Small Modular Nuclear Reactor (SMR) Research and Development (R&D) and Deployment in China

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Abstract –*Developing nuclear energy is the measure of meeting national economic development and satisfying the need of energy conservation and emission reduction. Large size nuclear power units are hardly suitable to the application of regional network and the non-electric fields. Small size reactor is needed from the great majority of developing countries and the vast Midwest area of China. Domestic cities and regions put forward an urgent request to nuclear energy heating, desalination, and district heating. Nuclear Power Institute of China (NPIC) had developed many Small and Medium Size Reactors (SMR) in China, Including: Nuclear seawater desalination; Nuclear district heating; Nuclear power commercial ship; Multi-purpose modular small pressured reactor.*
Keywords: *Small and medium size reactor, heating, desalination*

I. INTRODUCTION

Since the 1980s, Chinese economy is rapidly growing. But more and more energy demand and environmental problems caused by firing fossil fuels are key challenges for a sustainable development of China. In the period of 2000–2007, Chinese average growth rate of energy consumption was 8.9% per year and that of electricity consumption was as high as 13.0% per year. The composition of primary energy production (as coal equivalent calculation) was: 76.6% raw coal, 11.3% crude oil, 3.9% natural gas, 7.3% hydro power and 0.9% nuclear power[1]. Such a primary energy mix results in the emission of large amounts of SO_2 and CO_2. In 2006, the emission amounts of CO2 were 5.61 billion tons[2], and those of SO2 from the industry sector were 22.35 million tons[1]. For meeting the challenge, China is developing clean energies including nuclear energy and renewable energies such as wind power, solar energy, and so on. In recent years, China's nuclear electricity production is increasing. Up to now, nuclear power plants with a total capacity of About 10 GW(e), 1% of total electricity generation, new PWRs with a total capacity of over 10 GW(e) are under construction[3]. The construction of Gen-III PWR, AP1000 and EPR, are progressing well. According to the 'State Medium-Long Term (2005–2020) Development Programme of Nuclear Power' issued in Oct. 2007, the total capacity of operating nuclear power plants in 2020 will be 40 GW(e) plus 18 GW(e) under construction. Considerably increasing application of nuclear energy will greatly improve China's primary energy mix and effectively improve air quality.

In order to meet the goal of Chinese government, Several Chinese national industries have developed kinds of reactors, Such as CAP1400, ACP1000, CGP1000, HTR-200 and ACP100 etc. Among them, HTR-200 and ACP100 are SMR which are developed by Tsinghua University and China National Nuclear Corporation separately.

There are several reasons that drive Chinese national industries to develop SMR. SMR is suitable for small electricity grid, district heating, process heating supply and seawater desalination. According to different condition, different counties have different goals in China. In north of China, The demand of energy for city heat consumes is several hundreds of millions tons coal per year, sharing over 10% that the total energy consumption. Due to air pollution in winter, SMR district heating is one of the choices. While in east China, Energy consumption industry in our country, such as building materials, metallurgy, chemical engineering etc, set up their own thermal power plant. The emission occupies over 70% of the total emission in our country. Most of industries locate in east China coastal areas, the serious lack of fresh water resources having become the bottleneck of economic. So SMR used for process heating supply and seawater desalination is also one of the choices. In outlying areas of China, such as mountain area and islands，SMR will be the best choice for electricity generation.

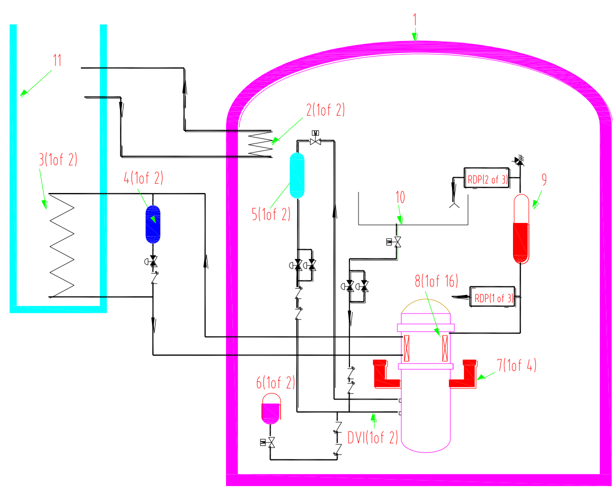
II. SMR R&D in China

II.A. ACP100

II.A.1 Introduction of ACP100

Since 2010, one kind of small and medium size water cooled pressurized reactor called ACP100 has been developed by China national nuclear corporation. ACP100 is an innovative reactor based on existing PWR technology, adopting "passive" safety system and "integrated" reactor design technology. After 3 years development, it has finished overall design, conceptual design and basic design. A number of testing facilities are under construction. R&D on safety related experiments will be carried out in the following 2 years. The construction of the ACP100 will be started around the end of 2014.

The ACP100 SMR containment houses the reactor cooling system (RCS) and the passive safety system, which is illustrated in Figure 1. The integral design of the reactor cooling system consists of an integral reactor vessel, four canned motor pumps, sixteen once-through steam generator (OTSG) located inside the reactor vessel and a pressurizer. In addition, the system includes valves and instrumentation necessary for operational control and safeguards actuation. The integral design of RCS significantly reduces the flow area of postulated loss of coolant accidents.



1:Containment; 2: Containment Condenser;
3: Emergency Cooler; 4: Emergency Makeup Water Tank
5: Coolant Storage Tank; 6:Injction Tank;
7: Primary Coolant Pump; 8: Steam Generator;
9: Pressurizer; 10: In-Containment Water Storage Tank;
11: Containment Cooling Water Storage Tank

Fig.1. Sketch of Reactor Cooling System and the Passive Safety System

The passive safety system mainly consists of the passive residual heat removal system and the passive safety injection system, the passive containment heat removal system and reactor depressurization system （RDP）.

The passive residual heat removal system consists of one emergency cooler and associated valves, piping, and instrumentation. The emergency cooler is located in the containment cooling water storage tank, which provides the heat sink for the emergency cooler.

The passive safety injection system consists of two coolant storage tanks, two injection tanks, an in-containment water storage tank and associated injection lines.

The passive containment heat removal system consists of two containment condensers, water storage tank and associated valves, piping, and instrumentation.

The RDP consists of valves stage1~3 which provide phased depressurization of the reactor coolant system, stage 1~2 RDP valves are connected to the pressurizer, and discharge saturated steam and two-phase flow to the in-containment water storage tank. The RDP Stage 3 valves are connected to the pressurizer surgeline. The RDP acts in conjunction with the passive systems to mitigate the consequences of loss of coolant accidents (LOCAs).

II.A.2 Technical Aspects

Main characteristics

The ACP100 design has the following remarkable technical features:

- Primary system and equipment integrated layout. The maximal size of the conjunction pipe is 5 to 8 cm, whereas the large NPP is 80 to 90cm.
- Large primary coolant inventory.
- Small radioactivity storage quantity. Total radioactivity of SMR is 1/10 of large NPP's, meanwhile multi-layer barrier is added to keep the accident source-term at a low level.
- Vessel and equipment layout is benefit for natural circulation.
- Assurance decay heat removal more effectively. 2 to 4 times of the efficiency of large NPP heat removal from the vessel surface.
- Smaller decay thermal power. 1/5 to 1/10 times of decay thermal power comparing that of large PWR after shutdown, and is easier to achieve safety by the way of "passive".

- Reactor and spent fuel pool lay under the ground level for better against exterior accident and good for the reduction of radioactive material release.
- No operator intervention needed in 72 hours of accident；
- Passive severe accident prevention and mitigation action, such as for containment hydrogen eliminator, cavity flooding etc. to ensure the integrity of pressure containment;

The modular design technique is easy to control the product quality and shorten the site construction period.

II.A.3 Main design parameters

The main technical parameters of ACP100 can be find in table Ⅱ.

TABLE Ⅰ

The Main Technical Parameters of ACP100

Parameter	Unit	Value
Thermal power	MWt	310
Electrical power	～MWe	100
Design life	years	60
Refueling period	years	2
Coolant inlet temperature	℃	282
Coolant outlet temperature	℃	323
Coolant average temperature	℃	303
Best estimate flow	m^3/h	6500
Operation pressure	MPa a.	15
Fuel assembly type	//	17×17 square assembly
Fuel active section height	㎜	2150
Fuel assembly number	//	57
Fuel enrichment	%	4.2
Drive mechanism type	//	magnetism lifting
Control rod number	//	25
Reactivity control method	//	Control rod, solid burnable poison and boron
Steam generator type	//	OTSG
Steam generator number	//	16
Main steam temperature	℃	>290
Main steam pressure	MPa a.	4
Main steam output	t/h	450
Main feed water temperature	℃	105

II.A.4 General layout of plant

According to postulated site, layout 2 set of 100 MWe integral PWR nuclear units. In order to enhance capability to exterior accident, Reactor building is located underground.

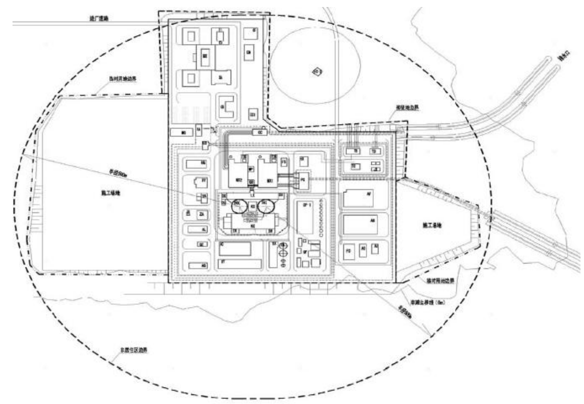


Fig.2. Two modules general layout of plant

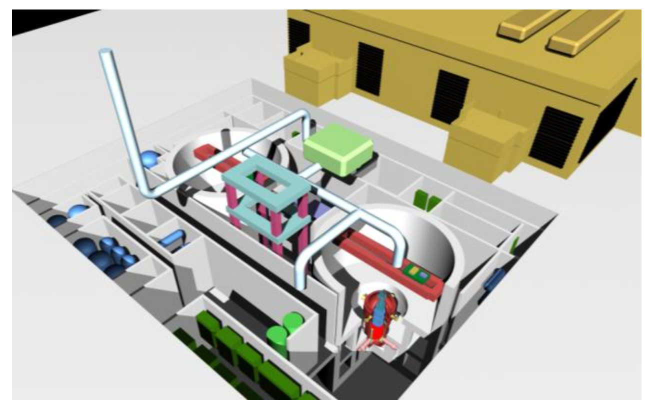


Fig.3. Two reactor buildings underground

II.A.5 Nuclear steam supply system

Integrated layout instead of loop type

- Main pump and reactor pressure vessel connected by short pipe
- Steam generator sets in reactor pressure vessel
- Nuclear steam supply system integrated to reactor module
- CRDM, pressure vessel, reactor internals, OTSG, and canned motor pump all mature technology

Reactor coolant system

- System function and composition

4 main pumps, 16 OTSG, 1 pressurizer

- System description

Operation pressure 15.0 MPa a., core Outlet temperature 323℃

Main steam system

- System function and composition

main steam system ,bypass system, moisture separator reheat system

- System description

operation pressure 4.0MPa,Temperature 285℃, Flow 450t/h

CRDM

- Step: 15.875mm/min；
- Max travel speed: 72mm/min；
- Electromechanical delay time:≤150ms；
- Temperature: 200℃
- Pressure housing design life: 60 years；
- Min. cumulative step number of non-
- Service: 6.0×106steps。

Fuel assembly

- 17×17 square pitch arrangement
- Fuel rod: 264
- Guide tube: 24
- Instrumentation tube: 1
- Total height: ～2500mm

Fig.4. Reactor with other main equipment connected

II.B.A Engineered safety feature plan

The safety design philosophy of ACP100 is to realize high level of safety and, at the same time, to simplify the design of the systems by the means of passive engineering safety system. There is no emergency diesel generator needed. The emergency measures outside the plant boundary should be made technically not necessary or reduced to a minimum level. The passive residual heat removal system can be capable of removing core decay heat without the need for AC electrical power for 72hours,the passive safety injection system can make up the coolant lose within a transient and accident, provide mitigation of all design basis accidents for 72hours,the passive containment cooling system can be capable of removing the heat released to the containment and sufficiently reducing the containment pressure and temperature by natural circulation during the 72hours when LOCA happened. Ensure the containment integrity under accident condition.

- The absence of large diameter piping associated with the primary system, removes the possibility of large break loss of coolant accidents (LOCA). The elimination of large break LOCA substantially reduces the necessity for emergency core cooling system components, alternate current (AC) supply systems, etc.
- Large coolant inventory in the primary circuit results in large thermal inertia and long response time in the case of transients or accidents.
- Inherent safety features: Integrated primary coolant system, eliminating large break LOCA; Long characteristic times in the event of a transient or severe accident, due to large coolant inventory and the use of passive safety systems; Negative reactivity effects and coefficients.
- Passive safety systems：Systems are duplicated to fulfil redundancy criteria. According to Chinese nuclear safety regulations, the shutdown system is diversified. Residual heat removal system, Emergency injection system, Safety relief valves which protect the reactor pressure vessel against over-pressurization in the case of strong differences between core power and the power removed from the RPV. All safety systems mentioned in this paragraph of the ACP100 are passive systems.

These design features above enhance the passive safety features of the ACP100.

II.A.7 Role of passive safety design features in defense in depth

- Level 1: Prevention of abnormal operation and failure

Contributions of ACP100 inherent and passive safety features at this level are as follows: Due to the absence of large diameter piping in the primary system, large break LOCAs are eliminated; Canned pump eliminates boron injection for pump sealing system.

- Level 2: Control of abnormal operation and detection of failure

The ACP100 passive safety features for this level are as follows: A large coolant inventory in the primary circuit results in a larger thermal inertia and in longer response times in the case of transients or accidents.

- Level 3:Control of accidents within the design basis

ACP100's safety systems are based on passive features obviating the need for actions related to accident management over a long period.

- Level 4: Control of severe plant conditions, including prevention of accident progression and mitigation of consequences of severe accidents

Contributions of inherent and passive features of ACP100 at this defense in depth level are as follows: When core uncover is assumed, only for analytic purposes, low heat-up rates of fuel elements in the exposed part of the core are predicted, if the geometry is still intact. The characteristic time of core melting is long, eventually preventing temperature excursion due to a metal-water reaction, which in turn limits the hydrogen generation rate; Reduction of the hydrogen concentration in the containment by catalytic recombiners; Sufficient floor space for cooling of molten debris; Extra layers of concrete to avoid direct exposure of the containment basement to debris.

- Level 5:Mitigation of radiological consequences of significant release of radioactive materials

The following passive features of ACP100 make a contribution to this defense in depth level: Relatively small fuel inventory, when compared to larger NPPs; Slower progression of accidents and increased retention of fission products (facilitated by such features as reduced power density, increased thermal inertia, etc.); The containment is located inside the airplane protection concrete and underground building, which reduces the release of fission products due to local deposition. The ACP100 concept provides for extended accident prevention and mitigation by relying on the principles of simplicity, reliability, redundancy, and passivity.

II.A.8 After "Fukushima" Action

After "Fukushima" accident, design and operation nuclear power plant should strictly comply the requirements of safety code. In addition, the combination of various internal and external accidents should be considered. The following accidents are analysed after "Fukushima" accident.

- The loss of off-site power supply and the emergency diesel power supply

ACP100 has integrated primary coolant system and removes residual heating to large capacity containment pool through heat exchanger depending on primary coolant natural circulation. The reactor will not lose cooling in case of the lose of power, and can sustain the residual heat removal for 72 hours.

- The combination of loss-of-coolant accident and loss of all the power

After the loss of coolant accident , ACP100 achieving core cooling and the containment heat removal completely due to the passive facility in this process, and the accident aggravation will not happen for the lose of power.

- Safety and accident risk of the spent fuel storage pool

The spent fuel pool of ACP100 small modular reactor lays under ground elevation and a standby makeup pool set outside of the plant, the fuel uncover will not happen under the extreme condition of the structure of spent fuel pool breaking under seismic condition and the cooling lost for the lose of power.

- Core-melt

ACP100 is the third generation PWR, with inherent safety characteristics, no large break LOCA etc., adopting complete passive safety feature which obviously reduce the accident probability and the consequence. Besides, consider the serve accident prevention and mitigation action, such as CIS, hydrogen recombiner and the corresponding accident management guide.

II.B.9 Testing & Verification

Six test research subjects will be taken in ACP100. Their names and schedule are following:
Control rod drive line cold and hot test
Control rod drive line anti-earthquake test
Internals vibration test research
Fuel assembly critical heat flux test research
RDP test research
Passive emergency core cooling system integration test
coolant storage tank and passive residual heat removal system test research

TABLE II

Verification testing and schedule of ACP100

Code number	Name	Period
1	control rod drive line cold and hot testing	2011-2013
2	passive safety system integration testing	2011-2013
3	internals vibration testing	2012-2013
4	fuel assembly critical heat flux testing	2011-2013
5	coolant storage tank and passive residual heat removal system testing	2011-2013
6	control rod drive line shock testing	2012-2013

III. DEPLOYMENT OF SMRS IN CHINA

III. A ACP100

III.A.1 Licensing

The following activities have been accomplished related with licensing.

- Signed a contract of SMR combined research with National Nuclear & Radiation Safety Center in 2011;
- Developed the following works: National Nuclear & Radiation Safety Center gave the comments on the SMR research report of design preparation phase; Had a technical exchange of SMR containment design after Fukushima nuclear accident; Passive integration test research technical exchange, and the test program was approved;
- Completed the Q1 questions and question reply of concept design stage, and the concept design was approved;

- Will sign several specific research programmers and standard design safety analysis combined research with National Nuclear & Radiation Safety Center in year 2013.

Ⅲ.A.2 Site Selection

The demonstration ACP100 nuclear power plant , with two 310Mwth reactors, will be located in Putian City, Fujian Province in the east coast area of China.

NOMENCLATURE

RDP Reactor Depressurization System
DVI Direct Vessel Tank
RCS Reactor Coolant System

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