched uranium-aluminum alloy. Its fuel element is composed of six tubes with different diameters. The core is moderated and cooled by pressurized water and reflected by beryllium. The reactor can be operated highly flexibly. Different number of fuel testing loops and radio-isotope production tubes can be accommodated in the reactor together with fuel assemblies and beryllium blocks in necessary number and proper combination. This flexibility makes the operational mode of the reactor and its real power entirely task-based.

Table 1 Main Research Reactors in China

<table>
<thead>
<tr>
<th>Group</th>
<th>Reactor</th>
<th>Type</th>
<th>Owner</th>
<th>Power(kW)</th>
<th>First Critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HFETR</td>
<td>Tank</td>
<td>S.W. Institute</td>
<td>125000</td>
<td>1979</td>
</tr>
<tr>
<td>2</td>
<td>HWRR-2</td>
<td>Heavy Water</td>
<td>CIAE</td>
<td>15000</td>
<td>1958, 1983</td>
</tr>
<tr>
<td>3</td>
<td>SPR</td>
<td>Pool</td>
<td>CIAE</td>
<td>3500</td>
<td>1964</td>
</tr>
<tr>
<td></td>
<td>Tsinghua</td>
<td>Pool</td>
<td>Tsinghua Univ.</td>
<td>2800</td>
<td>1964</td>
</tr>
<tr>
<td></td>
<td>SPRR-300</td>
<td>Pool</td>
<td>S.W. Institute</td>
<td>3000</td>
<td>1979</td>
</tr>
<tr>
<td></td>
<td>MJTR</td>
<td>Pool</td>
<td>S.W. Institute</td>
<td>5000</td>
<td>1991</td>
</tr>
<tr>
<td>4</td>
<td>MNSR</td>
<td>Tank-in-pool</td>
<td>CIAE</td>
<td>27</td>
<td>1984</td>
</tr>
<tr>
<td></td>
<td>MNSR</td>
<td>Tank-in-pool</td>
<td>ShengZhen</td>
<td>30</td>
<td>1990</td>
</tr>
<tr>
<td></td>
<td>MNSR</td>
<td>Tank-in-pool</td>
<td>Shandong</td>
<td>30</td>
<td>1991</td>
</tr>
<tr>
<td></td>
<td>MNSR</td>
<td>Tank-in-pool</td>
<td>Shanghai</td>
<td>30</td>
<td>1994</td>
</tr>
<tr>
<td>5</td>
<td>ZPR(fast)</td>
<td>Fast Reactor</td>
<td>CIAE</td>
<td>0</td>
<td>1976</td>
</tr>
<tr>
<td></td>
<td>HFETR(ZPR)</td>
<td>Pool</td>
<td>S.W. Institute</td>
<td>0</td>
<td>1979</td>
</tr>
<tr>
<td></td>
<td>HWZPR</td>
<td>Tank</td>
<td>CIAE</td>
<td>0</td>
<td>1982</td>
</tr>
</tbody>
</table>

In the second group is the Heavy Water Research Reactor HWRR. It was originally a Russian design and was constructed under help of the former Soviet Union in 1958. When its component and equipment getting aged in 1979, CIAE decided to take action of performing several major modification to the reactor. The "reconstruction" took four years and the reactor went to critical in 1983 again. The new fuel used is 3% U-235 enriched dioxide instead of the original 2% enriched metallic uranium and the rated power has been increased from 10MW to 15MW. The MHWRR in Algeria is basically of the same type of CIAE reactor except several improvement for getting higher safety level.
In the third group are four light water swimming pool reactors. The first three are of the same type using fuel assembly from UO₂-Mg metallic rod with a power around 3000kW. The fourth one, MJTR, reuses the spent fuel discharged from HFETR and also uses several new assemblies to reach enough reactivity, but with a lower power density.

In the fourth group are the Miniature Neutron Source Reactors. They are of tank-in-pool type structure with about one kilogram uranium-235 of 90% enrichment loaded in its core. The designed power of the reactors is only about 27 to 30 kW. These reactors reach high level safety through their large negative reactivity coefficient, passive natural circulation cooling, and limited build-in reactivity. The maximum neutron flux in the irradiation site reaches $1.0 \times 10^{12}$ n/cm² sec. The available maximum operation duration during one day is only six hours therefore limits utilization of the reactor. There are altogether four such reactors built in China domestically and another five abroad for Pakistan, Iran, Ghana, Syria and Nigeria.

Several reactors of zero power type belong to the fifth group. They are used for reactor physics experiment, design validation, neutron cross-section measurement, computer code check, personnel training, etc.

The following sections give a brief description on the utilization of these research reactors, their safety upgrading in recent years, status of a new research reactor which is under design, and topics of possible international cooperation.

2 Utilization of the Research Reactors

2.1 General Situation

The utilization of the reactors in one group in Table 1 is similar to each other; therefore one or two reactors are selected as representatives to demonstrate the utilization of this group.

Table 2 shows the main utilization for different reactors. Symbol * indicates activity carried out during past years or being underway, while symbol # indicates activity under plan or to be extended. They are further explained below.

The main radioactive isotope species produced now and in the past years include the followings:

- $^{99}$Mo-$^{99}$Tc,
- $^{198}$Au,
- $^{32}$P,
- $^{51}$Cr,
- $^{133}$Sm,
- $^{131}$Ba,
- $^{131}$I,
- $^{60}$Co,
- $^{90}$Y,
- $^{192}$Ir,
- $^{46}$Sc,
- etc.,

Recently, production of $^{166}$Ho is under consideration and is highly interested for possible international cooperation in its production technology.
Table 2  Utilization of the Research Reactors in China

<table>
<thead>
<tr>
<th>Item</th>
<th>HFETR</th>
<th>HWRR</th>
<th>SPR</th>
<th>MJTR</th>
<th>MNSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering Testing</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Radio Isotope Production</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td>#</td>
</tr>
<tr>
<td>Neutron Scattering</td>
<td>*</td>
<td>#</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shielding Experiment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon Doping</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>N-Activation Analysis</td>
<td>*</td>
<td>*</td>
<td></td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Neutron Radiography</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reactor Physics Experiment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seed &amp; Plant Irradiation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Topaz Color Altering</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For the silicon doping, the size of the product is in the range of Φ61mm to 110mm. The total production amount depends on the market requirement and is roughly around the magnitude of ten tons per year.

2.2 Neutron Scattering Experiment on HWRR

HWRR is the most important reactor in China in the field of neutron scattering experiment. The key feature in this regard is summarized below.

(1) Number of beam tubes

Four of six horizontal tubes in HWRR are used for the purpose of neutron scattering experiment.

(2) The Cold Neutron Source

- Moderator: liquid hydrogen
- Cold cell with 110mm in diameter and 50mm in thickness
- Temperature: 20K
- Gain: about 10 (for 4 to 20 A neutron)
- Neutron guide tube: 27m

(3) Neutron scattering facilities:

At present, six neutron scattering facilities are available

(a) Powder neutron diffractometer
(b) Four circle diffractometer
(c) Triple axis spectrometer
(d) Double-chopper time-of-flight spectrometer
(e) SANS spectrometer with a 64x64 elements He\(^3\) position sensitive detector
(f) Be-filter wide angle detector spectrometer

(4) Research fields
(a) Crystallographic and magnetic structures of rare-earth-iron permanent magnetic alloys
   mainly focused to the R2Fe17 and R Fe12 series, the atom occupancies and magnetic moments
   of magnetic atom were obtained by the Rietveld analysis program.
(b) High-Tc superconductor
   Such as a powder neutron diffraction study of High – Tc superconductor Hg-1223 by Pb
   substitution.
   Inhomogeneous antiferromagnetism study of YBa2Cu3O6+δ
(c) Biology
   The difference of association effect for serum albumin between humanity and ox has been
   determined by SANS.
(d) Single crystal structure analysis of non-linear optical material
   Such as Deuterium (Hydrogen) L-Arginine Phosphate monohydrate D(H)LAP.
   The length of hydrogen bond and molecular structural formula have been determined.
(e) Functional material (such as Invar alloys, shape memory alloys)
   Generalized phonon densities of states (PDOS) on amorphous Fe90- xCoxZr10 (x=10 and 40)
   were measured at room temperature on the time-of-flight spectrometer. The results show that the
   generalized PDOS below 17MeV become soft at the Invar concentration.

The main problems with the neutron scattering experiment on HWRR among others are:

(1) Since the design of HWRR was not engineered to optimize the condition for neutron scattering
   experiment, the magnitude order of neutron flux level at the inlet end of the horizontal beam tube is
   only about 10\(^{11}\) n/cm\(^2\)s, too low to justify the effectiveness of the reactor for this purpose.

(2) Some problems related to equipment of cold neutron source.

(3) Other problems such as budget difficulty, etc.

In contrast to the problems of the hardware, the experimental team is quite good with enough
capability of performing research work in this field. To keep and enhance the capability of the team
until the new research reactor CARR can be successfully utilized is also one of the major tasks of the
HWRR. On the other hand, we are also looking forward to some kinds of international cooperation
of using Chinese expertise for another country. By this way it's going to benefit both sides.

### 2.3 Further Development of MNSR

For some countries they temporarily have MNSR as their solely nuclear facility, applying MNSR as a tool for special radioactive isotope production is quite meaningful.

As has been mentioned in the introduction, MNSR can reach a neutron flux of $10^{17} \text{n/cm}^2 \cdot \text{sec}$ at its inner irradiation site under rated power of 30 kW but only for six hours continuous operation in one day. To prolong its available continuous operation hour is of wide concerns for the purpose of enlarging its utilization.

The above requirement can be reached by the following means.

1. Increase a new cooling system for water inside the inner vessel to limit the coolant inlet temperature rising during long term operation therefore reduce reactivity defect due to temperature effect;
2. Increase initial build-in reactivity to allow stronger compensation ability for xenon build-up after longer operation;

The cost of the hardware modification for the above purpose is estimated as 150,000 to 200,000 US $, one tenth of the total cost of the MNSR, representing an attractive prospect.

The following steps seem necessary and reasonable for the purpose:

1. Held a user's international seminar to exchange information of operation and application experiences on MNSR utilization;
2. Perform demonstrating software and hardware modification in one year in CIAE;
3. Backfitting the other existing MNSR's in the year next.

This idea has been worked out one year ago and we hope it can be implemented as soon as necessary budget has been prepared.

### 3 Re-evaluation and Upgrading of Safety for Old Reactors

#### 3.1 Basic Consideration

Old reactors with an age elder than thirty years were usually constructed before the time when the modern safety regulations and standards are systematically and completely implemented. Re-evaluation of the safety of old reactors on the basis of existing safety standards and guidelines is therefore of great value to enhance the safety level of these reactors. The outcomes of this re-
evaluation should be a list of modification and backfitting both in software and in hardware.

3.2 Activities Related with This Topic

(1) Re-evaluation of the reactor safety had been organized by China National Nuclear Safety Admininistry NNSA based on the existing safety regulations and standards. The outcomes of this re-evaluation should be a problem list for each old reactor.

(2) Analyze these items one by one based on safety importance using deterministic and / or probabilistic methodology to get technical priorities. A cost-benefit analysis taking the reactor remaining lifetime into consideration is necessary when making decision.

As an example, the four reactors HFETR, HWRR, SPR and MJTR in Table 2 had been required to implement the following generic improvement. Each reactor had taken one or two years to realize these requirements:

(1) to modify emergence plan and to improve emergence system;
(2) to update quality assurance program and to improve QA system;
(3) to re-evaluate earthquake safety;
(4) to update the fire fighting procedure, to increase a fire alarming system;
(5) to improve spent fuel storage pool;
(6) to thoroughly reform the old electricity system, to improve the old instrumentation and control system, to change old cable;
(7) to perform re-training for the operators.

For each reactor, it must also perform upgrading of special items described as follows:

For HWRR, the following items have be implemented
- to increase an emergence recirculation water system
- to increase a new earthquake-resistant safety rod shutdown system
- to increase two set of diesel units and a new set of 110V battery
- to increase a safety injection system

For SPR
- to increase a new UPS system
- power protection logic changed from “1 out of 2” to “2 out of 3”
- to increase a new period protection system and apply 2 out of 3 logic for it
- to increase an additional protection signal of water level for the swimming pool
- to replace motors of the secondary pumps
• to replace fans in the venting system

For HFETR

• to increase a new residual heat removal system
• to increase a secondary side emergence cooling system
• to enhance emergence electric system

The above upgrading has been completely realized on these reactors.

4 Progress of China Advanced Research Reactor CARR

Eventhough great efforts have been made on the safety upgrading for the old research reactors, ageing problem can still not be entirely avoided. Usually two kinds of problems are related to ageing. In the first category, the system, equipment or component experiencing ageing is easy to be replaced, then this kind of problem is actually treated by proper maintenance program. In the second category, some key part of the reactor experiencing ageing is irreparable or irreplaceable, or its replacement is not justifiable on the cost-benefit basis. In this case these parts of the reactor suffer from unrecoverable ageing degradation therefore limit the lifetime of the integrated reactor facility.

As an example, HWRR is expected to be firstly decommissioned around the year of 2005 to 2008 followed by SPR several years later. Both reactor suffer from ageing problem to their respective essential components due to corrosion degradation, and renovation action to prolong their operational lifetime is difficult based on updating technology.

In order to smoothly continue the neutron scattering research work and radioactive isotope production during the beginning years of the next century, a new research reactor named as China Advanced Research Reactor CARR has to be planned. Actually a feasibility study for the construction of this reactor has already been completed and approved at the end of 1997 by the authorized government organization. A preliminary design is now being on and to be completed in the spring of 2000. The construction will be started in 2001 and the reactor is expected reaching its first criticality around the year of 2005. By this schedule, CARR will replace HWRR when the later is about to be decommissioned.

CARR is a multipurpose reactor used for neutron scattering, radioisotope production, fuel and material testing, and other nuclear and industrial application. In order to meet the purposes, the reactor is designed to have a tank-in pool structure, light water as coolant, heavy water as reflector. The compact core is composed of 21 square lattice cells with a pitch of 77.2mm, in which 17 cells are occupied by the standard fuel assemblies. The fuel assembly consists of 21 plates each with 0.6mm thickness meat in the centre and 0.38mm thickness cladding on both sides. The fuel in the
meat uses 20% enriched $^{235}\text{U}$ dispersed in metallic aluminum base material. Each assembly contains 567.4g U-235. In order to reach a high power density, a coolant velocity of 10m/sec is necessary for the heat removal on the fuel plate. There are four control rods among the 21 cells. They are used for reactivity compensation and regulation. Two safety rods located in the heavy water closely outside the reactor vessel together with the four control rods integrately form the safety shut down system. The surrounding heavy water which can be dumped quickly is used as the second shut-down system. The unperturbed maximum thermal neutron flux in the heavy water is about $6 \times 10^{14} \text{n/s/cm}^2$ when the reactor is operated at rated power of 60MW. The uranium 235 inventory is about 11 kg.

Fig. 1 shows the horizontal layout of the reactor core and its surrounding beam tubes. Of the nine tubes, there is one cold neutron tubes and one hot tubes.

Fig. 2 gives principally the vertical view of the reactor. The coolant from the four plate-type heat exchangers goes into a flow-guiding tank and flows downwards through the channels between fuel plates to cool the core, and then enters into a decay tank. After staying in the tank for about 30 seconds to allow the radioactive $^{16}\text{N}$ being decayed, the coolant goes upwards into the outlet pipe which penetrates the wall of the swimming pool and connected to the main pumps.

In the heavy water tank, there are also various vertical tubes for different irradiation purposes including radio-isotope production, material testing, silicon doping, etc.

It’s highly desirable to have kinds of international cooperation and information exchange in design and also in equipment purchase. Information on operation and maintenance of similar research reactors in other country are of great value for the design of CARR.

5 Potential Cooperation in the field of Research Reactors

The potential international cooperation in the field of research reactors, which has already been mentioned in the text, can be summarized very briefly as follows:

- Further exchange of information, including reactor operation, maintenance, management, application, safety upgrading, design and decommissioning.
- Expert team on the neutron scattering can be used internationally if asked.
- Cooperative study on the production method for special radioactive isotope, such as Ho-166, is interested.
- Cooperation on the design of new reactor, including the experimental facility, is of concerned.
- Special equipment and material purchase.
Fig. 1  Horizontal layout of CARR
Fig. 2 Vertical view of CARR