DESIGN AND CONSTRUCT OF IN-HOSPITAL NEUTRON IRRADIATOR

Y. LI, P. XIA, D. PENG, S. ZOU, X.B. WU, J. ZHANG, Y. ZHANG
China Institute of Atomic Energy (CIAE),
Beijing,
China

T. LIU
Beijing Capture Tec. Co.,
Beijing,
China

Y. ZHOU
China Zhongyuan Engineering Corporation,
Beijing,
China

Abstract

The In-hospital neutron irradiator (IHNI) is designed based on the design of the Miniature Neutron Source Reactor (MNSR) for boron neutron capture therapy (BNCT), NAA, physics experiments, training and teaching. The reactor of the IHNI with thermal power 30 kW is an undermoderated reactor of pool-tank type, UO_2 with enrichment of 12.5% as fuel, light water as coolant and moderator, and metal beryllium as reflector. The fission heat produced by the reactor is removed by the natural circulation. On the both sides of the reactor core, there are two neutron beams, one is a thermal neutron beam, and the other, opposite to the thermal beam, is an epithermal neutron beam. An experimental thermal neutron beam is specially designed for the prompt gamma neutron activation analysis (PGNAA). In this paper, the design and experiment results of IHNI will be introduced.

1. INTRODUCTION

The IHNI is a pool-tank type reactor with 30 kW, the final loading is 302 fuel rods. It is designed and built by China Institute of Atomic Energy and Beijing Capture Technology Corporation for boron neutron capture therapy, neutron activation analysis, nuclear physics experiment, nuclear detector test, training and education based on Miniature Neutron Source Reactor (MNSR) which is designed and built by CIAE.

The reactor core assembly, surrounded by beryllium reflectors, is located at the bottom of the reactor vessel which is suspended from the S.S“I” beam structures which are embedded onto the reactor pool wall, see Figure 1.

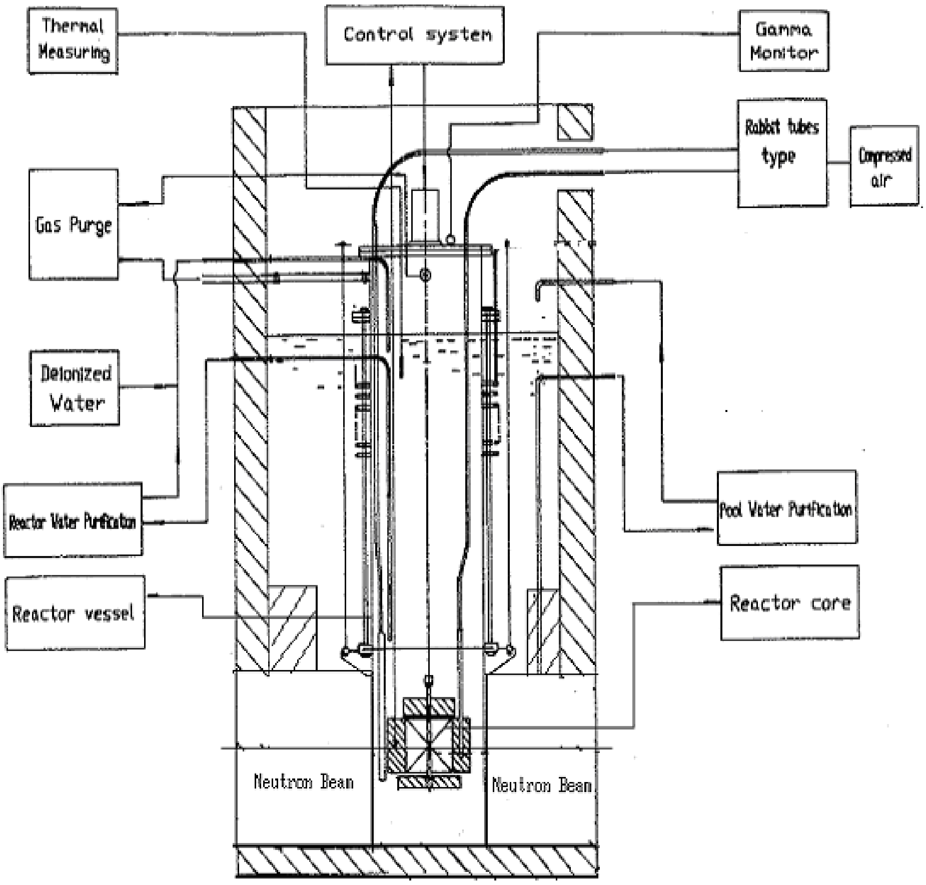

Fig. 1. IHNI and Its System.

The main specifications of the reactor are listed in Table 1.

TABLE I SPECIFICATIONS OF IHNI

No.	Item	Descriptions
1	Reactor type	Pool-tank
2	Fuel meat	UO_2
3	U-235 enrichment	~12.5%
4	Reflector	Metal Be
5	Moderator and coolant	Light water
6	Reactor power	~30kW
7	Thermal neutron flux	1×10^{12} $cm^{-2}s^{-1}$ inside side Be
8	Vertical channels	3 irradiation site inside side Be reflector 2 irradiation site outside side Be reflector
9	Control rod	One central control rod.
10	Operating mode	2.5 hours a day, 4 days a week
11	Lifetime	>20 years

12	Thermal Neutron beams	~1×10^9 $cm^{-2}s^{-1}$
13	Epithermal Neutron beams	~4×10^8 $cm^{-2}s^{-1}$

2. REACTOR AND ITS SYSTEMS

2.1. Reactor pool

The reactor pool is located at the center of the reactor hall. The reactor pool is an important biological shield and the heat sink. In order to eliminate the corrosion of reactor structures with water, the reactor pool is filled with deionized water of high quality. And in order to keep the pool water quality, the whole pool is covered with the organic glass cover plates.

The whole pool is a reinforced concrete structure, the suitable size of the pool is the 4×2.3 ×4.7m of upper part, 2.6×1.1×1.8m of lower part.

2.2. Reactor unit

2.2.1 Reactor vessel

The reactor vessel, a cylinder with total height of 6.14m, inner diameter of 0.6m, and 10mm thick, is built in two sections. The lower section is 1.26m in height, with an ellipsoid bottom head. The upper section is 4.88m in height. The reactor Vessel acts as the third defense barrier of the reactor for preventing the radioactive materials from releasing to the environment.

2.2.2 Reactor fuel

The heart of the IHNI facility is the reactor core, which is located at the bottom of the lower section of the reactor vessel. The reactor core consists of the fuel cage (“Birdcage”), the control rod guide tube and fuel elements. The fuel cage is a birdcage-shaped device made of zircaloy, which consists of an upper grid plate, a lower grid plate, a central control rod guide tube and five tie rods. Ten circles of lattices are concentricity arranged in the upper and lower grid plates, there are about 351 lattice positions in the grid, among which the central one is specified as the control rod guide tube position. The five tie rods are arranged uniformly at the eighth circle. The rest lattice positions are preserved for fuel rods. See fig.2.

2.2.3 Reflectors

Metal beryllium blocks are used as IHNI reflectors consisting of three types: the side annulus surrounding the reactor core, the bottom step disks and the top Be shims. The top Be shims will be gradually added to the top of the reactor core as burnup increases to compensate the reactivity losses. See fig.3.

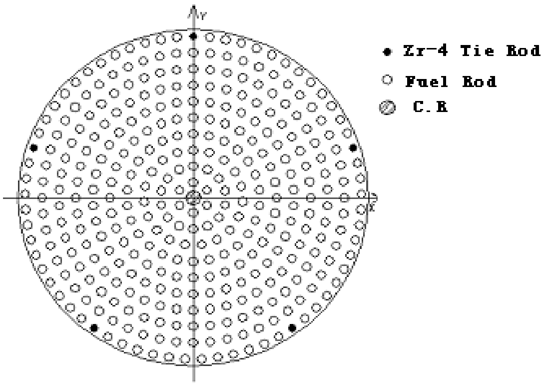

FIG. 2. Reactor fuel assembly.

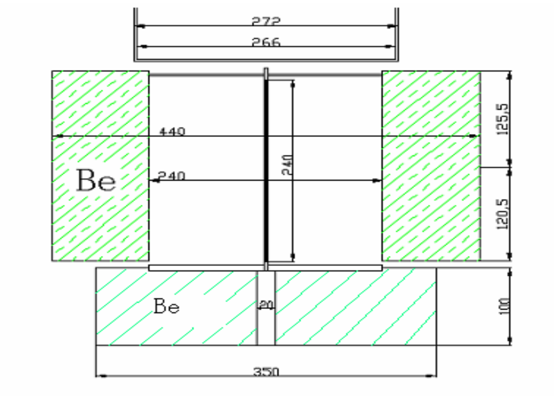

FIG. 3. Be reflectors.

2.3. Reactor control system

Microcomputer Control system can be used to operate the IHNI, the operational parameters can be shown on the screen, such as neutron flux, rod position, temperature etc.

The IHNI uses one central control rod, which also serves as shim rod, regulating rod, and safety rod. The control rod controls the reactor startup, shutdown and power regulation. It has a total length of 45cm, outer diameter 0.5cm with a stainless steel lower end being 1cm long and a heavy hammer being at its upper end. Its absorbing material is cadmium with a length of 28cm and outer diameter of 0.4cm.

The two neutron detectors used in the IHNI are fission ionization chambers of current type. They provide neutron flux measurement and control signals for the control system. Their positions are inside the side Be.

The control computer system provides two kinds of control modes: one is the automatic control mode which responds to the signals from the neutron detectors, the other is manual control mode which responds to manual operation. The main functions of the control computer are to startup, shutdown, and operate the reactor manually or automatically, to monitor the main operating parameters of the reactor, to display signals of normal and common abnormal operating conditions, to provide audible alarm and emergency shutdown protection under severe abnormal conditions.

Common abnormal signal alarms are displayed with red indication on the control computer. There are four kinds of common abnormal signals: reactor water level high, reactor water level low, pool water level high, pool water level low. When any of these common abnormals occurs, the corresponding red indication will be on, warning the operator to handle with it.

There are two kinds of severe abnormal alarm signals: the one is the temperature difference between the reactor core coolant inlet and outlet exceeding its limit value, the other is the neutron flux exceeding its limit value.

2.4. Reactor and pool purification systems

2.4.1. Reactor water purification system

The reactor water is enclosed in the reactor vessel. The reactor water, as the reactor coolant and moderator, contacts directly with reactor fuel elements, other in-pile components as well as the inner wall of the reactor vessel. The quality of the reactor water is directly related to the corrosion of the in-pile structural materials, mainly aluminium. The reactor water of bad quality could speed-up the corrosion rate of the in-pile structural materials, especially aluminium and the impurities of the reactor water could be activated to increase the dose level of the process rooms and hence to impair the safe operation of the reactor. Therefore, the purification system of the reactor water is a process system for maintaining safe operation of the reactor.

The reactor water purification system consists of a water pump, mechanical prefilter, mixed ion-exchange column and resin capturer etc. The canned pump draws reactor water. The water passes through the mechanical prefilter. The suspended solid particles are filtered out, then the water passes through the mixed ion-exchange column to eliminate cations and anions, finally the purified water is returned to the reactor vessel. This process is reiterated so that the reactor water is purified. The reactor water purification system has a flow rate of about 0.5 t/hr. The reactor water standards are as follows: Conductivity: 2μs/cm; PH value: 6.0±0.5; Cl^-, Cu^{++}, Pb^{++} content: $\leq$0.1 ppm

2.4.2. Pool water purification system

The quality of the pool water gives a direct influence on the corrosion of the aluminium alloy reactor vessel. An accepted pool water quality can reduce the corrosion rate, thus the service time of the reactor vessel can be increased.

The volume content of the pool is about 40m^3. A purification system for the pool water is provided. It consists of a pump, a mechanical prefilter, resin capturer, and two parallel mixed ion exchange columns. The pool water purification system has a flow rate of about 2 ton/hr.

The stainless steel pump draws water from the pool. The water first passes through the mechanical prefilter where the suspended particles in the water filtered out. Then the water passes through the mixed ion exchange columns where the cation and anion are eliminated. Finally the water is returned to the pool. This circulation is reiterated and thus the pool water is purified. The purification system for the pool water is operated once a week, and five hours each time. The pool water standards are as follows: Conductivity: 3μs/cm; PH value: 6.0±0.5; Cl^-, Cu^{++}, Pb^{++} content: $\leq$0.1 ppm.

2.5. Reactor gas purge system

The reactor gas purge system is used to discharge the harmful gases accumulated during operation in the 120 litres top space of the reactor vessel.

The sources of the harmful gases are as follows: Ar-41 and N-16 produced from the compositions of air dissolved in the reactor water due to the irradiation by neutrons; hydrogen resulted from the corrosion of the cladding and reactor structural materials; hydrogen and oxygen resulted from the decomposition of the reactor water due to γ irradiation; and, in addition, fission gases, such as krypton, xenon, iodine might be released from the fuel elements if fuel failure occurs.

The reactor gas purge system consists of an air pump, an air intake filter, an exhaust filter, and an iodine filter. The iodine filter is only put into operation under accidental conditions. The air flow rate of the air pump is 40m^3/hr. Under normal operation of the reactor, the gas purge system operates once a week and one minute each time. After filtration, the reactor gases are discharged into the environment. At the same time, fresh air passes through the air intake filter and fills the top 120 litres space of the reactor vessel. The operating time under accidental conditions depends on the degree of the contamination of the reactor gases. This system can only be put into operation when the reactor is shutdown, and cannot be operated simultaneously with the reactor water purification system.

2.6. Thermal hydraulic measuring system

The thermal hydraulic measuring system is used to measure and monitor the thermal hydraulic parameters of the reactor. They include coolant temperature at core inlet, temperature difference between core outlet and inlet.

- The detector for measuring coolant temperature at the reactor core inlet is a thimble sheathed platinum thermal resistance thermometer. Its secondary display instrument is located on the front panel of the main control console. The temperature measured at this point is basically the same as that at coolant inlet orifice of the reactor core after a period of steady operation at some power level. Therefore this temperature can represent coolant inlet temperature at steady operation;
- The temperature difference between core outlet and inlet is measured with two pairs of chromel-alumel thimble sheathed thermocouples. These two thermocouples are placed separately close to the inlet orifice outside the side annulus beryllium reflector and close to the outlet orifice at the upper part of the side annulus beryllium reflector;
- The reactor water level is measured with a magnetic float level gauge which is mounted to the reactor top cover plate. The reactor water levels below the lower surface of the reactor top cover plate 37cm to 47cm are the normal levels. Those water levels which are less than 37cm below the lower surface of the reactor top cover plate are high levels, those which are more than 47cm below the top cover plate are low levels. The corresponding alarm lights for reactor water low level and high level are provided on the panel of the main control console, and also provided on the control desk of the reactor water purification system.

2.7. γ radiation monitoring system

The γ radiation monitoring system of the IHNI is mainly used to monitor the failure of the fuel elements and the γ radiation at the working places.

There are six γ detecting probes in this system. They are distributed as follows: one is mounted on the wall of the reactor hall; the second lays on the reactor top cover plate to monitor the variations of the reactor power, reactor water level, and the activated gas concentration in the top space of the vessel as well as the failure of the fuel elements. The γ dose rate measured at this place is one of the important parameters for safe operation of the reactor; the third is mounted on the side wall of the ion-exchange column of the reactor water purification system to monitor the variation of the resin radioactivity level, fuel failure or the increase of the corrosion products of the in-pile structural materials would lead to the increase of the radioactivity of the resins; the forth-sixth are on the thermal irradiation room, epithermal irradiation room and outside the irradiation room respectively. These detecting probes connect with the control computer.

2.8. Rabbit systems

The system can be used for the sample irradiation and transfer. The sample can be transferred into and out the reactor core by pneumatic loop.

The pneumatic transfer loop consists of in-pile tube and out-of-pile tube. The two sections of tubes are connected at the reactor top cover plate.

The electrical control is conducted with computer. The irradiation time can be set according the requirement of the irradiated sample.

2.9. Compressed air supply system

The compressed-air supply system is mainly used to provide driving gas source for sample capsule transfer system in neutron activation analysis.

2.10. Deionized water supply system

This facility designed is used for production of pure water. The main design parameters: yield water flow: 0.5-0.7m^3/h, conductivity ≤1μs/cm, PH=6.0±0.5.

3. CONSTRUCT

TABLE II: CONSTRUCT SCHEDULE

From Jan. 2005 to Dec. 2007	Design
Oct. 11, 2007	Site approved by NNSA
From Jan., 2008 to Feb., 2009	Start to Construct
Aug. 21, 2009	Fuel loading approved by NNSA
Dec. 7,2009	Fuel loading and Criticality
Jan. 22,2010	Full power

4. PERFORMANCE AND CHARACTERISTICS

4.1. Inherent safety

IHNI has the limited excess reactivity with 4.5mk which is half of the β effective value, and negative temperature coefficient: -0.1mk/℃(40-20℃).

When a certain amount of positive reactivity is inserted into the reactor suddenly, the power will be increased suddenly, however, it will turn to the normal value due to the negative temperature effect.

Here is the figure of reactivity release, the maximum peak power value for 4.2mk reactivity release is 85.7kW. See fig.4.

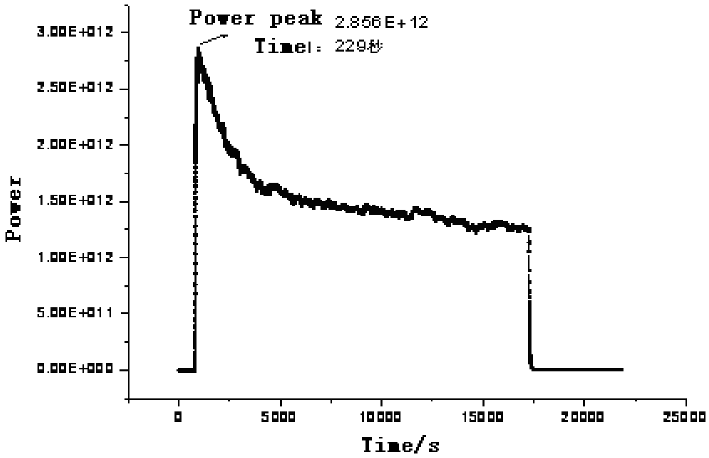

Fig.4 Power changes with insertion of 4.2 mk reactivity.

4.2. Low level of radiation

Owing to very low surface contamination of fuel elements and sufficient level of water protection, the radiation level at the operation of 30kW outside the reactor building is background level.

4.3. Reliable operation

The max. continuous operating time at the condition of 30kW is 12h, the wave of power is less then 3‰. See fig. 5.

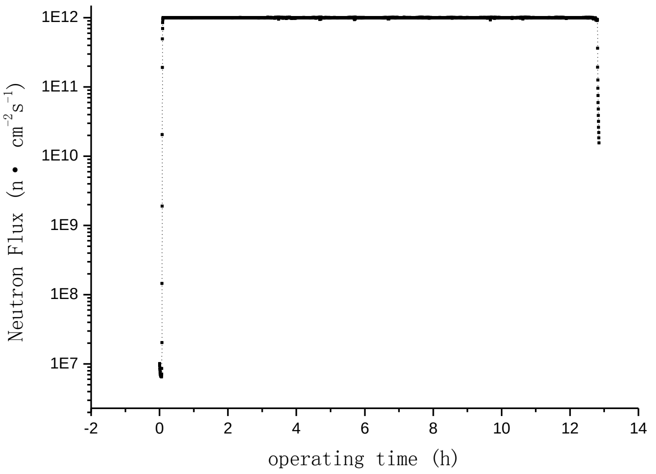

Fig. 5 Full power operation.