

Self-reliance and Innovation of Qinshan Phase II NPP Project

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Abstract: This article mainly describes the self-reliance and innovation of Qinshan nuclear power project of phase II, in-between it contains new reactor core design, as well as related experimental and calculation analysis, especially for new reactor design produced fluid-induced vibration model test, theoretical analysis and testing in-built reactor; aiming at two-loop NSSS a series improvement made for safety systems and related safety analysis to enhance their reliability and redundancy; according to specialty of two-loop NSSS an optimization made for NPP parameters and design of related equipments, for the purpose to make the output of NPP maximal; design of main reactor building and T-G building also improved according to characteristics of two-loop NSSS and site conditions. CRDM and refueling machine are researched and manufactured on base of self-reliance, their performance are better than design requirements, large portion of key equipments are localized through different way. In construction first time realized the integrated erection of containment dome. During the commissioning non-nuclear steam driving of T-G set, as well as 500 kV high voltage rising using emergent diesel generator, etc. are carried out. In period of operation still continuous innovation and improvement are made, so that to keep the good record of operation.

Key words: nuclear power project; phase II

1 Preface

Qinshan Nuclear Power Project Phase II is the first commercial nuclear power plant that has been self-designed, self-constructed, self-managed and self-operated by China. The project was launched on June 2, 1996 and completed on March 3, 2004 with equipments localization rate of 55%. Per kilo-watt cost was USD1330 which is far below USD 1800 of similar NPP imported in the same period. Both units have been operated well after putting into commercial operation, showing higher economical and safe performance. Main performance indicators reach or excess the international mid-value level and get better economical and social benefits.

Qinshan Nuclear Power Project Phase II abides the Nuclear Power development guideline of “keeping

self-reliance with Sino-foreign cooperation”. Many important technological improvements and innovation has been carried out in design, construction, equipment manufacture, commissioning, operation and management so that the safety, performance and reliability of the plant are improved. The comprehensive performance of the plant has reached the similar international advanced level of NPP in 1990s. It has set a new record for the self-reliance construction of nuclear power plants after construction of Qinshan Nuclear Power Project Phase I.

Self-innovation of Qinshan Nuclear Power Project Phase II shows in the aspect of Self-Design, Self-Construction, Self-Commissioning, Self-Operation and Self-Management with Higher equipments localization level.

Received 18 August 2007

2 Self-Reliance Design & Technological Innovation

Design self-reliance is key point of the Nuclear Power self-reliance. Only in the design technologue know “how to do it, and why do it such way”, than can reach the initiative in construction and management, realize the self-construction, self-operation and self-management.

Qinshan NPP phase II takes Daya bay NPP as a reference, following international standard design concept of 300 Mwe one loop and characteristic of two-loop NPP, adopts international advaced rules and standarts, through technologue import, research and experiment, masters the nuclear power key technologue, selects technical project, general parameters, key technical index and carries out project design on base of self-reliance. The important research and deveopment work and experimental verification are relied on domestic nuclear power research and experimental base and other related investigation institutes. On premiss of self-reliance imports part design software, implements consultation on some difficult design issues with foreign companies. Following the further enhanced safety requirements for NPPs in world, establishes related technical requirements for systems and equipments, and realizes in their design. The main technical innovations are as follows.

2.1 Design of Reactor Core

Qinshan Second NPP is a nuclear power plant of pressurized water reactor with two loops. As for reactor core is concerned, Qinshan Second NPP is a completely new design which is different from the two-loop NPP of pressurized water reactor in world.

As the reactor core of Qinshan Second NPP is loaded with 121 , 17×17 AFA-2G fuel assemblies , with 33 control rod assemblies as well as primary and secondary neutron source assembly, so that the domestic design and manufacture technology of the introduced nuclear fuel assemblies and related assemblies for million kWe level NPP can be used directly. The selection of AFA assemblies is beneficial for standardization of domestic fuel assemblies.

While the reactor and reactor coolant system have to be redesigned, besides the analysis and computation of physics, thermo-hydraulics and mechanics, the intensive scientific research and test for key technical problems are also conducted such as reactor hydraulic test and flow distribution in reactor core as well as flow-induced vibration model test of reactor internal in order to verify the correctness of design and offer guidance for design optimization.

Mean linear power density of fuel rod in reactor core is 16.09 kW/m which is not only 15 % lower than that of introduced NPP, also lower than that of international similar two-loop NPP and improves the thermal safety allowance of the reactor core, which meet the requirements of advanced reactor stipulated in URD of US and conform to the international tendency of further improving the safety of NPP. The advanced fuel management of 1/4 fuel handling policy is taken into consideration in the design process of Qinshan Nuclear Power Project Phase II , which takes place of the management of 1/3 fuel handling policy to improve the utilization rate of nuclear fuel. So that on the premise to guarantee nuclear safety, the economical benefits are improved as good as possible.

2.2 Determination of Main Parameters

Considering the performance figure and characteristics of optimization design of domestic 600 MW level turbo-generator unit, Qinshan Second NPP project defines the primary parameter of Qinshan NPP and appropriately raise the primary parameter to make each loop contributes 330 MWe, which is higher than the contribution of each loop (about 295 MW) in two-loop NPP of pressurized water reactor in world (US and Japan).

On the basis of imported fossil power technology and in the consideration of the parameters and characteristics of steam turbine of NPP, the steam turbine set is redesigned and the module assemblies is selected optimized, namely one BB057N module for high pressure cylinder of steam turbine and three BB0474R modules for low pressure cylinders. Two moisture separation reheaters are established between the high pressure cylinder and the low pressure cylinder. The mode of three

high pressure re-heaters, three low pressure re-heaters and one deaerator for the power conversion system in the second loop is chosen to enhance the output and thermal efficiency of both units; The output of steam turbine set is 689 MW under the annual mean water temperature (18 °C) and is 650 MW under the highest water temperature (31 °C) in summer. Concurrently, the generator hydrogen-cooled system's efficiency is improved on the basis of optimization design to make maximum contribution of generator set reach 700 MW. Accordingly, the capacity of the main transformer is also improved from original design of 240 MVA to 250 MVA for each phase, so the total generator output could transfer to the grid after deduction of the plant consumption.

It can be found out that the contribution of turbo-generator unit in Qinshan Phase II is the largest among these in the same type of two-loop NPP of pressurized water reactor. The gross efficiency of NPP is near 36 % (under design temperature of sea water 18 °C) and is the higher one in that of two-loop NPP. The capacities of turbo-generator unit and high voltage transformer used in Qinshan Phase II are also the highest one among that of domestic units in that time.

2.3 Design of Reactor System

The reactor system is composed of fuel assemblies and other related assemblies, core internals, reactor pressure vessel and its support, control rod drive mechanism, thermal insulation and reactor head package.

In order to verify the design characteristics of reactor system, the corresponding hydraulic model experiments and computational analysis are conducted including the hydraulic characteristic tests such as inner pressure drop distribution of reactor coolant in reactor pressure vessel, flow distribution of inlet and outlet of reactor core, flow passage of reactor core, bypass flow proportion in reactor core and partial fluid velocity. According to the result of experimental investigation, optimize the design of flow passage structure, adjust the design of flow distribution plate and ensure the even distribution of flow rate in reactor core to meet the requirements of thermal design of reactor core. And

then figure out the coefficient of resistance in each part to offer the reference for defining pump lift of main coolant pump. Whereas the design of inner components in reactor is classified as class II non-prototype, not only the model of flow-induced vibration test of 1:5 model and theoretical analysis and calculation are conducted, but also the actual measurement of flow-induced vibration in actual reactor with higher pressure and higher temperature is conducted during commissioning. Through actual measurement in reactor and comprehensive examination, it is verified that the influence of flow-induced vibration of reactor internals is very small total meets the requirements of nuclear safety rules. In the meanwhile, the measured data greatly accord with the results of model test and calculation analysis. It is very difficult to conduct the actual measurement for flow-induced vibration in reactor under high temperature and high pressure. Even if in foreign countries, this kind of test is only conducted in few prototype reactors. It is the first time of this test in domestic NPP.

The design of control rod drive line is another important item which is directly related to safety operation of reactor. The time of rod drop is an important performance indicator for safe shutdown of the reactor. In order to verify its design, besides experimental analysis for all factors influencing drive line performance, the integrated examination of drive line on thermal test stand is also executed to examine the operating performance and rod drop performance of control rod drive line in normal and abnormal operating condition, lifetime of drive mechanism, guiding performance of guiding assembly and abrasion of control rod. Furthermore, the multipoint excitation seismic test is also conducted to verify the operating characteristic and rod drop performance of control rod drive line under the state of earthquake.

In order to extend the working lifetime of reactor pressure vessel and decrease irradiation damage of fast neutron flux rate in reactor pressure vessel, the measures such as widening the thickness of water layer in annular downcomer space between core internals and reactor pressure vessel are adopted to make that the

calculated value of total inner surface fast neutron irradiation at the end of lifetime of reactor pressure vessel is $1.2 \times 10^{19} \text{ n/cm}^2$ which is much lower than the limitation of designed value of $5.0 \times 10^{19} \text{ n/cm}^2$. This value is greatly lower than the French M310 design for Daya Bay NPP and ensures that working lifetime of reactor pressure vessel is more than 40 years with the expected lifetime of 60 years.

The reactor pressure vessel adopts single integrated forging with vessel flange part and nozzle part and single forging for reactor core cylinder part, canceling the welding seams in active zone, which can greatly improve the radiation resistance performance of pressure vessel. The RTNDT of materials is lower than -20°C , which guarantees that the brittle fracture can never take place during the designed lifetime.

Comprehensive mechanical analysis for reactor pressure vessel under all kinds of operating conditions is conducted according to rules and performance specifications, including stress analysis, fatigue analysis and fracture analysis. Considering the features of two loops, two safety injection nozzles are directly installed in pressure vessel. So the thermal shock induced during safety injection should be analysed to make sure there is no damage to the reactor vessel.

2.4 Design of Reactor Coolant System

Reactor coolant system is composed of reactor pressure vessel, core internals, control rod drive mechanism, steam generators, reactor coolant pumps, pressurizer, reactor coolant pipings, surge line and related valves.

Two loops are symmetrically arranged with 60° angle between inlet and outlet nozzles in reactor pressure vessel. Compared with the referenced NPP, the angle between cold and hot leg nozzle of reactor coolant pipe is changed from 50° to 60° , which is propitious to the compensation of thermal expansion and buffering of earthquake load. Pressurizer surge line for the first time adopts the design with oblique arrangement successively heightened to reduce the fatigue damage arising from the stress disproportion in tube wall due to cool and hot water delamination in surge line.

In equipment design and type selection the latest

technology of foreign nuclear equipment design and type is adopted. Cold RPV head is applied in the RPV design to lower the operating temperature of the head by injecting lower temperature coolant through a bypass to cool the RPV head. In addition, material Inconel 690 of the control rod drive mechanism adapters and its welding is used to protect stress corrosion, which prevents the occurrence of crack in welding seams between CRDM adapters and reactor vessel head. In the design of steam generator, the major improvement is the total amount of heat transfer tubes, its arrangement and the type of support plate (with four-leaves quincunx hole) to obviously improve the heat transfer efficiency and flow resistance with heat transfer area of $5\,630 \text{ m}^2$ which is larger than required design margin. The steam generator adopts integrated forging with bottom head and steam nozzle head as well as conical forging with straight cylinder part. The heat-transfer tubes adopts Inconel 690. The design of feedwater supply ring is improved with spray stand pipes and additionally impose sludge collector hereunder to reduce sludge deposit on tube plate. Improve the design of moisture separator and dryer to increase the dryness of steam outlet (Dryness is 99.9 %). In the meanwhile, the chemical requirement of feedwater is enhanced, so that the operating performance and reliability of steam generator is improved. In virtue of improvement of reactor coolant pump design, the efficiency of pump is raised to 79 % and more than four million kilowatt-hours can be saved in one year. The main pump also adopts high temperature enduring mechanical seal to improve the reliability of mechanical seal and avoid the leakage of primary coolant system arising from invalidation of mechanical seal under the circumstance of power down in whole plant. The specific volume of pressurizer is increased from 0.144 to 0.162, which can compensate pressure fluctuation even better and upgrade the stabilization of system operation during the system warmup, temperature or power change and load rejection.

2.5 Design of Nuclear Auxiliary System and Safety System

According to the features of two loops and plant location, a series of improvements are made in the

process of design. Such as:

(1) Whereas the large loss of coolant accident (LOCA) for a two-loop NPP is greatly larger than that of a three-loop NPP, safety injection system shall additionally install two reactor vessel direct injection to improve the efficiency of safety injection in order to ensure the cooling of reactor core. In the meanwhile, in order to ensure the efficiency of high-concentration boron injection through safety injection under the accident of main steam line break, the injected boron should be through boric acid injection tank into the cold leg of main coolant loop in first 3 minutes, afterwards open the by pass to start reactor pressure vessel direct injection, for the purpose to avoid the abrupt increase of positive reactivity arising due to the reactor temperature effect. After detailed transient analysis of accident, the above mentioned project shows its ability to meet the requirements of safety.

(2) Whereas the portion of lost feed water for a two-loop NPP is greatly larger than that of three-loop NPP under the accident of break of main feed water piping. So the originally designed auxiliary feed water system, i. e. two sets of electric pump ($2 \times 50\%$) and one set of steam-driving pump ($1 \times 100\%$) to supply feed water to steam generator can no longer meet the requirements of safety. Qinshan NPP phase II adopts A and B two independent lines of auxiliary feed water system, each line separately supplies one set of steam-driving pump and one set of electric pump. The redundancy of the machine-driving components in system is $4 \times 100\%$, which improves the reliability of system. It accords with research direction of current advanced pressurized water reactor.

(3) The corresponding modification of residual heat removal system is also conducted according to the features of two loops. Two series separately take water through two parallel suction pipes from two hot leg of different loop, collect and then flow into main effluent pipe through two sets of residual heat removal pump. The main effluent pipe is separately connected with two sets of residual heat removal heat exchanger, gathered then divided into two lines, separately connected with cold leg of different loop, so that to improve the reliability

of system, system is also supplied with by-pass to adjust temperature of main coolant loop.

(4) According to the features of two loops, atmospheric relieve system is designed such way that the each main steam pipe is connected with two parallel relieve valves to meet the criteria of single failure

(5) Owing to high silt content in sea water in Qinshan region, a large amount of experiment and research are carried out in order to avoid silt accumulation in circulating cooling water system, especially in plant safety cooling system, including sea water corrosion protection and silt accumulation test in plant safety cooling pumps and plate type heat exchangers. According to the result of research the related measures are accepted, for example, flow speed selection in flow passage and back flush in plate type heat exchangers, etc. Practice shows that the test and research as well as the taken measure are successful.

(6) In order to improve feed water quality in steam generators and reduce the failure of heat-transfer tube, the polishing system for condensing water is added for the second loop.

2.6 Design of Main Plant Building

The three dimension design technology is first time applied in plant building design of domestic NPP, that ensures the design quality and improve efficiency. The four-buttress of containment vessel is changed into dual-buttress according to practical situation of plant building arrangement and accordingly design the dual-anchoring 360° pre-stressed steel strand system. In the commissioning stage, the reactor building is experienced of the containment strength test and leak test under the 1.15 times design pressure. The testing result shows integral leak proofness and whole structural performance of containment vessel has completely met the design requirements. The whole leakage rate of containment vessel in 24 h is only $0.0473\% \text{ W} \cdot \text{d}^{-1}$ much lower than the maximum allowed leakage rate in standard gauge of $0.164\% \text{ W} \cdot \text{d}^{-1}$.

Owing to big swing of tidal level in Qinshan region, the pumping lift of circulating water is too high when NPP is designed according to the dry plant site. Hence, wholly lower 7.2 m of the elevation of conven-

tional island to reduce the electrical consumption of the circulating water system. Therefore, the resistance of main steam piping from whipping and the protection of reactor building from water flooding as well as the issue of the installation of condensers etc. should be solved.

First time adopt the calculation and analysis method for foundation design of turbo-generator unit for new plant in domestic practice and verify the correctness of design and calculation through foundation's static and dynamic (including T - G no load and full load operation condition) vibration test on site.

2.7 In the Aspects of Control, Protection And Data Processing System

Apply the current latest achievement in IC and computer technology and successfully develop the reactor protection system and rod-control and position system with IC. Adopt DCS based plant computer system of nuclear power plant and adopt distributed computer control system in conventional island as well as apply digital control system for waste treatment system. These initiatives will accumulate experience for developing complete digital control system for further established NPP.

2.8 Mitigation Measures for Severe Accidents and Accidents beyond Design Basis

According to the research in protection and mitigation of severe accidents in new generation NPP, the corresponding research and improvement in Qinshan Nuclear Power Project Phase II is carried out.

(1) Set up a fifth emergency diesel generator of nuclear safety class to release the severe accident of totally loss of power supply in and out of plant. The fifth diesel generator not only can be used as additional power supply in loss of whole power supply but also replace original emergency diesel generator to improve the availability of NPP.

(2) A filter system for pressure relieve of containment is adopted to avoid failure of containment arising from overpressure in case of severe accident and maintain the integrality of containment. Meanwhile, maintain radioactivity dosage relieved to the environment within the allowed level. After comparison and analysis, a filter relieve system with wet sliding pressure is

selected. The system composed of the two levels of Venturi water bathing filter and metal fiber filter and its filter efficiency is more than 99.9 % for aero-colloidal, 99 % for iodine and 80 % for organic iodine, the efficiency is superior to sand filter.

(3) Furthermore, the analysis of accidents beyond design basis is made and corresponding mitigation measures are taken, such as total loss of feed water supply for steam generators, total loss of heat sink, complete failure of low pressure safety injection pumps of two series or total loss of containment spraying pumps in two series and refusing operation of emergency reactor shutdown system.

(4) Additional passive hydrogen recombination device will be added in the extension units of Qinshan Phase II Project to avoid hydrogen explosion and remove a large amount of hydrogen produced through zirconium-water reaction in case of severe accidents; extend the pressure relieve function of pressurizer to avoid high pressure core melting.

3 Independent Construction

The construction work are carried out on base of self-construction and self-management with the innovation in all the process of construction. Hereinto, the main aspects are stated as below:

3.1 Erection of Whole Steel Dome of Containment as One Set

The steel linear erection in containment is the key measure to shorten construction period, as a first step the erection of whole steel dome of containment is carried out in Qinshan Phase II. For this purpose, detailed analysis is made concerning the loads of dome, inner assembling components, piping and sling as well as the hoist capacity of lifting device at different height, position and angle. Besides, the dome rigidity and possible deformation, the control measures of perimeter of upper cylinder and the perimeter and diameter of dome, the measures of abutting joint with upper cylinder of containment vessel and clearance adjustment are studied out. In virtue of sufficient scientific analysis and preparation, the first domestic erection of whole containment steel dome is first in our country

completed successfully and the construction progress speeded up consequently.

3.2 Installation of Main Equipments

According to the different structural features of main equipments, specially design V type roll-over-stand device of pressure vessel, overturn stand for steam generator, lifting device for reactor internals, lifting device for pressurizer, lifting device for top coping assembly of reactor pressure vessel, automatic welding and cutting machine for “ Ω ” welding seam in control rod drive mechanism, and draw out the corresponding construction scheme and procedure and the welding technology and construction procedures for main piping, surge line of pressuriser to ensure the installation quality and progress requirements of main equipments.

3.3 Installation of Concrete Volute Pump

Concrete volute pump casing is a huge concrete structure, and not only owns the load-carrying capacity of reinforced concrete structure but also ensure to maintain the streamline form required by hydraulic characteristic of pump and the capability of sea water corrosion resistance and silt erosion resistance. Therefore, compounds of high strength concrete C60 is developed. In the meanwhile, some of the four concrete pump casing may be pour in hot summer and the others in cold winter. However, the high strength concrete C60 is easily to crack in the process of pouring. In order to ensure the construction quality, a series measures of concrete pouring and temperature conserving are worked out.

3.4 Computer Aided Cable Installation

Through the application of cable installation software, the working efficiency and progress speed are greatly improved. Meanwhile, the exact data and e-files for completion record of cable installation are prepared.

4 Localization of Equipments

In the process of equipment procurement for Qinsan Nuclear Power Project Phase II, the localization of key equipments is realized through research and development, technology introduction and co-manufacture,

as well as the capability of complete sets supply is improved. Of 55 key equipments in Qinsan Nuclear Power Project Phase II, 47 are localized. The key point of realizing localization of equipments is to master the core techniques and key technology of equipment manufacture.

2# reactor pressure vessel is self-designed and first time independently domestic manufactured. At present, the key techniques such as big size narrow gap automatic welding with thick wall, welding technique between heterogeneous metals using Inconel 690 welder at safe-end, horizontal fine-machining technique, whole component heat treatment technique, cold expanded joint technique of CRDM penetration tubes and stress / strain measurement technique before and after hydraulic pressure test etc. are mastered and capable of completely domestic design and manufacture.

One complete steam generator of 2# unit is domestically manufactured. These techniques such as pile welding of tube plate with Inconel 690, deep drilling and inspection techniques of tube plate, installation of heat-transfer tubes, hydraulic expansion and seal welding as well as the installation and fixing of anti-vibration rods etc. are mastered.

The reactor internal components in 2# reactor are domestically manufactured, which applies weld structure. The corresponding welding technique and inspection technology have been mastered. Reactor internals are precision machined products. All the manufacturing such as machining, assembling and final machining are completed in China except barrel and guiding tubes. In addition, The design technology of reactor internals has been mastered. The reactor internals in extension project will be completely localized.

By virtue of associated efforts of design institute, manufactory and owner, through electromagnetism, principle and engineering prototype research and test the control rod drive mechanism finally is completed the examination of 8.5 million steps on the comprehensive test stand of high temperature and high pressure, these results are greatly exceeded the design requirements and reached the advanced world standard. The techniques of electromagnetic coil manufacture and

encapsulation with lacquer pouring are mastered, as well as the key materials such as coil framework, high temperature resistant wires and encapsulation lacquer are realized for localization, also the key components such as connector assembly of nuclear class are successfully developed .

All the pressurizer are designed and manufactured in China. The installation and automatic welding of high power density electric heater, the installation of spray are mastered, process the fatigue damage analysis and test which arising from thermal shock to the nozzles of pressure relieve valves, safety valves and spray valve.

Engineering prototype of refueling machine is successfully manufactured through R&D, examination and testing such as grasp mechanism, transmission drive, small-size multi-disk brake device, digital continuous speed adjustment and PLC logic control, and finally has been passed examination, the performance is better than imported equipments, two refueling machines are supplied to Qinshan NPP.

Using high purity cadmium for neutron absorption the compact spent fuel storage tanks obviously improve the capacity of storage of spent nuclear fuel in fuel building of NPP. Hereinto, the key technology includes seal weld, molding and leak test etc. ,all these storage tanks are successfully manufactured in China.

The super pipeline is the important device connecting nuclear island and conventional island with the nozzles for safety valves and relieve valves. It is also connected with primary steam isolation valve under the requirements of Class II nuclear safety and earthquake resistance. Hereinto, the main key difficulties include the rolling technology for large diameter, thick wall and new material(TU48c) investigation, precise machine processing and welding technology. In addition, through domestic research and development the localization of following equipments is realized, such as containment equipment and personnel lock, fuel transfer device for spent fuel and new fuel as well as drum type rotating sieve etc. .

Through the co-design with foreign companies, the turbo-generator set for unit 1 and 2 have been

localized. The steam parameter of steam turbine set used for NPP is low and it is a saturated-steam. Hereby, the steam flow is large and the flow-through part in steam turbine shall be redesigned to increase the flow-through area; increase the measures against erosion in high pressure cylinder and dehumidify in low pressure cylinder, and pile weld of the erosion resistant layer in blades of last two stages shall be added; in addition, adoption of advanced international technology such as oil worm wheel booster pump, blades with controllable reaction degree and whole integral blade with apron string, all these made the output of steam turbine set reaching 689 MW. On the base of 600 MW imported electric generator set technologue, through improvement of cooling effect including rotor gas gap-fetch, the maximum power of electric generator set reaches 700 MW which is completely made in China. Other equipments in conventional island such as moisture separation and reheaters, condensers, high pressure and low pressure heaters, deaerators, condensate pumps, main transformers have been localized.

Moreover, the special materials for NPP which are needed to meet the requirements of nuclear safety are developed according to the requirements of equipment localization, for example, steel liner of containment vessel, all kinds of nuclear class steel used in vessel, pipeline and welding materials.

5 Independent Commissioning

According to the mode of independent commissioning in Qinshan Nuclear Power Project Phase II, the owner is responsible for the management of commissioning and according to the general considerations of “integration of commissioning and operation” until full power commercial operation, conducts the independent commissioning which accords with the international standard. The commissioning included several stages such as single system test, functional tests in cold state and hot state, first fuel loading, functional test before critical state, critical test and lower power test, power ascension, integrate functional test of NPP. The total amount of testing items is 760, hereinto, involving more than 300 systems and 200 000 equipments. In

these tests, it is successfully achieved that the hydraulic pressure test is once successfully completed, containment strength and tightness test is once successfully completed, using non-nuclear steam first time driving new turbo-generator set is once successfully completed, nuclear fuel loading and critical experiment, subsequent connection with electric network, power ascension and 168 h full power operation examination are also once successfully completed. These tests totally spend thirteen and one half months. A large amount of innovation is conducted in the process of commissioning, mainly include:

(1) Hydraulic test in main system is conducted in dynamic state through controlling the discharge deviation to control pressure elevating and dropping speed in system and stabilize the pressure in system to make the rate of pressure elevation and reduction about 0.1 MPa/min which is lower than the limited value of 0.4 MPa/min. The hydraulic test for primary system shall bear 1.33 times of design pressure, namely 22.9 MPa.

(2) Containment strength and tightness performance test. The strength testing pressure is 1.15 times of design pressure. Each group of plumb lines is arranged in one of four directions of containment cylinder to measure the radial and tangential direction shift at three different elevations and the changes of cylinder height. 76 strain gages are attached to cylinder ambience, dome, base plate and haunch zone of containment cylinder and around the equipment lock to measure the local strain. The measured result shows that the maximum tangential strain of cylinder is 380μ and longitudinal strain is 180μ which accord with the requirements of specification. The leak test is conducted through arranging 63 temperature and humidity measuring points in containment vessel through the change of temperature and pressure to calculate and define the total leakage rate in 24 h. The testing result shows that the leakage is only 0.047 % air mass of containment volume which is much lower than the acceptance criteria of 0.164 %.

(3) The main 500 kV voltage boosting from zero. The emergency diesel generator in plant is used to conduct zero-initial voltage boosting for main 500 kV elec-

tric system. By means of junction conductor of 6 kV through house load transformer and main transformer the voltage of main high voltage system will be step by step boosted to 500 kV. The equipment insulation and voltage withstand test are implemented without special device of voltage boosting from electric network. It means that the test and commissioning for electric system in plant is able to carry out in advance before the completion of 500 kV lines from electric network.

(4) Actual measurement in reactor for flow-induced vibration of reactor internals. According to the requirements of nuclear safety rules, the actual measurement on reactor for the flow-induced vibration is required for first built reactor of NPP without reference plant. In Qinshan Phase II, the barrel of reactor internals and some control rod guiding tubes which is stressed most heavily are tested on reactor. As well as through the actual measurement of inherent frequency of barrel and support columns of bottom instrument guiding tubes in air and theoretical analysis the behavior of both parts under flow-induced vibration are analyzed and evaluated. The actual measurements on reactor include dual-pump and single pump operation, start-up and idling rotation during shut down of main coolant pumps etc. total 38 tests. These tests proof that the impact of flow-induced vibration on reactor internals is very small and high cycle fatigue damage factor is very low. The conclusion is in accordance with the result of model test and theoretical analysis.

(5) The non-nuclear steam driving of turbo-generator set; Using the non-nuclear steam produced by primary coolant pumps and heaters of pressurizer the turbo-generator can be driven before reactor fuel loading, so that the commissioning of conventional island is able in advance and save the investment of startup boiler. While the 600 MW nuclear turbine set is a large aggregate, it needs to conduct analysis of possibility of this target. Hereby, the total amount of non-nuclear steam produced such way and the total amount of necessary steam to drive turbo-generator set till full speed are calculated to make sure that the non-nuclear steam driving will be once successfully completed.

(6) Develop corresponding testing method and

software to conduct the testing and measurement of main operating parameters of NPP, including critical experiment, design margin of steam generator, steam dryness testing with isotopic tracer, power and heat consumption test of turbo-generator set, for the purpose to prove that the main operating characteristics of NPP are met the requirements of design. In addition, the safety performances of NPP are tested in the process of commissioning, such as the idling rotation test of primary coolant pumps, measurement of control rod dropping time, test of natural circulation of reactor coolant system, load-rejection test on detached operation without connection with electric network, as well as whole plant power supply cut off test. The result of testing proves that the safety performance of NPP accords with the requirements of specifications and reaches the design indicators.

(7) A computer software is developed for simulation analysis for load-rejection in detached operation as well as the coordination capability of all controlling systems in nuclear island and integrated control capability of whole system are verified, the result is used as the reference for control system parameters setup to avoid the occurrence of turbo-generator trip and reactor shutdown after load rejection accident and improve the safety and reliability of NPP.

6 Independent Operation and Management

Since September, 1995 the production and operation preparation program is reviewed and adopted, it

means that the production and operation work of Qinshan Nuclear Power project phase II are started completely.

According to the project construction schedule of second level, Qinshan NPP constitutes the corresponding schedule of production and operation, establishes production organization on different level and for different period, defines their task and responsibility, defines the work relationship and interface among each production organization of different level, as well as institutes the production management system and editing plan of technical specification.

Through 8 years hard work, more than 2 000 technical specifications, 160 production management procedures, 21 training teaching materials are compiled, establishes independent programmed operation management system of nuclear power plant, completes editing and review of 13 technical documents and reports used for application of operation licence, organizes a production and operation team, young and powerful, with reasonable constitution and good technical skill, makes firm foundation for excellent operation of nuclear power plant.

After commercial operation of two units, the operation achievement is good, all the index are fulfilled or over fulfilled from design requirements, creates better economical benefit and social benefit, it shows the nuclear power is safe, reliable, clean new energy resource.

6.1 Load Factor

Since commercial operation the load factor and amount of power generation are listed in following table

Table 1 The load factor and power generation

	Unit 1		Unit 2	
	Power generation/ T W • h	Load factor /%	Power generation/ T W • h	Load factor/ %
2003	4.617	81.2		
2004	4.694	82.2	4.043	98.53
2005	5.282	92.76	4.851	85.19
2006	3.143	55.2	5.142	90.30

6.2 Radioactive Emission Control

The two units only need 48 t nuclear fuel each year and have realized “zero pollution emission”. According to the monitoring data for radiation in five years opera-

tion, the irradiation dose and emission in environment are greatly lower than the national standard. It means that Qinshan Nuclear Power Project Phase II is highly environment friendly. The details are listed as below:

Table 2 Radioactive exhaust gas waste and liquid waste discharge

Items	Waste gases			Waste liquid	
	Inert gases /Bq	Iodine /Bq	Particle /Bq	Tritium /Bq	Others /Bq
2002	4.40 E +04	2.31 E +02	1.88 E +05	1.60 E +12	1.56E +09
2003	1.31 E +06	1.20 E +07	1.92 E +06	9.46 E +12	5.14E +09
2004	2.17E +07	3.75E +07	5.29E +06	7.2E +12	2.18E +09
2005	1.18E +08	5.25E +06	2.73E +06	3.39E +11	1.83E +09
2006	1.22E +06	1.01 E +06	3.61 E +06	2.68E +13	3.09E +09
Target value of power plant management	8.5 E +13	2.55 E +9	6.80 E +9	4.00 E +13	2.55E +11
National standard(GB6249)	2.50 E +15	7.50 E +10	2.00 E +11	1.50 E +14	7.50E +11

Note: Target value of power plant management is the management objectives of 2006

Table 3 Individual and collective dose

Items	2002	2003	2004	2005	2006
Maximum of individual dose/mSv	0.26	4.242	5.443	7.21	6.318
Limitation of individual dose(National standard)/mSv	20				
Collective dose/Person·mSv	22	316.79	589.3	737.15	713.12
Collective dose (Mid-value in 2005 International standard) /Person·mSv	733				

Table 4 Amount of Medium-lower nuclear waste

Items	2003	2004	2005	2006
Solid radioactive waste/m ³	164.29	190.09	195.65	172.68
Management objectives of power plant/m ³	120	240	260	240

6.3 Criterion and appraisal of WANO

Table 5 Criterion of WANO

Name	Unit	2003	2004	2005	2006	WANO Mid-value in	
Unit capacity factor	1	79.2 %	80.17 %	90.57 %	55.24 %	86.8 %	
	2		96.23 %	82.82 %	88.78 %		
Unplanned capacity loss factor	1	2.32 %	2.682 %	0.016 %	10.11 %	1.6 %	
	2		0.87 %	1.340 %	0.00 %		
Forced loss rate	1	2.82 %	3.236 %	0.017 %	15.47 %	1.2 %	
	2		0.89 %	1.593 %	0.00 %		
Unplanned automatic scrams per 7000 h under core critical	1	0.97	0.97	0.00	1.4	0.0	
	2		1.23	0.0			
Safety system performance indicator	High pressure safety injection system	1	0.000 56	0.00 000	0.020 72	0.000 10	0.000 8
		2		0.000 00	0.010 03	0.000 00	
	Auxiliary water feed system	1	0.005 45	0.000 00	0.000 00	0.000 00	0.000 7
		2		0.017 4	0.000 01	0.000 27	
Emergency AC system		1	0.001	0.000 18	0.000 21	0.001 7	
Fuel reliability/Bq·g ⁻¹	1	2	0.037	0.037	0.037	1.96	
	2		0.037	0.037	0.037		
Chemical performance	1	1.99	1.424	1.102	1.051	1.00	
	2		2.22	1.170	1.019		
Radiation exposure/man·Sv	1	0.316 8	0.570 09	0.368 91	0.356 56	0.733	
	2		0.019 79	0.368 91	0.356 56		

6.4 Refueling & Maintenance

The organization and management of overhaul in Qinshan Phase II are completely finished by power plant since its first overhaul of first plant units, including overhaul plan establishment, item definition, file preparation, contractor's preparation and resources preparation etc. .

(1) Matrix management mode of overhaul

With reference to advanced international management experience, firstly the management innovation of NPP in the area of refueling and overhaul is conducted and the concept of matrix management is advocated to implement the management mode of "based on project management, make administrative management as assistance and support, combine them together". An overhaul manager is appointed and on its leadership the corresponding overhaul team is organized according to practical demands.

Under the unified command of general manager department of the plant, the team of overhaul project led by overhaul manager is responsible for the organization and operation of refueling and overhaul with the supplementary supports of administrative staff at each level to reasonably allocate the limited manpower and material resources and optimize the plan of overhaul. Every item of work is managed, harmonized and controlled on schedule to make sure that the safety, quality, schedule and cost are under comprehensive control.

(2) Three safety-oriented principles of overhaul management

According to the management features of two units plant in order to ensure the safety and stable operation of other unit, hereby the plant draws up three principles of overhaul management :

—All work shall be oriented to safety and decision-making shall also be conservative to ensure the safety and quality of overhaul;

—Make the plan as leader and maintain the seriousness of plan to ensure every overhaul project be executed normally and orderly;

—Ensure the safety and stable operation of plant and make the work of refueling and overhaul under comprehensive control. Under the same conditions, give

priority to operating plant unit.

(3) Establish ten year preventative maintenance database

On the demand of overall development of the power plant, according to fuel burn-up circulation planning and in-service inspection program compile the medium and long term overhaul program, as well as according to preventative repair outline, periodic test supervision outline and performance test program compile a ten-year preventative maintenance database in order to balance the workload of maintenance and repair for each unit in each year, to reasonably allocate and utilize all kinds of manpower and other resource, guide the preparation work related to spare parts etc. .

After endeavor and continuous optimization for more than five years, the items of database cover many aspects in preventative maintenance and repair, in-service inspection, regular tests and performance test which involve more than 40,000 items of different jobs and more than 10,000 different kinds of information. In the meanwhile, in the database the standard working document package is compiled to define the needed materials, documents, precondition and logical relationship for the implementation of each work. Database was integrated with warehouse management, equipment management and financial management into an organic entity through the large equipment management software of CMS to offer reference for the compilation of daily work plan and overhaul work plan and provide a platform to optimize the organization of daily work and overhaul work and to accumulate experience.

(4) Continuously optimized reference planning database for overhaul planning

The reference planning database for overhaul planning of Qinshan Second NPP mainly include ten-year overhaul reference planning, annual overhaul reference planning and all kinds of specific reference planning such as preparation of overhaul, pre-overhaul, containment penetration test, examination and repair of distribution board, maintenance and repair of turbo-generator units.

The establishment of reference planning database for overhaul planning provides a standard platform for

the compilation of overhaul planning and accumulation of experience. Not only the workload of planning compilation can be reduced and the working efficiency of planner will be improved, but also the shortcoming of planner can be avoided due to lack of experience of planners at different level. In the meanwhile, in virtue of experience accumulation of planners and continuous optimization of planning reference, these measures are beneficial to the standardization and normalization of overhaul planning management

Along with the improvement of the inspection and repair capacity of employees in plant and of contractors and the enhancement of supervision, witness and control capacity of managers, the quality of overhaul is efficiently controlled.

Until now, Unit 1 and 2 have respectively experienced four times and three times overhaul. The management level of overhaul is continuously improved, so that the period of annual overhaul is shortened from 62 days to 30 days. Through overhaul, the performance of equipments and operating environment of plant are greatly improved and all indicators of nuclear safety; radiation safety; gas, liquid and solid wastes management; as well as the quality, schedule and cost of overhaul are strictly controlled and consequently outstanding achievements have been gained.

(5) Actively conduct probabilistic risk assessment (PSA) of operating NPP

Implementation of PSA of operating NPP is in favor of finding out the weak points of operating NPP in aspect of safety and equipments to provide reference for technological improvement and ten-year renovation and to create the conditions to introduce risk informed technology to guide the maintenance strategy. For this purpose, we start to establish reliability database through collection and analysis of operating and accident data as well as conduct the investigation and analysis for initial events, and then establish the corresponding database and define the related work in previous period.

(6) Innovation of maintenance and repair

In order to reasonably control the quality and schedule of overhaul and improve the reliability, maintainability of equipments in power plant, we continuously

ly conduct the improvement and innovation mainly stated as below:

➤ Close the main reactor head lid during low water period; save more than 2 days for key path

➤ Make fully use of specific tools to save working period of overhaul, including big and small boot lifter (save 6 days for fueling); the using of SG new closure plate to make eddy current test of heat-transfer tubes possible in period of MIS inspection of reactor pressure vessel (save 5 working days); heighten the temporary reactor head lid and lengthen reactor head guide rod etc. .

➤ In-service fault diagnosis of control rod drives mechanism.

➤ Improve material protection technology in sea water for sediment entrainment erosion resistance of plant-service safety water pumps.

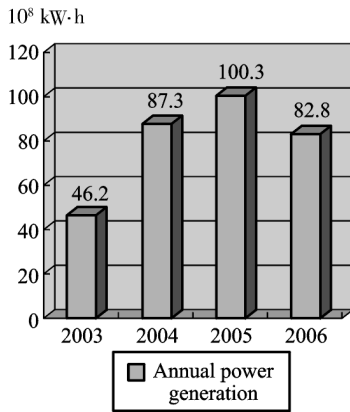
➤ Introduced no-paper recorder of nuclear safety grade in main control room

7 Economic Benefit

The unit investment of Qinshan Phase II is USD 1, 330/kW which is the lowest one in domestic built NPP and is lower than the average construction cost of NPP in developed countries with obvious economic advantages. The annual power generation of Qinshan Phase II is about 9 billion kilowatt-hours which significantly temper with the pressure of power utilization in East China with enormous economic benefits. Its annual output value is about CNY 3.6 billion with profit of CNY 0.33 billion and tax revenue of CNY 0.7 billion.

Annual power generation (unit: a hundred million kwh)

The investment return rate is high. The design lifetime of Qinshan Phase II is 40 years with total investment of CNY 14.4 billion and investment return rate of 8.5%. On the premise of load factor of 80%, it is estimated that the total yield will reach CNY 79.7 billion within 25 years of investment return period and tax paid will be CNY 18.2 billion with net profit of CNY 11 billion. During the lifetime of 40 years, it shall show wonderful economic benefits and its yield will reach CNY 130.2 billion with tax paid of CNY 32.8 billion and net



profit of CNY 24.5 billion.

8 Improvement of Extension Project

According to national development planning of NPP, the extension project of Qinshan Nuclear Power Project Phase II has been approved to commence. In line with the principle of “Duplication plus Improvement” stipulated by government, a series important technological innovation is planned for the extension project according to the new requirements of nuclear safety, application of new technology, development of nuclear power technology and feedback of operation experience. It can be foreseen that the capacity of independent development of our national nuclear power shall step up a new stage.

The planned important technological innovation in extension project mainly has the characteristics as following:

(1) Carry out the analysis of serious accidents, PSA and implementation of design improvement to enhance the plant capacity for precaution and mitigation of serious accident according to the requirements of new nuclear safety rules.

Aiming at the serious accident with occurring probability of 10^{-5} in NPP, the additional passive autocatalytic hydrogen recombiners are added to dispel large area hydrogen outburst threatening the integrity of containment vessel besides the adopted measures used for unit 1 and 2 in Qinshan Phase II. The steam explosion in and out of pressure vessel is considered and appropriate measures are adopted, it may threaten the integrity of containment vessel. In order to avoid reactor core melt

in high pressure, the extension pressure relief function of the pressurizer is taken into consideration. In the meantime, the technological improvements for over design basis accident are conducted, such as prevention of the misdilution of boron acid and denudation of reactor core.

(2) Adopt new standard to improve integrated design level according to the experience feedback from construction and operation

Along with the development of nuclear power technology and the experience accumulation of construction and operation, the standards of foreign and domestic NPP design are continuously amended and design level of NPP is correspondingly improved. The standards of RRC series adopted in the design of nuclear island in Qinshan Phase II (Extension) Project are also upgraded. In order to meet the requirements of new standards and specifications, many improvements of adaptable technology innovations are conducted in the design of extension project. At present, ten items of important technological improvement have been defined in extension project. Besides the above mentioned items, other technologies are also included such as isolation of main feed water in accident condition, improvement of fire protection system, extension of operation diagram, improvement of plant-service safety water pump house, adoption of advanced fuel components, longer fueling circle, improvement of digital instrumental control and the improvement of chemical adding control of containment spraying system. In addition, absorbing the feedback of operating experience of 1# and 2# units and define near 1,000 technological innovations to improve the performance of operation and maintenance. In the meanwhile, the experience of successful reconstruction and design in foreign NPP is also actively introduced and referred. For example, LOT93 and VD2 are the improved items raised and suggested in ten-year safety evaluation of French CPY plants. In extension engineering, the above-mentioned improved items are carefully analyzed in design stage and 172 applicable items are adopted. The accident of filter jam in containment bottom water collection pool has been taken place in international NPPs. Hence, great attention is paid to this problem in exten-

sion project and the analysis of jam possibility occurring in LOCA will be produced, and then the measure of the enlarged margin for filtering area of filters and improved arrangement of filters will be adopted, besides strict control of the materials of heat insulating layer and dope of containment vessel.

(3) Continue to enhance the progress of equipment localization and endeavor to realize the localization target of 70 %.

The share of localization equipments in extension project shall be increased through improvement of the quality performance and technical level of domestically made equipments. For example, the output of turbo-generator unit is raised to 700 MW at annual average cooling water temperature (18 °C) after turbo-generator design optimization.

(4) Actively adopt new technology and shorten construction period

The construction period of single unit in extension project will be shortened from original 72 months to 60 months. New technology will be adopted in key paths of project schedule, besides summary of construction experience of unit 1 and 2 and optimization of constructional organization.

9 Conclusion

The prospected construction objectives and technological indicators of Qinshan Nuclear Power Project Phase II have been realized. In the process of construction and operation of Qinshan Nuclear Power Project Phase II, the integrated level of national nuclear industry in design, research and development, construction, commissioning, operation and equipment localization is largely enhanced, a large number of high quality nuclear engineers are successfully trained and growing up, experiences of building larger commercial NPP are accumulated, a big leap of self-constructing commercial NPP is realized. It fully proves that the road of self-reliance and innovation is correct.

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