Completion of 1250 MW-Class Nuclear Turbine Project for Sanmen and Haiyang Nuclear Power Stations in China as World's First AP1000 Reactor

HIROMU SAGIMORI[*1] SUEMITSU NAKATSURA[*2]

KOICHIROU YAMAMOTO[*3]

Mitsubishi Heavy Industries, Ltd. (MHI) and Mitsubishi Power, Ltd. have delivered four of the nuclear turbine power generation facilities for commercial-use, the world's first AP1000 reactors at Sanmen Nuclear Power Station Units 1 and 2 and Haiyang Nuclear Power Station Units 1 and 2 in China. This project consists of equipment supply and technology transfer to a Chinese turbine manufacturer. We designed the steam turbines and heat exchangers and supplied the key equipment for the secondary turbine plant. For the steam turbine, a 54-inch integral shroud blade was adopted as the last blade and advanced technologies were adopted to improve performance, such as eliminating the control stage of the high-pressure turbine and improving the low-pressure exhaust casing. Both plants have had no issues since fuel loading and were able to start commercial operation early after a very short test operation period of 4 to 5 months, so we were highly evaluated for our technological capabilities, performance, quality and reliability from customers.

1. Introduction

China is actively promoting the construction of new nuclear power plants as a measure to respond to increasing electricity demand due to economic development and to prevent global warming. We have formed a consortium with Harbin Electric Corporation Co., Ltd. and have received an order for four nuclear turbine power generation facilities for AP1000 reactors since September 2007. In this project, while transferring the design and manufacturing technology of the nuclear turbine plants to Harbin Electric Corporation Co., Ltd., we provided equipment supply, construction and test operation support to the customer and started commercial operation of four units in 2018 to 2019. This report introduces an overview of the steam turbine and plant equipment delivered in this project, the construction schedule and the test operation results.

2. Project outline

Table 1 and **Figure 1** show the main plant specifications and locations of Sanmen Nuclear Power Station Units 1 and 2 and Haiyang Nuclear Power Station Units 1 and 2.

Table 1 Main plant specifications

Item \ Power station	Sanmen Units 1 and 2	Haiyang Units 1 and 2
Customer	Sanmen Nuclear Power Co., Ltd.	Shandong Nuclear Power Co. Ltd.
Reactor	AP1000	AP1000
Thermal output	3,415 MWth	3,415 MWth
Electrical output	1,251MWe	1,253MWe
Contract	September 2007	February 2008

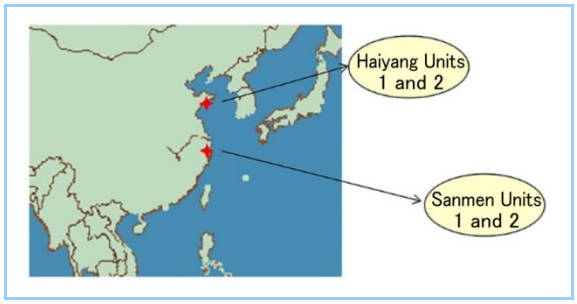

Figure 1 Locations of power stations

*1 Manager, Steam Turbine Engineering Department, Steam Turbine Technology & Production Integration Division, Mitsubishi Power. Ltd.
*2 Chief Staff Manager, Takasago Nuclear Power Plant Department, Project Management Division, Mitsubishi Power. Ltd.
*3 Senior Manager, Takasago Plant Engineering Department, Project Management Division, Mitsubishi Power. Ltd.

The Sanmen Nuclear Power Station is located in Sanmen County, Zhejiang Province, south of Shanghai. It has a site prepared for the construction of six units. On the other hand, Haiyang Nuclear Power Station is located in Haiyang City, Shandong Province, east of Qingdao, and has a site prepared for the construction of eight units. This project calls for the construction of the first two units on the premises of each of these two power stations (four units in total). We shared the manufacturing of the equipment with the Harbin Group companies, our consortium partners, and we were responsible for the design and manufacturing of the main equipment and components of steam turbines and heat exchangers for the secondary turbine plant. **Figure 2** illustrates the main structure of this project.

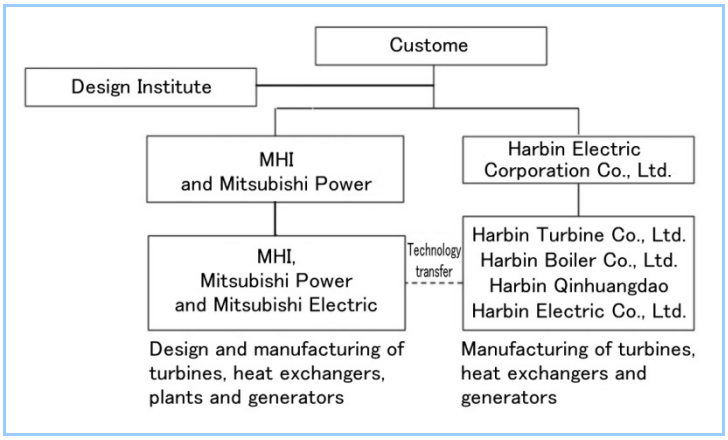

Figure 2 Project main structure

3. Steam turbine

The steam turbine consists of one high-pressure turbine and three low-pressure turbines. We were responsible for designing all of the turbine equipment and manufacturing the equipment of the rotating parts mainly. The steam turbine is based on Tomari Nuclear Power Station Unit 3, which is a domestic PWR (pressurized water reactor), but adopted advanced technologies where the number of low-pressure casings was increased to three to match the thermal output of the primary system. The performance (output) was also improved by eliminating the control stage of the high-pressure turbine and by improving the low-pressure exhaust casing. **Figure 3 to Figure 5** give a cross-sectional view and an external view of the steam turbine. Our manufacturing scope included rotating parts such as the rotors and the rotating/stationary blades, as well as the main valves.

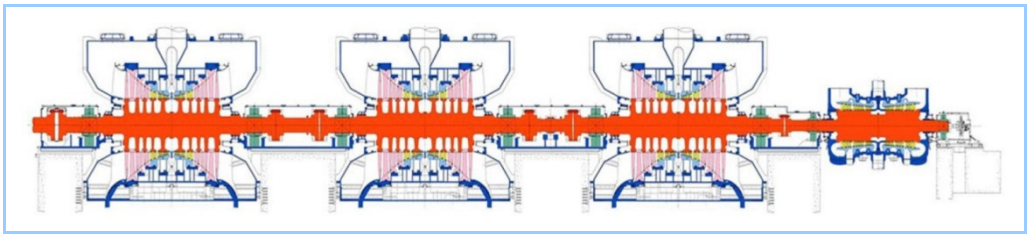

Figure 3 Cross sectional view of steam turbine

Figure 4 External view of Sanmen Unit 1 steam turbine

Figure 5 External view of Haiyang Unit 1 steam turbine and generator

3.1 High-pressure turbine

The high-pressure turbine has a double-flow design, with four main steam inlet pipes connected to the center of the casing and each flow consisting of 10 stages of all reaction blades without a control stage. As the number of feed water heater stages is increased, two stages of extraction with different pressures are taken from the blade row of the high-pressure turbine. The casing is enlarged based on Tomari Unit 3 and has a structure that supports high-pressure two-stage extraction. A monoblock rotor without a center bore is used.

3.2 Low-pressure turbine

The low-pressure turbine consists of three casings and each of them has a double-flow design. Each flow consists of 10 reaction stages including a 54-inch integral shroud blade (ISB). This 54-inch ISB is a highly efficient and highly reliable last blade developed by our company[(1)] and the reliability of its design has been proven by 9 machines in operation for more than 10 years since the first application to actual equipment in 2006[(2)]. The exhaust casing was improved through an increase in size to reduce exhaust loss and enhance performance. A monoblock rotor that does not cause stress corrosion cracking was adopted and high reliability was attained. The low pressure turbine is shown in **Figure 6**.

All bearings have a structure where they are supported directly by the foundation to increase the rotor support rigidity and improve vibration characteristics of the shaft system. The gland rings are supported by the bearing box and the internal casings are also supported directly by the foundation in order to eliminate any change in the clearance due to the vacuum load and avoid rubbing between the stationary and rotating parts.

Figure 6 Low-pressure turbine rotor

4. Plant equipment

The turbine plant consists of a 2-stage reheat and 7-stage regeneration cycle, and we handled the basic design. Based on the system and equipment configuration that has been proven in domestic PWRs, we have adopted advanced technologies such as installing a high-pressure feed water heater in two stages to improve performance and removing the spare feed water pump to reduce cost (refer to **Figure 7** for an overview of the system configuration). The turbine building is I-shaped and arranged with respect to the reactor building. It is a steel frame building (Sanmen)* with 3 floors above ground and 2 floors below ground. Although the AP1000 reactor has non-safe primary equipment inside the turbine building, a very compact building size as a turbine building of the class (about 117 m in length and about 50 m in width) was achieved.

*: For Haiyang Power Station, a concrete building structure was adopted.

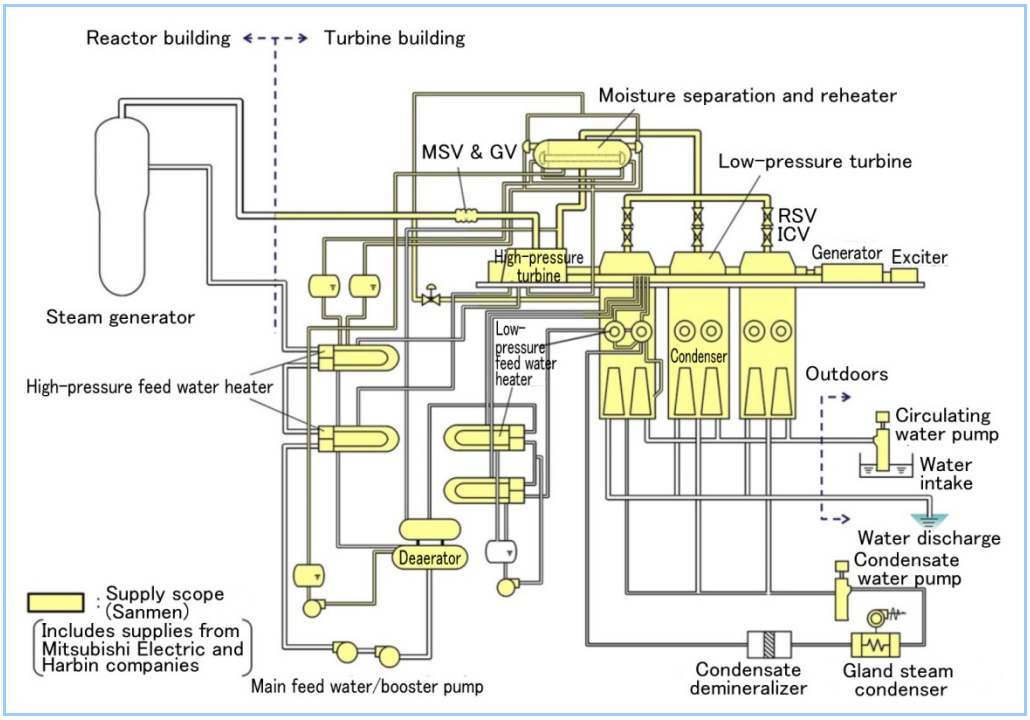

Figure 7 Turbine plant schematic system configuration

The moisture separator and reheater (MSR), condenser, feed water heater and deaerator, which have a significant influence on the performance of the turbine plant, were designed by our company and manufactured by Harbin Group companies. We also handle the basic design of the turbine bypass valve and it was supplied by Harbin Turbine Co. Ltd. The main auxiliary equipment, such as the main feed water pump, booster pump, circulating water pump and condensate pump, was supplied by our company.

The MSR is a two-stage reheating type using turbine extraction and main steam as a heating source. It adopts a high-performance chevron vane and has the ability to separate 99.5% or more of the moisture in the cycle steam. **Figure 8** is a bird's-eye view of the MSR. The condenser is a seawater-cooled 3-shell single-pressure condenser, and design parameters such as the cooling water flow rate and the cooling water temperature increase were set based on the results of the cooling water system optimization study. Titanium tubes and titanium clad tube sheets are used to improve corrosion resistance to seawater. The condenser performance was also improved by optimizing the tube bundle arrangement. The main feed water pump consists of 33.4% capacity x 3 units and the circulating water pump consists of 50% capacity x 2 units. These pumps are recognized to be highly reliable by customers and no spare pumps is installed. For the circulating water pump, a variable-vane mixed flow pump, which has been proven in Japan, was adopted for the first time in China. This design can reduce the shaft driving power of the pump by controlling the vane opening.

Since these were the world's first turbine plants for AP1000 reactors, we spent a lot of time checking and adjusting the interface conditions with the reactor side. In particular, the steam turbine and plant equipment control device, which were required by the customer to be the same as the device for the primary equipment, were combined with our turbine plant for the first time. As for the steam turbine protection device, they were multiplexed and four set with highly reliable duplicated CPU systems were installed, which were a configuration adopted for the first time for our turbine plant. Therefore, in order to verify whether our turbine control protection function was implemented, various logic verifications and combination test verifications by the control device manufacturer and control device confirmation tests at the power plant site were conducted, and it was confirmed that the control requirements were satisfied without any interface problems in the test operation phase.

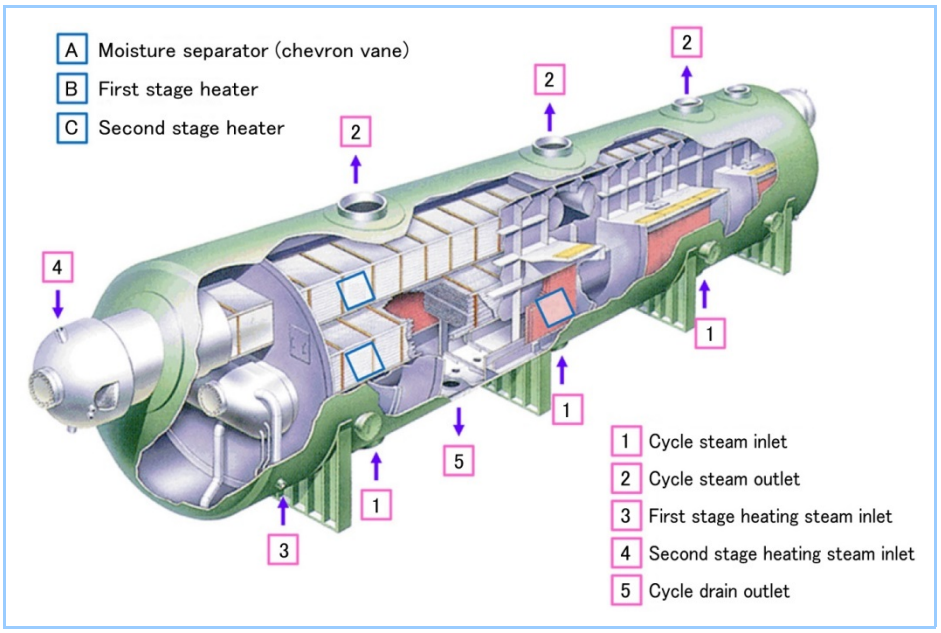

Figure 8 Bird's-eye view of MSR

5. Construction and test operation

5.1 Construction and test operation schedule

The equipment manufactured by our company was shipped from 2011 according to the contract with the customer and was installed according to the on-site schedule. During the construction, the Fukushima Daiichi Accident occurred due to the Great East Japan Earthquake and it became necessary to confirm the safety of the reactor in China. Accordingly, it took time for fuel loading and initial criticality. However, after achieving initial criticality, the test operation proceeded smoothly and commercial operation commenced. Based on the contract with the customer, we dispatched technical advisers for the construction and test operation to support the on-site work. **Figure 9** presents the construction schedule of Sanmen Units 1 and 2 and **Figure 10** is the test operation schedule.

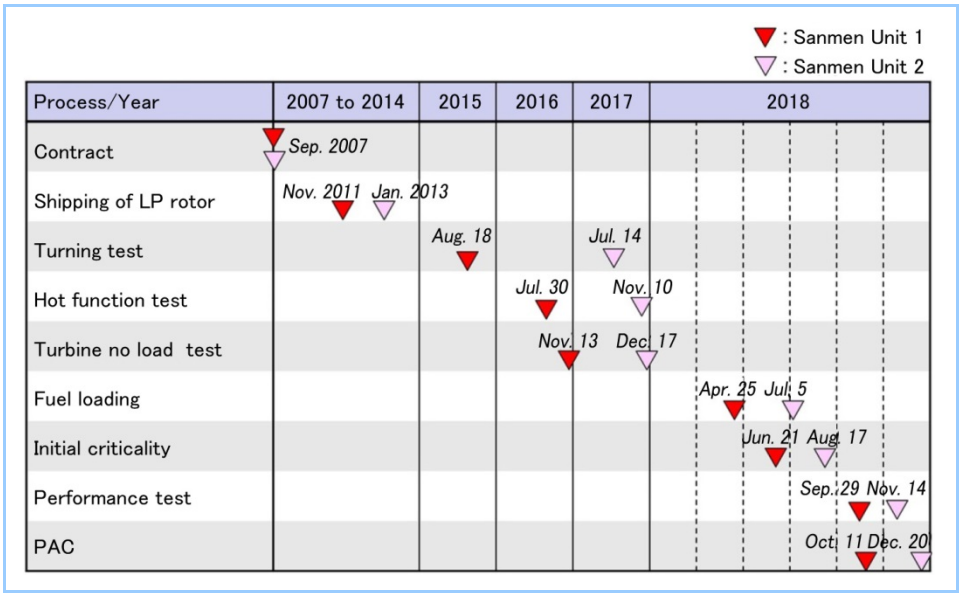

Figure 9 Project schedule (Sanmen Units 1 and 2)

The test operation period after fuel loading was as short as 4 to 5 months for Sanmen Units 1 and 2 and was completed without any problems. The test operation period after the first synchronization was only about 3 months, but the load rejection test at each load stage, the blackout test, heater cut operation, condenser single operation, overspeed trip test and load change test etc. were all carried out. We were able to complete the test operation including these tests in a

short period of time by creating the test procedure with the customer, the accurate verification of the control logic and our high-quality design technology based on many years of experience. This demonstrated the quality and reliability of our turbine plant equipment.

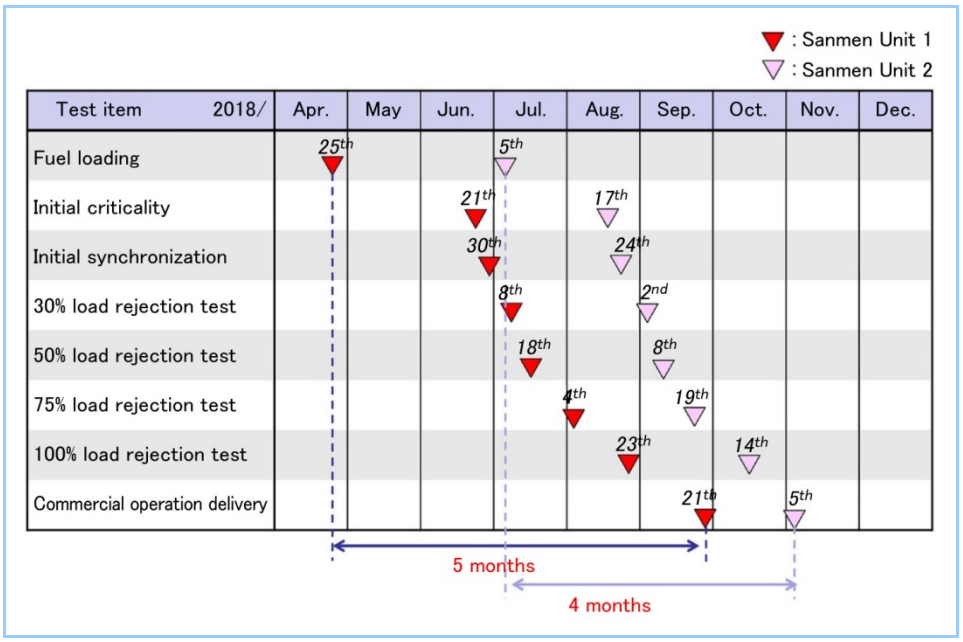

Figure 10 Test operation schedule (Sanmen Units 1 and 2)

5.2 Test operation results

The high-pressure and low-pressure steam turbine rotors were manufactured by our company and all four units have reached the rated load operation without performing rotor balancing. The maximum shaft vibration value in rated load operation was about 40 μmp-p, while the guaranteed value is 100 μmp-p, showing good shaft vibration characteristics. **Figure 11** provides the shaft vibration value of each unit.

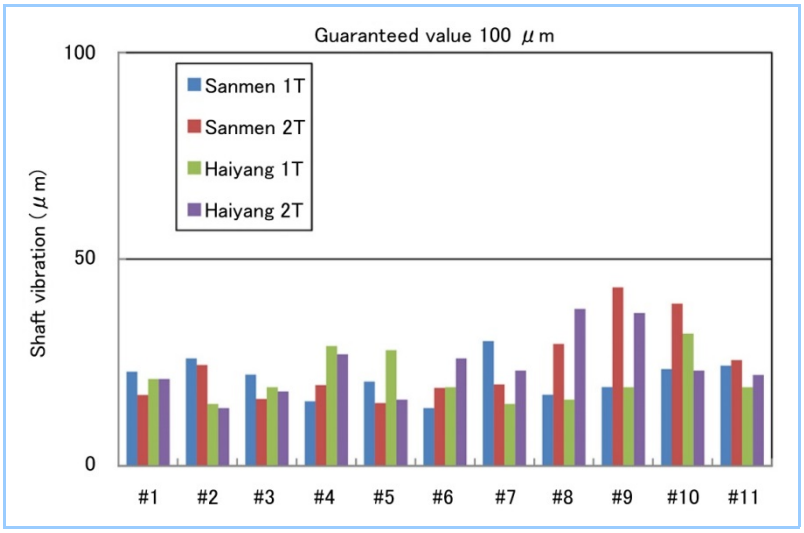

Figure 11 Shaft vibration value during rated load operation

Figure 12 gives the measurement results of the electric output (under the rated vacuum condition) in the performance test. All units achieved +0.6% to +0.9% excess of the guaranteed electrical output value (Total excess electrical output of 4 units is about 40MW). These results were achieved due to advanced technologies such as the 54-inch ISB, the elimination of the high-pressure turbine control stage and the improvement of the low-pressure exhaust casing, as well as because of our high-quality manufacturing technology.

In addition, we fully satisfied the guaranteed values for bearing vibration, auxiliary power and equipment noise. This demonstrates the capabilities of our turbine plant.

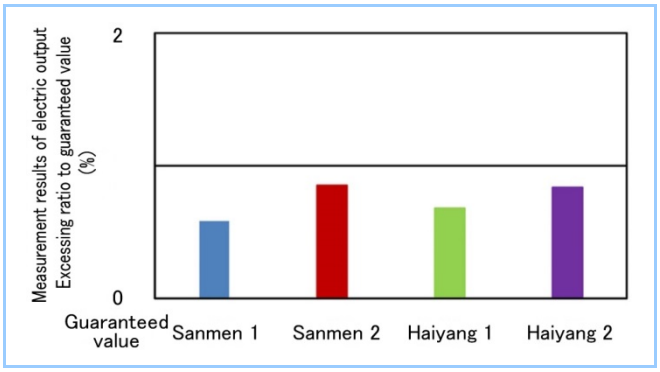

Figure 12 Performance test results (electrical output)

6. Conclusion

We delivered four of the world's first nuclear turbine plants (about 5000 MWe in total) for commercial-use AP1000 reactors at Sanmen Nuclear Power Station Units 1 and 2 and Haiyang Nuclear Power Station Units 1 and 2 in China. After fuel loading, the steam turbines we manufactured started commercial operation in 2018 to 2019 after a very short test operation period of 4 to 5 months without any problems. In addition, all four units fully satisfied the guaranteed values of performance, vibration, noise, etc. We completed the delivery while greatly satisfying our customer and earning their trust.

We will continue to contribute to Chinese, Indian and other overseas nuclear power generation markets—as well as those in Japan—using our high-quality, high-reliability and high-performance turbine plants, including the newly developed 74-inch last blade.

References

(1) Eiichiro Watanabe et al., Development of High Efficiency and Reliability Low Pressure End Blade, Mitsubishi Heavy Industries Technical Review, Vol.38 No.2 (2001), p.92～95

(2) Hiromu Sagimori et al., Completion of Turbine Replacement with 54-inch Blade Low Pressure Turbine at KRSKO Nuclear Power Plant with Very Short Outage Period, Mitsubishi Heavy Industries Technical Review, Vol.43 No.4 (2006), p.37～40