OVERVIEW ON NEW RESEARCH REACTORS IN CHINA

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Abstract

In China, 2 research reactors are now under construction. Correspondingly, this paper consists of 2 parts. Part 1 will focus on China Advanced Research Reactor (CARR), the reactor characteristics, utilization, safety related systems and other main systems will be described in this part. Part 2 will focus on China Experiment Fast Reactor(CEFR), the general design and the safety features in particular will be illustrated in this part.

1 CHINA ADVANCED RESEARCH REACTOR(CARR)

CARR is an inverse neutron trap, tank-in-pool research reactor. Its fuel element is plate type, coolant and moderator is light water, and reflector is heavy water. The main equipments and structures, such as coolant guiding tank, reactor core, heavy water tank and decay tank are laid in the reactor pool. The primary coolant flows downwards through the reactor core, and then pumped to the heat exchanger where the heat is transferred to the secondary coolant. The heat of secondary cooling system is transferred to the atmosphere by a hyperbolic cooling tower.

1.1 Reactor complex

All of the relevant factors, such as neutron flux, refueling management, reactivity control and the layout of application tubes, should be taken into account in reactor complex design so as to meet the multi-purpose requirements. Main equipments of reactor complex are described as follows.

1.1.1 Reactor core

The reactor core is composed of 17 fuel assemblies and 4 control rod assemblies, in addition, there are 2 safety rod assemblies located in the heavy water tank.

Each fuel assemblies consists of 21 fuel plates, the fuel meat is U3Si2, the enrichment of U235 is 19.75%, the cladding of the fuel plate is 6061 aluminum alloy. The thickness of fuel meat and cladding is 0.6 mm and 0.38 mm respectively.

The absorb material of control rod and safety rod is hafnium.

1.1.2 Decay tank

The decay tank is located under the reactor core, which is used to collect coolant out from the reactor and to reduce the radioactivity of the coolant. The decay tank is the installation and positioning basis of other equipments inside the reactor pool.

The decay tank is a multi-level cylindrical vessel, it mainly consists of the inner cylinder, middle cylinder, outer cylinder, upper plate, lower plate and clapboards. The diameter of outer cylinder is same as the diameter of the reactor pool liner. The clapboard is radial arrayed between the inner cylinder and the middle cylinder, and between the middle cylinder and the outer cylinder, which constitutes the coolant flowing path. In addition, there are two holes in the upper plate so as to establish coolant natural circulation after reactor shutdown.

1.1.3 Heavy water tank and coolant guiding tank

Heavy water tank and coolant guiding tank are stainless steel vessels. The inner diameter of heavy water tank and guiding tank is 2200 mm and 1364 mm respectively. These two tanks, assembled as a whole, are located on the decay tank. The depth of heavy water is 2320 mm, and the heavy water is covered by a helium (He) layer with 190 mm thickness. The heavy water and coolant is separated by the reactor pressure vessel (RPV) which can be replaced within reactor lifetime. The diameter of the RPV is 459 mm, and material aluminum alloy.

There are 9 beam tubes, and their foresides are located in heavy water tank. The guiding tank is located on the heavy water tank, and its upper plate is the installation and positioning basis of vertical tubes and the cylinder of control rod drive mechanism. There are 21 vertical tubes and 2 safety rod guide tubes which penetrate the guiding tank and then enter into the heavy water tank. The material of vertical tubes is aluminum alloy, these tubes are able to be replaced in reactor lifetime.

1.2 Main parameters

The main design parameters of CARR are listed in Table 1.

TABLE 1: MAIN DESIGN PARAMETERS OF CARR

Parameter	Unit	Value
Power	MW	60
Equivalent diameter of active area	cm	39.92
Height of active area	cm	85
Load of ^{235}U	kg	10.968
Enrichment of ^{235}U	wt%	19.75
Fuel meat material		U_3Si_2-Al
Fuel cladding material		6061-Al
excess reactivity	Δk/k%	19.57 (Cold state)
Shutdown margin	Δk/k%	2.97
Maximum thermal neutron flux	$cm^{-2}s^{-1}$	$\sim 1.0\times 10^{15}$
Primary coolant flow rate	m^3/h	2385
Primary coolant inlet pressure	MPa	0.936
Primary coolant inlet temperature	°C	35

Primary coolant outlet temperature	°C	56
Heavy water flow rate	m^3/h	300
Depth of reactor pool	m	15.54
Inner diameter of reactor pool	m	5.5

1.3 Main systems important to safety

1.3.1 Reactor shutdown system

CARR has four control rods and two safety rods.

The control rods are of follower type, their structure and their drive mechanism are same, therefore, each control rod can be selected as regulating rod and the rest three severs as shim rod. Four CRDMs are located in a chamber beneath the reactor pool. CRDM adopts the electromagnetic scheme. The magnet is in the sealed cylinder, and the electromagnetic coil is outside. When the coils are electrified, the magnet will follow the coil. Through the connecting pole, the magnet connects the control rod so as to drives the control rod moving up and down. When the electromagnetic coil is power off, the control rods will fall into the reactor core under gravity. The electromagnetic coil is driven by a step motor.

Safety rods are driven by a hydraulic mechanism which includes the hydraulic drive cylinder, connecting pole, pumps, valves, etc. The hydraulic drive cylinder is located on the top of coolant guiding tank, the pumps are located in the CRDM chamber. The hydraulic cylinder is composed of the inner cylinder and outer cylinder, when the heavy water flows from the inner cylinder into the outer cylinder, the safety rods will be raised and finally be kept above the reactor core. The lifting, maintaining and dropping of safety rod is achieved by controlling the switch of a pump and electric-magnetic valves. In the case of power off, safety rod can be automatically released.

Two approaches are used to shutdown the reactor, i.e. inserting safety rods and control rods into the core by gravity as well as discharging the heavy water to make the core loss its reflector. The former approach is trigger by both first reactor protection system (FRPS) and second reactor protection system (SRPS), and the later by SRPS. Signals of FRPS and SRPS to trip the reactor are listed in Table 2 and Table 3 respectively.

TABLE 2: VARIABLES TRIGGERING THE CONTROL ROD AND SAFETY ROD FALLING

1	Reactor power	Over setting value
2	period of reactor power	Under setting value
3	Primary coolant inlet temperature	Over setting d value
4	Primary coolant outlet temperature	Over setting value
5	Primary coolant inlet pressure	Under setting value
6	Primary coolant inlet flow rate	Under setting value
7	secondary coolant inlet pressure	Under setting value
8	Dosage of coolant	Over setting value
9	Dosage above reactor pool	Over setting value
10	Dosage of stack drainage	Over standard value
11	Radioactivity of inert gases in reactor hall	Over setting value
12	Inlet temperature of heavy water	Over setting value
13	Outlet temperature of heavy water	Over setting value

14	Heavy water flow rate	Under setting d value
15	Power supply	OFF
16	Frequency of off-site power	Under setting value
17	Pressure in operation hall	Over setting value
18	The ratio of thermal power to nuclear power	Over setting value
19	The ratio of heavy water thermal power to reactor power	Over setting value

TABLE 3: VARIABLES TRIGGERING THE HEAVY WATER DRAINAGE

1	Reactor power	Over standard value
2	Primary coolant outlet temperature	Over standard value
3	γ dose of primary coolant	Over standard value
4	Power supply	OFF

1.3.2 Emergency core cooling system

This system consists of two (2×100%) emergency pumps in parallel which are supplied by emergency power. These pumps suck water from the reactor pool, and they are running while the reactor is in operation, in this case, ECCS is used to cool the water of reactor pool through a heat exchanger. In case of accident, such as LOCA/LOFA, ECCS performs its safety function to remove the residual heat of the reactor core.

The outlet pipe of ECCS pump connects to PCS pipe through check valve, and also connects to the heat exchanger mentioned above. During reactor normal operation, ECCS water can only enters heat exchanger but PCS pipe due to the PCS pressure is higher than that of ECCS. In case of LOCA or LOFA, the PCS pressure will be lower than that of ECCS, the check valve will open passively so that ECCS coolant is able to enter PCS pipe and then reactor core.

Fail-to be-start can be avoid thanks to the ECCS pumps are continuously running while the reactor is in operation.

1.3.3 Confinement

The confinement is the last physical barrier confining radioactive materials, it is design so that the radiation level and radioactivity release comply with ALARA principle, and without exceeding the authorized limits.

CARR confinement is a 30 m×30 m×23 m (L×W×H) reinforced concrete structure with safety class SC-2 and seismic category I. The leakage rate of the confinement is less than 5▽ v/v/d/.

When the hypothetical accidents occur, the normal ventilation is shutdown immediately, and the celerity isolation valve in the duct is closed at the same time so as to retain the radioactive material inside the confinement. In order to prevent the pressure in the reactor hall from exceeding design limits (about 12 hours after the confinement is isolated), pressure monitors are installed and the signal is sent to main control room. When the pressure in the hall exceeds setting value, the operator put the post-accident exhaust system into operation until the pressure in the reactor is below a specified value. The exhaust air is sent to the atmosphere by the chimney through electric heater, pre-filter, HEPA filter, iodine absorber and post HEPA filter.

Variables triggering confinement isolation are: the radioactivity of inert gases in reactor operation hall is over setting value, or the dosage of stack drainage is over setting value.

1.4 Utilization

- Neutron scattering technology and its application;
- Radioisotope production;
- Neutron activation analysis;
- Nuclear physics research and nuclear data measurement;
- Fuel and materials irradiation test;
- Silicon Neutron transmutation doping (NTD).

2. CHINA EXPERIMENTAL FAST REACTOR

China Experimental Fast Reactor (CEFR) is a pool type reactor with 65 MW thermal power and 20 MW electrical power. The reactor core, primary loop sodium pump and the intermediate heat exchanger are located in the sodium pool. The primary loop and the intermediate loop use liquid sodium as heat carrier. The equivalent diameter of the reactor core is 60 cm, and the height is 45 cm.

2.1 Reactor core

2.1.1 Fuel assembly

The first core uses UO_2 fuel assembly with 64.4% U-235 enrichment. U-Pu dioxide fuel will be adopted afterward. There are 81 hexagonal fuel assemblies in the equilibrium core, and each fuel assembly contains 61 fuel rods which are of 6 mm diameter. Stainless steel is adopted as the material of fuel cladding. The upper and lower ends of fuel pellet make up the axial conversion zone which consists of 10 cm and 25 cm depleted uranium respectively.

2.1.2 Control rod assembly

8 control rod assemblies, including 2 regulating rod assemblies, 3 shim rod assemblies and 3 safety rod assemblies, are arranged in CEFR. B_4C with 91% B-10 enrichment is adopted as the neutron absorber of safety rods and shim rods, while natural B_4C is chosen as the neutron absorber of regulating rods. Each hexagonal assembly consists of 7 absorber rods which are of 12.2 mm diameter and 51 cm height. The cladding of absorber rod is stainless steel with 12.9 mm inner diameter and 14.9 mm outer diameter.

3 shim rod assemblies and 2 regulating rod assemblies make up the primary shutdown system.

3 safety rod assemblies make up the secondary shutdown system.

2.1.3 Reflector assembly

According to the heating circumstance, the reflector assembly of CEFR has two kinds of structure, one of which consists of 7 steel rods of 20 mm diameter, while the other consists of 1 steel rod of 54 mm diameter. There are 336 hexagonal reflector assemblies in CEFR. It is designed to ensure that the first circle of reflector assemblies near the reactor core can be replaced by fuel assemblies, and the 3 inner circles of reflector assemblies can be replaced by conversion assemblies which contain depleted uranium dioxide.

2.1.4 Shielding assembly

There are 4 layers with a total of 230 hexagonal shielding assemblies in the periphery part of the reactor core. Each shielding assembly consists of 7 shielding rods which are made of B_4C with 19.8% B-10 enrichment. The shielding assemblies are cooled by natural circulation of sodium. The diameter of B_4C pellet is 16.2 mm. And the cladding of shielding rod is stainless steel of 19.2 mm diameter.

2.1.5 Reactor vessel

The reactor vessel consists of main vessel and its heat shielding, protecting vessel and its supporter, and thermal insulation layer. The main vessel is of 12 195 mm height with a cone upper end and an ellipsoidal lower end, the inner diameter of intermediate cylinder is 7960 mm, and the wall thickness is 25mm. The protecting vessel, with 8185 mm inner diameter and 25 mm wall thickness, is outside the main vessel. The height of the reactor vessel is 12765 mm.

There're two loops of primary sodium cooling system in the main vessel. Each loop consists of a sodium pump and two intermediate heat exchangers(IHX). The sodium in main vessel is divided into hot sodium zone and cold sodium zone. The hot sodium flows downward along in the IHX, and then flows into the cold sodium zone after transferring the heat to the secondary sodium which flows upward.

There're two independent heat exchangers in the main vessel. They belong to the two loops of residual heat removal system respectively.

2.1.6 Control rod drive mechanism

Every control assembly is driven by a single drive mechanism, i.e. there're 8 control rod drive mechanisms in CEFR. They're located on the top of sodium pool. There're two kinds of drive mechanisms in CEFR. One is used for safety rod, and the other for shim rod and regulating rod.

2.2 Main Parameters

The main design parameters of CEFR are listed in Table 4.

TABLE 4: MAIN DESIGN PARAMETERS OF CEFR

Parameter	Unit	Value
Thermal Power	MW	65
Electric Power	MW	20
Plant life	year	30
Bum-up, first load max.	MWd/t	60 000
Bum-up, target max.	MWd/t	100 000
Fuel exchange	Day	80
Fuel (First Loading)		UO_2
Primary loop type		Pool
Number of circuits per loop		2
Number of IHX per circuit		2
Steam pressure	MPa	14

2.3 Safety related important systems

2.3.1 Reactor shutdown system

Two sets of emergency shutdown systems are equipped in CEFR. Actuating mechanism of first shutdown system (FSS) consists of two 3 shim rods and 2 regulating rods, and which of secondary shutdown system (SSS) consists of 3 safety rods. All the 8 control rods are equipped with driven mechanism respectively. Driving devices of two shutdown system meet the requirement of diversity, e.g.:

— FSS driving device is equipped with magnetic damper and no electromagnetic clutch. SSS driving device is equipped with electromagnetic clutch and no magnetic damper;
— FSS releases control rods by power-off of the electric motor, SSS releases control rods by power-off of the electromagnetic clutch;
— FSS control rods are dropped by gravity, SSS control rods are dropped by gravity and spring.

FSS and SSS are triggered by two independent reactor protection systems respectively. Protection variables include reactor period, reactor power, outlet temperature of reactor core, Na liquid level of the main vessel, flow-rate primary Na, flow-rate secondary Na, feeding-water loss of steam generator, closedown of turbine main throttle valve, loss of power supply, earthquake, etc.

Two sets of reactor protection system are separated in two rooms, each of which contains 3 redundant channels that set in different cabinets.

2.3.2 Residual heat removal system

Residual heat removal system (RHRS) transfer the reactor residual heat to final heat sink (atmosphere) on the occurrence of loss of SG feeding-water, loss of power supply, and earthquake.

RHRS is composed of two same independent loops, each mainly consists of an independent heat exchanger in the reactor vessel, intermediate loop, and air coolers outside the containment. Cooling capacity of each loop is 0.525 MW.

In the accident condition, reactor residual heat will be transferred to the hot sodium zone by means of primary pump inertia and natural circulation. The heat will be transferred to intermediate loop through independent heat-exchangers located in the hot sodium zone, and finally to the atmosphere through air coolers.

Outlet valve of air cooler is the only component requiring power, in consists of two patrs driven by two motors respectively; the motors are powered by class 1E power supply system. In the accident condition, outlet valve is opened by reactor protection system, and it can also be opened by manually. It takes 60 seconds to open the outlet valve. wherein

2.3.3 Containment system

CEFR containment system consists of confining boxes and the confinement wherein the confining boxes located.

There are three confining boxes, respectively argon confining box (BOX1), protection cover on the top of the reactor pool(BOX2), aerosol confining box (BOX3).

BOX1 confines radioactive argon released from reactor vessel in caseof overpressure. When argon pressure reaches 0.06 MPa, the liquid-sealing device opens to transfer argon to room 302 for temporary storage and decay, and then to the chimney through ventilation system. Leakage rate of room 302 is less than 4%Δv/v/d (0.03 MPa).

BOX2 is located on the shielding cover of the reactor pool, which is a confining shell made of carbon steel plate. When the radioactive level exceeds the setting value, emergency ventilation system starts up to replace the normal ventilation system and to maintain the negative pressure, by which the radioactive argon and Na aerosol can be prevented from escaping into the confinement.

BOX3 prevents the diffusion of smoke and aerosol produced from Na fire. Groove is laid beneath the pipes and equipments, in case of accident, the leaked Na will flowed into the groove where isolated space will be formed so that the Na fire can be put out automatically. In addition, BOX3 is equipped with Na fire extinction equipments, e.g. nitrogen system.

The confinement is a 36 m×36 m×57 m（L×W×H）enclosed space, which can retain and sedimentate the radioactive material released from the confining boxes. Leakage rate of this concrete structure (thickness 1m) is 5Δv/v/d under 100 Pa.