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SUPER ENGINEERING

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Technology and management innovation of the first-of-a-kind (FOAK) demonstration project — HPR1000

Developer: Fujian Fuqing Nuclear Power Co., Ltd.
General Contractors: China Nuclear Power Engineering Co., Ltd. (responsible for engineering design, equipment procurement, construction, commissioning and trial operation), Nuclear Power Institute of China (responsible for nuclear reactor and primary system design), East China Electric Power Design Institute (responsible for conventional island and conventional island balance of plant (BOP) design)
Construction Contractors: China Nuclear Industry 24 Construction Co., Ltd., China Nuclear Industry 23 Construction Co., Ltd., China Nuclear Industry Fifth Construction Co., Ltd., etc.
Supervisor: China Nuclear Engineering Consulting Co., Ltd.

1 Project overview

As a result of 60 years of independent innovation of China's nuclear industry, Hualong One nuclear reactor (hereafter referred to as HPR1000, see Fig. 1) is developed based on 30 years of experience in nuclear power research, design, manufacturing, construction and operation with the world's advanced nuclear power concept and feedback from previous nuclear accidents. With more than 100 scientific research projects completed, HPR1000 has finally become a success as a 1000 MW Gen III nuclear power technology with completely independent intellectual property rights. It has met or exceeded requirements of international Gen III nuclear power users in terms of safety, economy and performance indicators, making China jump into the ranks of advanced countries of nuclear power technology.

The No. 5 unit of Fuqing Nuclear Power Plant, the first-of-a-kind (FOAK) demonstration project of HPR1000, is located in the front of Qiwei Mountain in Qianxue Village, Sanshan Town, Fuqing City, Fujian Province. The No. 5 unit of Fuqing Nuclear Power Plant was commenced on May 7, 2015, and was put into commercial operation on January 30, 2021, creating the best performance of the Gen III FOAK nuclear power units whole world over. As for the project, more than 350 systems and 80 sub projects were involved, 113517 pieces of construction drawings were published, and more than 100000 people have participated in the construction of the project.

The brand of Hualong One involves 716 domestic patents, 65 international patents, more than 200 overseas trademarks, 125 software copyrights and more than 1500 core scientific research reports, covering the fields of design, fuel, equipment, construction, operation and maintenance. Therefore, a complete intellectual property system has been formed, meeting the requirements of full participation in international market competition. At present, a total of 11 units are under construction at

Fig. 1 Panorama of the FOAK demonstration project — HPR1000.

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home and abroad for HPR1000, and HPR1000 has been one of the most acceptable Gen III nuclear power models, which is praised as a new "national business card".

2 Technological innovation

Currently, a number of major technological innovations have been made for HPR1000, comprehensively and evenly implementing the in-depth defensive design principle and design reliability principle of nuclear safety, and innovatively proposing the safety design scheme of combination of "active + passive" with the passive safety system that can effectively deal with loss of power source as the supplement of the efficient, mature and reliable active safety system. HPR1000 has been equipped with perfect prevention and mitigation facilities for serious accidents, and its two probabilistic safety indexes of core damage and large-scale radioactive release are one order of magnitude smaller than the limit value stipulated in the latest safety regulations. Besides, its overall technical performance has reached the advanced level of the Gen III nuclear power technology in the world (Table 1).

Table 1 Main design parameters of HPR1000 power plant

Parameter name	Parameter value
Normal rated power of reactor core	3050 MW_t
Design life	60 years
Refueling period	18 months
Normal electrical power of unit	$\geqslant$1100 MW_e
Number of fuel assemblies	177
Availability of power plant	$\geqslant$90%
Ultimate safety ground motion (SL-2)	0.3g
Layout of power plant	Single reactor
Operation mode of power plant	Load tracking (mode G)
Core damage frequency (CDF)	$<1\times10^{-6}$ /(reactor·year)
Frequency of release of large amounts of radioactive materials to the environment (LRF)	$<1\times10^{-7}$ /(reactor·year)
Occupational radiation dose	$<$0.6 mSv/(reactor·year)
Non-intervention time of operator	30 minutes
Autonomy time of power plant	72 hours

2.1 Original "Chinese Core"

A total of 177 fuel assemblies (Fig. 2) with completely independent intellectual property rights have been adopted for the core of HPR1000. Compared with the French 157 Core used in the past nuclear power technology, the adoption of the 177 Core greatly reduces the average linear power density of the core while increasing the output power of the core, not only increasing the power generation capacity of nuclear power plant, but also improving the safety margin of nuclear power operation. The successful development of 177 Core is an important guarantee for HPR1000 to go global, and also can drive the development of the whole nuclear power industry chain in China, making China rank in the forefront of the world.

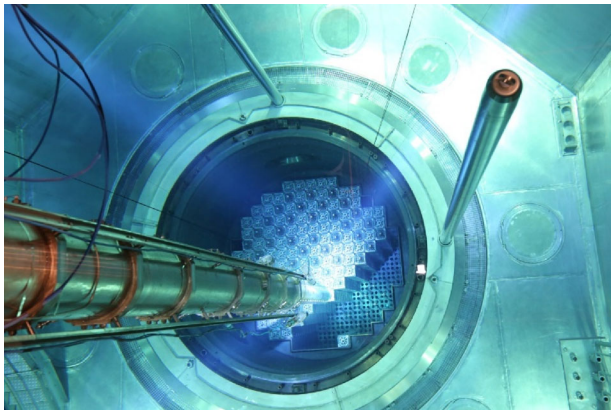

Fig. 2 Fuel loading.

2.2 Features of "active + passive" safety design

The safety design concept of combination of "active + passive" has been originally adopted for HPR1000, and passive secondary side-core residual heat removal system, passive cavity injection cooling system and passive containment heat removal system have been added, which not only retains the mature and efficient features of active system, but also makes full use of the inherent features of passive system based on natural circulation, gravity and no power supply, improving the advanced and reliable nature of security measures. All newly added passive systems have been tested and verified (Fig. 3),

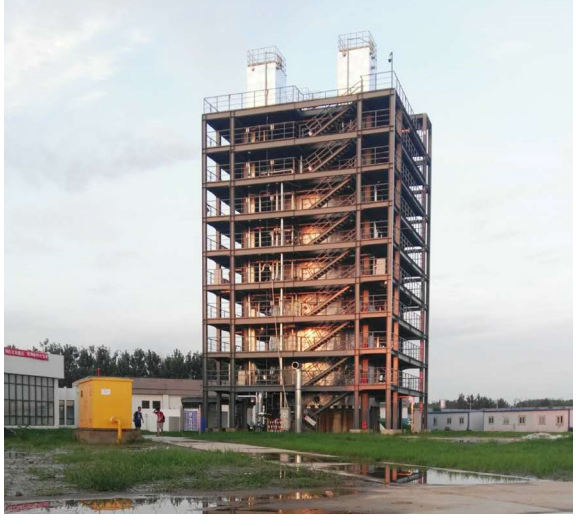

Fig. 3 Comprehensive test device of HPR1000 containment.

providing diversified security measures to ensure core cooling and the integrity of the pressure vessel and the containment, strengthening the in-depth defense and significantly improving the safety of the nuclear power plant.

2.3 Innovative nuclear island and containment design

The designed maximum ground acceleration of HPR1000 nuclear island is 0.3g, which can improve the seismic capacity in an all-round way. Single reactor design has been adopted, which can reduce interaction between units, lessen common mode failure of safety system caused by fire and flooding, and improve the flexibility of site selection. Double containment design has been adopted for reactor building (Fig. 4), providing additional barrier for the containment of radioactive materials and strengthening the resistant capability of reactor to external disasters. Besides, the external wall of key buildings of the nuclear island is specially designed to resist the impact of large aircraft, which can ensure the safety of the reactor.

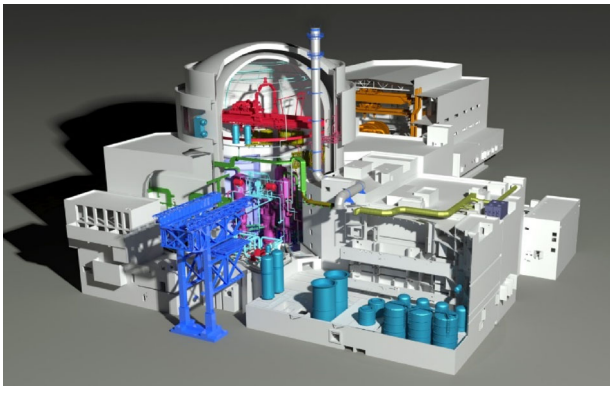

Fig. 4 Three dimensional model of nuclear island of HPR1000 power plant.

2.4 Independent Chinese Fuel 3 fuel assembly

Chinese Fuel 3 (CF3) fuel assembly technology has been successfully developed for HPR1000. The fuel cladding is made of N36 advanced zirconium alloy with independent intellectual property rights, with the excellent thermal hydraulic and mechanical performances, fully meeting the high fuel consumption requirement of 18 months or even longer refueling cycle and the seismic requirement of 0.3g, and compatible with the core structure of the domestic Gen II improved nuclear power units.

2.5 Establishment of independent nuclear power standards system

Based on the FOAK demonstration project, HPR1000 independently creates a set of pressurized water reactor nuclear power standards system which covers the full life cycle of the nuclear power plant (including general basis, preliminary work, nuclear power design, equipment manufacturing, construction, commissioning, operation, and decommissioning). In addition, a group of national standards and industry standards of nuclear power, equivalent to the international level, have been formed, which can fully meet the mass domestic construction and export requirements of HPR1000.

The international standard *Design criteria for the thermal insulation of reactor coolant system main equipments and piping of pressurized water reactor nuclear power plants* (ISO 23466:2020), officially issued on October 26, 2020, is China's first international standard of nuclear power and also the first ISO standard in the nuclear field. Its release indicates that China's independent nuclear power technology has gained further international recognition.

2.6 Promotion of digital nuclear power construction

HPR1000 has independently developed a batch of design and analysis software at its development stage, including nuclear power design and analysis software package NESTOR (covering physical design of nuclear reactor, shielding and source item design, thermal-hydraulic and safety analysis, fuel assembly related design, equipment and system related design and other key core areas), intelligence aided decision system of severe accident management guideline, core damage evaluation system, core software for mechanical calculation of nuclear pipeline (CNPIPE), special software for LBB (leak-before-break) technology, etc., generating a total of 125 software copyrights.

The FOAK demonstration project of HPR1000 actively pursues digital and intelligent reform, which has realized cross-territory digital collaborative design and virtual construction on the basis of "Internet + building information modeling (BIM)", and comprehensive coverage of management information system for whole business fields of design, procurement, construction and commissioning and whole management dimensions of progress, quality, safety and cost; and has also carried out pilot applications of new IT technologies including mobile technology, face identification technology and high-performance calculation platform, laying technical foundation for subsequent construction of intelligent nuclear engineering.

3 Management innovations

As a complex super engineering, HPR1000 faces great management challenges. With the innovative application of the project management method based on system engineering theory, the demonstration project has built an integrated management platform for the Engineering

Procurement Construction Startup (EPCS), to promote the independent innovation and development of the whole industry chain with "small core and large cooperation" as the overall coordination. With design-leaded overall situation, coordinated planning, and risk-driven management, the integration and efficient collaboration of the EPCS are realized.

3.1 Integrated industry chain resource with "small core and large cooperation"

The demonstration project establishes the globalized collaborative innovation research and development (R&D) platform for government, industry, and academia. In terms of model R&D, it has united 17 domestic universities and research institutes and 14 foreign companies and universities to sign hundreds of scientific research cooperation agreements, which effectively integrated technical resources. In terms of equipment R&D and manufacturing, it has made full use of the mature nuclear power equipment manufacturing system in China and united 58 state-owned enterprises and more than 140 private enterprises to jointly break through the localization of 411 pieces of core equipment. Over 5300 equipment suppliers, distributed all over the country, have provided more than 70000 sets of equipment for the demonstration project. The "Made in China" mode for core equipment has promoted the improvement of the overall R&D and manufacturing level of domestic high-end equipment.

3.2 Integration and efficient cooperation of EPCS

The demonstration project has applied integrated schedule, multi-level coordination, cross-organization and multi-disciplinary joint special team, and other management mechanisms to give full play to the integrated synergy advantages of the EPCS mode in the aspect of overall promotion and efficiency improvement. With the application of table-top exercise, comprehensive risk management, and TOP10 major risk management and control and by risk-driven business to achieve full participation, full area coverage, and full process prevention and control, comprehensive risk prevention capabilities have been enhanced, which ensures the smooth completion of the project (Figs. 5 and 6).

3.3 Improvement of full life cycle management

The demonstration project pays attention to enhancing the systematicness of the management flow, continues to keep pace with the advanced standard and continuously improves management level. Integrated management and R&D design system for intellectual property as well as "Internet +" integrated three-dimensional collaborative R&D design platform for nuclear energy has been established. Integrated management for the bulk material, funding chain (network) management for the digital control system (DCS), equipment prototype appraisal, equipment supplier performance evaluation and other management optimizations have been implemented. Regional management, system-oriented special management, daily work plan management and other good construction practices have been promoted. Commissioning has been organized in advance, which effectively integrates installation and commissioning resources. Monte Carlo risk quantitative analysis method and construction efficiency method are used for construction period analysis, and earned value technology is used for project performance evaluation, forecasting cost at completion, and construction and installation contract payment.

Fig. 5 Containment dome lifting of HPR1000 25 days ahead of schedule.

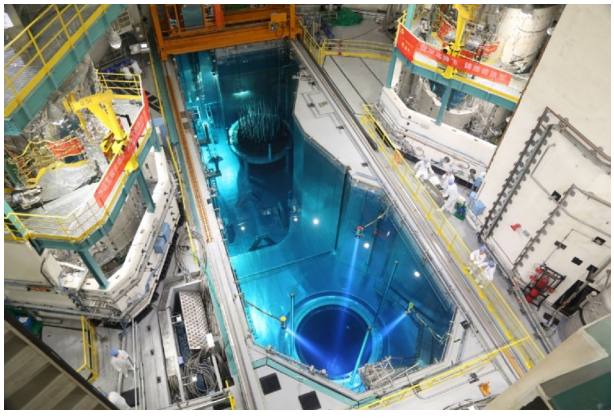

Fig. 6 Completion of the first loading.

4 Conclusions

The FOAK demonstration project of HPR1000 — Fuqing No. 5 unit was officially put into commercial operation, which indicates that China has broken the monopoly of

foreign nuclear power technology and formally entered the ranks of advanced countries in nuclear power technology. It is of great significance for China to realize the leap from a great nuclear power to a powerful nuclear power, and it has further strengthened the confidence of the countries along the Belt and Road for HPR1000. The brand of Hualong One is also significant for China to enhance the competitiveness of the nuclear power industry, optimize the energy structure, achieve the strategic goals of "carbon dioxide emission peak" and "carbon neutral", and boost the establishment of a new domestic and international dual-cycle development pattern.