STATUS OF RESEARCHES ON ADVANCED NUCLEAR ENERGY SYSTEM IN CHINA

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Introduction

Energy resource is the basis of the national economy development. Along with the growth of economy and population, and improvement of people's living standard, electric power demands will be inevitable increased.

It is estimated that around the middle of this century China requires an installed capacity up to 1 200 GW. In order to realise this target, fully taking into account the production capacity of coal, oil, natural gas and the renewable energy sources such as waterpower, a fairly large gap still remains. To fill in this gap, the nuclear power is regarded as a best choice in China case because it is safe, reliable, economic-acceptable, realisable, and could be used in large scale, to replace coal burning step by step. The thermal power by burning coal constitute a leading position in electric power structure in china, which leads a serious environmental pollution and makes great pressure to national transportation system. The nuclear power as a clean energy source will be a best choice and play more and more important role in adjusting existing energy structure in China for the sustainable development of national economy.

Right now still only three nuclear power plants are in operation, which only share about 0.7% of total capacity in the China mainland. Four nuclear power plants (NPPs) with eight units are under construction. It could be envisaged that the total capacity of nuclear power in 2005 would reach 8.5 GWe as shown in Table 1. Other four new NPPs with eight units of 1 GWe each are under consideration to start construction before the year 2005.

Table 1. **Mainland nuclear power plants**

NPP	**Type**	**Power** (MWe)	**Start-up**	**Status**
Qinshan-I	PWR	300	1993	in operation
Dayabay	PWR	2×900	1994	in operation
Qinshan-II	PWR	2×600	2002	in operation
Lingao	PWR	2×944	2003	under construction
Qinshan-III	PHWR	2×720	2003	under construction
Tianwan	PWR	2×1 000	2004	under construction

To develop nuclear power in large scale, two problems must be solved. Firstly, as we understand the technically and economically exploitable natural uranium resources are limited domestically or overseas, so the uranium utilisation rate has to be raised greatly. Secondly, long-lived radioactive nuclear wastes have to be in disposal to remove its impact to environment and public fear to nuclear power.

Right now only small amount of spent fuels from NPPs has been accumulated in China. But the situation will be very serious in the future according to a prediction of nuclear energy development in China. The annual generation of waste is estimated to 2 275, 7 500 and 10 000 m^3 respectively for the year 2004, 2010 and 2020.

Because of the limited uranium resource in China, we pursue the closed-cycle policy for the nuclear fuels instead of once-through mode. We also believe that reprocessing is essentially a non-proliferation process. Our commercial spent fuel reprocessing plant is anticipated to be built around 2020. So, disposal of the high-level wastes is not an urgent matter in China for the time being. Some preliminary work is under way, such as siting of repository and migration behaviours of some key nuclides under deep geological conditions.

Considering MA and LLFP transmutation with more efficiency and non-criticality risk for new nuclear application, the fast breeder reactor technology and the accelerator-driven sub-critical system (ADS) have been started to develop as a national research projects in China.

Fast reactor technology development in China [1]

FBR is a good candidate for sustainable development of nuclear energy due to it can greatly increase uranium utilisation rate up to 60-80%, and it can be used as a burner to MA and LLFP deducing the stockpile of long-lived nuclear wastes. It is estimated that the transmutation rate to MA by FBR is roughly 50kg/Gwe/y in the case of 2.5% MA loaded in the fuel bars.

The basic researches for FBR in China could be divided in to two Phases. The activities from the middle-end of 60s to the year 1987 focus on fast neutron physics, thermohydaulics, materials, sodium technology and some sodium components in small size. During this period about 12 sodium loops and test facilities have been built up including a fast neutron zero power facility DF-V containing 50 kg ^{235}U. From the year 1987 to 1993, all research activities were arranged with a target of 65 MWt experimental fast reactor. The emphasis was put on fast reactor design study, sodium technology, and fast reactor safety, fuels and materials as well as sodium components. During this period about 20 sodium loops and testing facilities have been established and tested. After above period's researches the R&D of fast reactor technology are carried out as the design demonstration tests which more than 30 items.

The preliminary strategy study for fast reactor development points out that Chinese fast reactor engineering development will be divided in to three steps. As the first step, China Experimental Fast Reactor (CEFR) supported by the National High Technology Programme is under execution. In the second step, Prototype Fast Breeder Reactor (PFBR) will play as a prototype for next step Large Fat Breeder Reactor (LFBR) and as a module for Modular Fast Burner Reactor (MFBR) plants which may be suitable for MA burning. The LFBR and MFBR are third step in fast reactor development. The Table 2 gives the technical continuity of Chinese FBR engineering development and main technical selections.

The conceptual design of the CEFR with the power 65 MWt was started at 1990 and completed at 1993 including the confirmation and optimisation to some important design characteristics. Its preliminary design was completed in August 1997.

The CEFR is a sodium cooled experimental fast reactor with (Pu,U)O_2 as fuel, but UO_2 as first loading, Cr-Ni austenitic stainless steel as fuel cladding and reactor block structure material. Two main pumps and two loops for primary and secondary circuit respectively. The water-steam tertiary circuit is also two loops, but the super heat steam is incorporated into one pine, which is connected with a turbine-generator of 25 MWe.

Table 2. **Technical continuity of Chinese FBRs**

	CEFR	PFBR	LFBR	MFBR
Design beginning	1990	2001	2013	2013
Commissioning	2005	2015	2025	2025
Power, MWe	25	300	1 000-1 500	4-6×300
Coolant	Na	Na	Na	Na
Type	Pool	Pool	Pool	Pool
Fuel	UO_2 MOX	MOX Metal	Metal	MOX+Ac Metal+Ac
Cladding	Cr-Ni	Cr-Ni ODS	Cr-Ni ODS	Cr-Ni ODS
Core outlet temp., °C	530	500-550	500	500-550
Linear power, W/cm	430	450-480	450	450
Burn-up, MWd/kg	60-100	100-120	120-150	100
Fuel handing	DRPs SMHM	DRPs SMHM	DRPs SMHM	DRPs SMHM
Spent fuel storage	IVPS WPSS	IVPS WPSS	IVPS WPSS	IVPS WPSS
Safety	ASDS PDHRS	ASDS+PSDS PDHRS	ASDS+PSDS PDHRS	ASDS+PSDS PDHRS

Where DRPs means Double rotating plugs, SMHM Straight moving handling machine, IVPS In-vessel primary storage, WPSS Water pool secondary storage, ASDS Active shut-down system, PSDS Passive shut-down system, PDHRS Passive decay heat removal system.

The CEFR block is composed of main vessel and guard vessel which is supported from bottom on the floor of reactor pit with the diameter 10 m and height 12 m, reactor core and its support structure, internal structures on which two main pumps, four intermediate heat exchangers and two DHRS heat exchangers are supported. The double rotation plugs on which control rod driving mechanisms, fuel handling machine and some instrumentation structures are supported on the neck of the main vessel.

The CEFR is located in the China Institute of Atomic Energy (CIAE), about 40 km far away from Beijing City, which owns about 10 million inhabitants. According to the raising environment safety consideration, it is stipulated to have more strictly requests to radioactive materials release standards for normal operation, design basis accident (DBA) and beyond design basis accident (BDBA) which are 0.05 mSv/a, 0.5 mSv/accident and 5 mSv/accident for CEFR.

After two years review to preliminary safety analysis report by Chinese National Nuclear Safety Administration (CNNSA), the CEFR construction permission was issued in April 2000 and the CEFR was started to construct the 3 m×69 m×82.5 m foundation base of CEFR reactor building and completed in the November 2000. Then construction work stopped for two reasons: one is that the CNNSA asked us to make additional analysis, especially, of the sodium spray fire accidents and another is just winter arriving. After the additional analysis of some accidents has been submitted and approved by the CNNSA, the full construction permission for the CEFR was issued, in the early of spring, on March 15, 2001 the CEFR construction was restarted. The 57 m main building for nuclear island has been completed in this August. The main milestones for CEFR in the future include using electricity from grid in September of next year, the hot testing in September of 2004, and first criticality at the end of 2005.

Progress in ADS system research [2-3]

As a candidate of nuclear system which could meet more safer requirement than recent those to decrease the risk of core melt and unforeseen release of radioactive materials and could transmute the MA more efficiently, a new research field on accelerator-driven sub-critical system (ADS) was proposed in China in the year 1995 and a five years programme (phase 1, 1998-2002) has been launched. The main progress is summarised as follows.

Ion Source A microwave ion source is under developing for a demonstration prototype of a accelerator-driven sub-critical system at CIAE, 60 mA hydrogen beam has been extracted from the source through a 7.3 mm aperture in diameter, proton ratio is more than 85%, reliability has been test for 100 hours without any failures. The parameters of the source during the test include extraction voltage 30kV, microwave power 800 W, and vacuum pressure 1×10^{-3} Pa.

Accelerator The superconducting linac is a good selection of ADS accelerator because of its high efficiency and low beam loss rate. Our ADS accelerator consists of a 5 MeV radio frequency quadruple, a 100 MeV independently phased superconducting cavity linac and a 1 GeV elliptical superconducting cavity linac. The accelerating structures and main parameters are determined and the research and development plan is considered.

Table 4. **The main parameters of RFQ**

Input energy (keV)	80	total length (m)	7.1
Output energy (MeV)	5	intervane voltage (kV)	70
Beam current (mA)	30	transmission	95
Working frequency (MHz)	352	synchronous phase (deg)	90-30
Normal transverse RMS		modulation	0.29-0.32
Emittance (πmmmrad)	0.2	average aperture (cm)	1-1.94
Normal longitudinal RMS		cavity RF losses (MW)	0.58
Emittance (πMeVdeg)	0.2	beam power (MW)	0.15
		total RF power (MW)	0.73

A preliminary physical design of 5 MeV proton Radio Frequency Quadruple (RFQ) accelerator for the ADS system has been carried out, with the design parameters given in Table 3. The design study on intense proton Linac has been completed with design target of outlet current intensity 30 mA (continuously), out let energy 1 GeV.

AD-FBR System A medium size sodium cooled fast breeder reactor driven by an accelerator with 1 GeV/16 mA shows its advantages over the ordinary one, such as less Pu inventory required, higher breeding ratio and reasonable transmutation rate (which may support two units 1 000Mwe PWR) at expense of less 15% energy output. The calculation gives us some idea about how the fast sub-critical reactor is in favour of the MA's transmutation and fissile breeding.

AD-PHWR System The pressurised heavy water moderated reactor (CANDU type) was adopted for the analysis both for Th-U and U-Pu fuel cycles. The beam pipe and lead target substituted four central pressurised tubes. It is shown that AD-PHWR is favouring to Th-U fuel cycle not only higher burn up, but also with slight breeding capability. While in U-Up fuel cycle, the fuel may self-sustainable only with relative higher beam current, smaller K value and with a little higher burn-up than ordinary CANDU.

Spallation Target As the proton beam window and the spoliation target are the interface of the accelerator and the sub-critical reactor, which is the important component of the ADS. From the engineering application point of view the basic problems such as spallation neutron yield, energy deposition, the irradiation damage and radioactivity accumulation are concerned.

The calculations to the standard thick target were made by using different codes. The simulation of the of the thick Pb target with length of 60 cm, diameter of 20 cm bombarded with 800, 1 000, 1 500 and 2 000 MeV proton beam was carried out. The yields and the spectra of emitted neutron were studied. The spallation target was simulated by SNSP, SHIELD, DCM/CEM (Dubna Cascade Model/Cascade Evaporation Mode), and LAHET codes.

The simulation results were compared with experiments. The comparisons show good agreement between the experiments and the SNSP simulated leakage neutron yield. The SHIELD simulated leakage neutron spectra are good agreement with the LAHET and the DCM/CEM simulated leakage neutron spectra.

Materials Radiation damage effects were studied by using SHIELD codes system. The researches concern radiation damage cross section, displacement production, gas production in target, container window structure materials induced by intermediate energy proton and by neutron. And the study of radiation damage in the thick Pb target with long 60 cm, radius 20 cm was completed. The experimental study of radiation effects have been carried out for the home-made modified 316L stainless steel and standard stainless steel and tungsten irradiated by 80 MeV ^{12}C or 85 MeV ^{19}F ions. The experimental results show that the radiation resistant property of stainless steels is much better than that of tungsten and the home-made modified 316L. The compatibility tests for the forging tungsten with coolants have been performed in sodium at 500, 600 and 700°C and in water at 100°C.

In the next three years, a VENUS facility will be completed. This facility will be used to study the neutron flux distribution, neutron energy distribution, the neutron enhancement, the reactor fission rate, and k_{eff} in sub-critical assembly driven by pulsed fast external neutron source. The facility consists of two parts, a pulsed-neutron generator and a sub-critical assembly. The pulsed-neutron generator is a 300 keV Cockcroft-Walton type accelerator for generating 14 MeV neutrons by (d, t) reaction. The sub-critical assembly will be designed in different lattice structure with different enrichment U fuel and polyethylene to provide different spectra.

The P&T technologies related to ADS system will be also studied.

Concluding remark

The two new nuclear systems FBR and ADS have been started to develop with a rather moderate project in China and they are all still in the early stage. For fast reactor development, its first step, CEFR is foreseen to reach its first criticality at the end of 2005. The second step 300 MWe Modular Fast Reactor (MPFR) is under consideration. For ADS, we are making great efforts to accomplish the research tasks worked out in the first phase programme and enthusiastically preparing to step to the second phase programme which is marked by experimental facility VENUS.

As said before the researches for these two new systems are both in the early stage, the budgets spent up to now are limited, so we have long way to go to develop these advanced nuclear energy systems**.**

REFERENCE

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