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The Shandong Shidao Bay 200 MW_e High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: An Engineering and Technological Innovation

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A B S T R A C T

After the first concrete was poured on December 9, 2012 at the Shidao Bay site in Rongcheng, Shandong Province, China, the construction of the reactor building for the world's first high-temperature gas-cooled reactor pebble-bed module (HTR-PM) demonstration power plant was completed in June, 2015. Installation of the main equipment then began, and the power plant is currently progressing well toward connecting to the grid at the end of 2017. The thermal power of a single HTR-PM reactor module is 250 MW_{th}, the helium temperatures at the reactor core inlet/outlet are 250/750 °C, and a steam of 13.25 MPa/567 °C is produced at the steam generator outlet. Two HTR-PM reactor modules are connected to a steam turbine to form a 210 MW_e nuclear power plant. Due to China's industrial capability, we were able to overcome great difficulties, manufacture first-of-a-kind equipment, and realize series major technological innovations. We have achieved successful results in many aspects, including planning and implementing R&D, establishing an industrial partnership, manufacturing equipment, fuel production, licensing, site preparation, and balancing safety and economics; these obtained experiences may also be referenced by the global nuclear community.

1. Introduction

After the construction permit license was issued by the National Nuclear Safety Administration (NNSA) of China and all government approval procedures were complete, the first concrete of the high-temperature gas-cooled reactor pebble-bed module (HTR-PM) demonstration power plant was poured on December 9, 2012, in Rongcheng, Shandong Province, China. According to its 59-month schedule, the power plant should connect to the grid in 2017. The civil work of the reactor building was finished on June 30, 2015, and all milestones have been on schedule up to that date. Fig. 1 shows the construction site on December 9, 2012 and on May 25, 2015.

The HTR-PM is aimed to extend nuclear energy application beyond the grid, including cogeneration, high-temperature heat utilization, and hydrogen production. After the severe accidents

(a) (b)

Fig. 1. Construction of the high-temperature gas-cooled reactor pebble-bed module (HTR-PM) in Shandong Province, China, (a) on December 9, 2012 and (b) on May 25, 2015.

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at Three Mile Island, Chernobyl, and Fukushima Daiichi, the construction of this demonstration plant is also intended to prove that, in addition to improving the safety of light water reactors (LWRs), innovation can provide another solution for inherently safe nuclear energy technology.

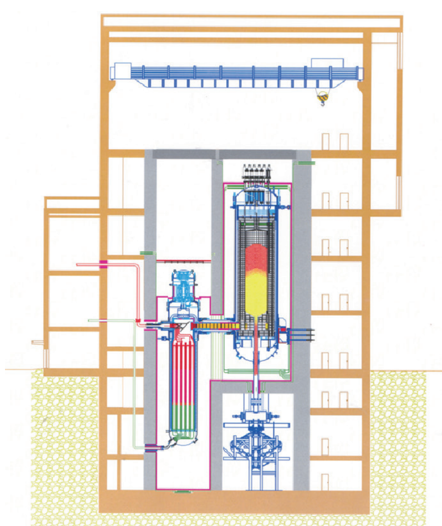
The world nuclear community has made great efforts to find solutions for the problem of nuclear energy safety. Of these, the modular high-temperature gas-cooled reactor (MHTGR) is one of the most innovative and challenging technologies. In the 1980s and 1990s, governmental support led to a great deal of R&D being performed on the 200 MW_{th} high-temperature gas-cooled reactor (HTR)-module of the Siemens/Interatom Company in Germany, and on the 350 MW_{th} MHTGR of General Atomics (GA) in the US [1]. These projects have been very successful in technical development; however, actual construction of the demonstration plants has not yet begun, for a variety of reasons. China and Japan constructed their own test reactors, HTR-10 and high-temperature test reactor (HTTR), around the year 2000. South Africa has been working on the pebble-bed modular reactor (PBMR) since the 1990s. In the *A Technology Roadmap for Generation IV Nuclear Energy Systems* published in 2002 [2], the very high temperature reactor (VHTR) was selected as one of the six candidates for Generation IV nuclear energy systems. One of the key requirements of Generation IV is to eliminate off-site emergency response during severe accidents. The outlet temperature of the VHTR was intended to be 900–1000 °C, but tends to be 700–1000 °C, causing the name to be changed to V/HTR. The US Department of Energy (DOE) conducted the Next Generation Nuclear Plant (NGNP) according to the *Energy Policy Act of 2005* and is working to establish an MHTGR demonstration plant project through a government/industry partnership. The journal *Science* reported the work on the South African PBMR and the Chinese HTR-PM in its news focus in the August 2005 issue [3].

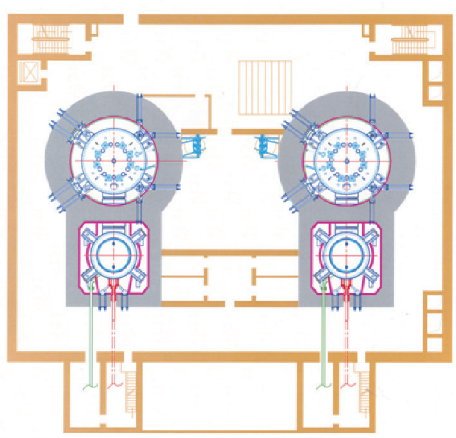
In China, the R&D program for the high-temperature gas-cooled reactor (HTGR) of the Institute of Nuclear and New Energy Technology (INET) at Tsinghua University began in the mid-1970s, and accomplished the construction of the HTR-10 test reactor in the 1990s [4]. We are now moving forward to conduct the HTR-PM demonstration project as a technical leader in the industry. In February 2008, the 200 MW_e HTR-PM demonstration plant was approved as part of the National Major Science and Technology Projects, and was named the "Large Advanced PWR and HTR Nuclear Power Plant." According to the roadmap report of the project, the prospects for HTR and HTR-PM development in China are: ① to be a highly efficient nuclear power technology, as a supplement of pressurized water reactor (PWR) technology; ② to be a major technology in nuclear process heat; and ③ to contribute globally through innovation in advanced nuclear technologies.

2. Technological innovations

As shown in Fig. 2, the HTR-PM [5] consists of two pebble-bed reactor modules coupled with a 210 MW_e steam turbine. Each reactor module includes a reactor pressure vessel (RPV); graphite, carbon, and metallic reactor internals; a steam generator; and a main helium blower. The thermal power of one reactor module is 250 MW_{th}, the helium temperatures at the reactor core inlet/outlet are 250/750 °C, and steam at 13.25 MPa/567 °C is produced at the steam generator outlet. Table 1 presents the main technical parameters of the HTR-PM.

The HTR-PM takes the HTR-10 as a prototype, and uses the German HTR-module and the US MHTGR as references. During R&D of the HTR-PM, international achievements and experiences with HTGR were carefully studied, and much of the research was performed in collaboration with German scientists in the field of pebble-bed HTGR. However, collaborations are insufficient for constructing the first HTR demonstration plant in the world, for these reasons: ① The HTR-module and MHTGR were not constructed in Germany or in the US, respectively, despite being deeply studied; ② the engineering designs and equipment manufacturing technologies were not transferred, except for some approved software and several technical consulting agreements; and ③ knowledge and experience were lost as the scientists and engineers in Germany grew older and companies were closed down. Therefore, Chinese scientists and our industrial partners must develop first-of-a-kind equipment and complete the construction of a demonstration plant by relying on our own industry and experience. Although the concept of the MHTGR is the same, the implementation of the engineering and technology is different. We describe the innovative technologies of the HTR-PM in the following subsections.





(a) (b)

Fig. 2. The HTR-PM demonstration nuclear power plant. (a) Front view; (b) top view.

Table 1
Main design parameters of the HTR-PM.

Parameter	Unit	Value
Rated electrical power	MW_e	210
Number of modules		2
Reactor module thermal power	MW_{th}	250
Active core diameter/height	m	3/11
Primary helium pressure	MPa	7
Helium temperature at reactor inlet/outlet	°C	250/750
Fuel element diameter	mm	60
Heavy metal loading per fuel element	g	7
Number of fuel elements in one reactor core		420 000
Enrichment of fresh fuel element		8.6%
Main steam pressure	MPa	13.25
Temperature of main steam/feedwater	°C	567/205

2.1. 250 MW_{th} reactor module power

Before 2006, the 458 MW_{th} reactor module was studied with an annular core, in which the spheres were placed in the annular regime. Two schemes were compared in the middle of the annular core: graphite spheres and a graphite column. Problems with the graphite sphere scheme included: difficulty convincing the licensing authority that there was a clear and certain boundary between the fuel and the graphite spheres; the outlet helium temperature becoming more non-uniform because part of the helium flowed through the central graphite spheres; the worth of control rods in the side reflectors proving to be insufficient; and so forth. In the graphite column scheme, problems also existed: The graphite column had to be replaced in the reactor lifetime; more than three discharging tubes were necessary at the bottom of the reactor, inducing a complicated fuel sphere flow; there were difficulties with the structural stability of the central graphite column; and so forth. In September 2006, the technical scheme of the reactor core was determined: It was decided to change it from 1 × 458 MW_{th} reactor module to 2 × 250 MW_{th} reactor modules. The primary concern regarding the changed reactor design was the capital cost increment. After careful calculation, the total plant capital costs of the 1 × 458 MW_{th} and 2 × 250 MW_{th} reactor schemes were found to have a finite difference, so the budget remains unchanged.

2.2. 19 helical heat transfer tube assemblies in one steam generator

Every assembly has a heat transfer capability of 13 MW_{th}, and can be tested and verified in the 10 MW_{th} helium engineering test facility (engineering test facility—helium technology (ETF-HT), engineering test facility—steam generator (ETF-SG)) under the conditions of 80% full power at full scale. The water flow rate in the heat transfer tubes can be determined based on the tests. Other advantages of the assemblies include in-service inspection, mass production and installations in parallel, and compatibility with the limited manufacturing experience of the Chinese industry.

2.3. Electric-magnetic bearings main helium blower

The main helium blower, which uses electric-magnetic bearings, is placed in the reactor primary circuit pressure boundary to ensure the helium seals and prevent lubricant leakage into the primary circuit. For the HTR-PM, the main helium blower uses electric-magnetic bearings purchased from the international market. In the engineering prototype of the main helium blower, the electric-magnetic bearings which developed by INET has been tested in order to fully verify the fit of bearings and shafts. The engineering prototype has run full-power, full-speed tests in hot states and a nitrogen environment for 100 h and 500 h, and has also completed full-power tests under helium operation conditions (250 °C/7 MPa) that are identical to those of the HTR-PM.

In view of the importance of the main helium blower, another main blower prototype with dry gas seals and oil bearings has been developed as a backup solution. The motor and oil bearings are placed outside of the pressure vessel and the blower is inside the vessel. Dry gas sealing is used to limit the leakage of the shaft penetration. A maintenance seal has also been designed so that the dry gas seal device can be replaced under sealed helium conditions.

2.4. 24 control rod drive mechanisms and 6 small absorber sphere shutdown systems

The former design of the HTR-PM reactivity control system contained 8 control rod drive mechanisms (CRDMs) and 22 small absorber sphere (SAS) shutdown systems, matching 30 graphite blocks in the circumferential side reflectors. Because of limited upper space, the 22 SAS shutdown systems shared 11 SAS drive systems. During the reactor start-up and partial power operation up to a 40% power level, SASs in the side reflector bores were driven out of the reactor core by helium, and control rods were inserted to maintain the criticality. The running main helium blower induced a pressure drop in the reactor internals and introduced difficulties and uncertainties into the operation of the SAS shutdown systems. After detailed engineering design and testing, we found that the SAS shutdown systems we developed cannot fulfill their requirements in a limited time. Therefore, we decided to change the reactivity control system to 24 CRDMs and 6 SAS shutdown systems. The reactor can be shut down, started up, and operated only through the CRDMs, and the SAS shutdown systems become a reserved shutdown system. In addition, it is now easier to drive the SASs back to the storage vessel under reactor shutdown conditions, and without running the main helium blower.

2.5. Fuel-handling system

We tested a full-scale prototype of the integrated discharge machine, in which fuel spheres were discharged one by one and broken fuel spheres could be separated. An unsolved difficulty, no qualified bearing being found, caused us to separate the discharge machine and broken sphere separator. The new engineering prototype of the fuel-handling system has been tested and proved to be successful. The final technical solution of the system meets the requirements for helium seals, the lubrication of rotating machines under helium conditions, and maintenance.

2.6. Canister-based dry spent fuel storage system

Each canister has a capacity of 40 000 spent fuel spheres and can be placed in the spent fuel storage building with concrete shields. Since data is lacking on metal corrosion near the sea, forced ventilation is used by air flow in a closed cycle. In a loss-of-power accident, the decay heat can be removed by the natural air circulation. The canister can also be placed in a standard LWR transport cask and be transported if necessary.

The experimental reactor consortium (AVR) test pebble-bed HTGR in Germany has been in operation for 21 years, from 1967 to 1988, with a total availability factor of 66% [6]. It is very successful as a test nuclear reactor. In 1990, the Association of German Engineers (VDI) and the Society for Energy Technologies published a report titled *AVR—Experimental High-Temperature Reactor: 21 Years of Successful Operation for a Future Energy Technology* [6]. After testing more than 10 types of fuel spheres in the AVR in the late 1980s, the detected radioactivity in the primary helium circuit was found to reach very low levels when using high-quality TRISO fuel spheres. Lessons have been learned from the early-stage HTGRs, such as AVR, thorium high-temperature nuclear reactor (THTR) in Germany, and SFV in the US. Additional measures were taken in the designs of the module HTGRs that were developed following these early units, including the German HTR-module and the US MHTGR. Such measures have been further referenced in the practice of the HTR-PM.

3. Progress and experience

3.1. General technical concepts

We evaluated the helium gas turbine and steam turbine technologies, and chose the steam turbine in 2002. After that, the technology roadmap was gradually formed, from the subcritical overheated steam turbine, to the supercritical steam turbine, and finally to the future helium-steam combined cycle. In 2006, we decided on two reactor modules of each 250 MW_{th} and coupled with one 210 MW_e steam turbine for the HTR-PM. The configuration of these two reactor modules will provide us with experience for multiple-module nuclear power plants in the next development.

3.2. Research and development

In January 2008, the implementation plan for the HTR-PM project was approved by the State Council of China; The R&D technology roadmap was detailed and defined within this plan. In response to newly identified phenomena and the technical requirements of the HTR-PM, we studied key technologies and designed equipment on a research basis. Once prototypes of key equipment were manufactured and related test facilities were established, we carried out full-scale engineering verification experiments in hot states and the helium environment. Verified equipment and systems include the main helium blower, steam generator, fuel-handling system, CRDMs, SAS shutdown systems, helium purification system, and spent fuel storage system. While costing a considerable amount of money, labor force, and time, these experiments exposed and solved many engineering technical problems. Fig. 3 shows the HTR-PM engineering laboratory located at INET in Tsinghua University, in which most of the test facilities are installed. Table 2 lists most of the engineering verification experiments for the HTR-PM.

3.3. Industry partnership

We realized the technical and investment risks of the first demonstration plant, and worked to gain support from the Chinese government. In 2006, the HTR-PM demonstration plant was determined to be one of the 16 National Science and Technology Major Projects. Governmental support is crucial for the survival of this project. The Chinergy Co., Ltd. was founded in 2003 as architecture engineering (AE) and EPC contractor of plant's nuclear island, and the Huaneng Shandong Shidao Bay Nuclear Power Co., Ltd. (HSNPC) was founded in 2007 as the plant owner. The Shanghai Electric Corporation and Harbin Electric Corporation were authorized to manufacture the main nuclear steam supply system (NSSS) components.

Fig. 3. The HTR-PM engineering laboratory at the Institute of Nuclear and New Energy Technology (INET) and a 10 MW_{th} helium engineering test facility.

Table 2
Test facilities of the HTR-PM project.

Test facility	Full name	Main parameter	Application	Degree of completion
ETF-HT	Engineering test facility—helium technology	10 MW_{th}, 7 MPa, 250–750 °C, helium	Heat source to verify steam generator and other systems	Facility finished
ETF-SG	Engineering test facility—steam generator	One full-scale assembly, 10 MW_{th}, 13.25 MPa, 205–570 °C, water	Secondary loop and third loop to verify steam generator	Facility and testing steam generators finished
ETF-HC	Engineering test facility—helium circulator	Full-scale, 4.5 MW_e, 7 MPa, 250 °C, helium	Verification of helium circulator	Helium tests finished
ETF-FHS	Engineering test facility—fuel-handling system	Full-scale, 7 MPa, 100–250 °C, helium, two chain	Verification of fuel-handling system	Tests in final stages
ETF-CRDM	Engineering test facility—control rods driving mechanism	Full-scale, 1 MPa, 100–250 °C, helium	Verification of control rods; driving mechanism	Tests finished
ETF-SAS	Engineering test facility—small absorber sphere system	Full-scale, 7 MPa, 100–250 °C, helium	Verification of small absorber sphere system	Tests finished
ETF-SFS	Engineering test facility—spent fuel system	Full-scale, air, 0.1 MPa	Verification of major components of spent fuel storage system	Tests finished
ETF-HPS	Engineering test facility—helium purification system	7 MPa, 25–250 °C, helium; purification flow rate: 40 $kg \cdot h^{-1}$	Verification of purification efficiency (greater than 95% and system resistance less than 200 kPa)	Tests finished
TF-PBEC	Test facility—pebble-bed equivalent conductivity	3 m in diameter, 60 mm graphite sphere, 1600 °C	Measurement of pebble-bed equivalent conductivity	Facility commissioning
TF-PBF3D	Test facility—pebble-bed flow 3D	0.1 MPa, room temperature, air, 1:5 scale	Three-dimensional simulation test for pebble-bed flow	Facility manufacturing
ETF-DCS	Engineering test facility—distributed control system	Full-scale	Verification of distributed control system architecture and major control systems	Tests finished
ETF-RPS	Engineering test facility—reactor protection system	Full-scale, 4 channels	Verification of reactor protect system	Tests finished
ETF-MCR	Engineering test facility—main control room	Full-scale	Verification of human-machine interface	Tests finished

3.4. Equipment manufacturing

In 2008, according to the chosen technical scheme, the manufacturing contracts for the RPV, steam generator, metallic reactor internals, main helium blower, and so forth, were signed. After 2008, the general design of this equipment remained unchanged, although many changes took place in the detailed engineering. The RPV and metallic reactor internals were manufactured by the Shanghai Electric Corporation. Benefiting from the development of the nuclear power manufacturing industry in China, Chinese workshops have the capability to manufacture large-size RPV and metallic reactor internals. After overcoming some initial difficulties in forging manufacturing and detailed engineering, the manufacturing of RPV and metallic reactor internals is proceeding smoothly. Fig. 4 shows the status of the RPV in September 2015. The steam generator is the most difficult piece of equipment to manufacture in many of its aspects, including its materials, rolling and bending the heat transfer tubes, assembling the heat transfer units, final assembling, welding, production schedules, special tooling and workshops, and engineering verification experiments. We developed a prototype of the main helium blower, and carefully planned and steadily promoted many engineering verification experiments. Although these experiments also cost a considerable amount of time and money, we discovered and improved many technical details to ensure the operation of the HTR-PM.

3.5. Fuels

In 2005, a prototyping fuel-production facility was constructed at INET with a capacity of 100 000 fuel elements per year, in order to solidify the fabrication craft. We then began construction on the HTGR fuel-production factory in Baotou, Northern China, in 2013, installed the fuel-production equipment in 2014, and started the commissioning and trial production in 2015. The irradiation test of five fuel spheres of the HTR-PM started in October 2012 in the high flux reactor (HFR) in Petten, the Netherlands, and finished on December 30, 2014. As one of the key technologies in the HTR-PM project, the fuel spheres have been proved to achieve their expected performance.

Fig. 4. Manufacture of the HTR-PM reactor pressure vessels by the Shanghai Electric Corporation; status as of September 2015.

3.6. Licensing

The technical documents titled *Important Criteria for HTR-PM Safety Reviews* were finished in 2006 by the China NNSA. Following that, major nuclear safety reviews at the construction permit license stage were finished in 2009. The post-Fukushima safety inspection was finished in 2011, and the list of verification experiments and the acceptance conditions were confirmed before the final safety analyses report reviews. Carried out gradually, the safety review of the HTR-PM obeys current nuclear safety regulations appropriated mainly for the PWR, and has some different requirements due to specific features, according to the approved review criteria established in 2006. These requirements follow the rules defined by the China NNSA and maintain the principle of the conservation. The Chinese Nuclear Safety Licensing uses similar standards and procedures as those of the International Atomic Energy Agency (IAEA) and the US Nuclear Regulatory Commission (NRC). Over the past 20 years, the China NNSA has been able to verify in depth the safety details of various kinds of nuclear power plants around the world. This information helps them to verify the safety features of different types of reactors, including the HTR-PM. The construction of the HTR-10 and two-stage licensing also help to advance the licensing on the HTR-PM.

3.7. Site

Between 2002 and 2004, we visited more than 10 provinces in China in order to find a potential site for the HTR-PM demonstration plant. Finally, we chose the Shidao Bay site in Rongcheng, Shandong Province, and determined the application of this project to be generating electricity for the grid. Future applications of the HTR-PM should include cogeneration and high-temperature heat applications. As a heat supply reactor, it should be close to existing heat consumers, and supply 100% backup capacity. The elimination of off-site emergency response and a reduced radius of the low population zone (LPZ) are necessary for heat consumers. It is very difficult to find an appropriate nuclear site near a heat consumer. Due to these difficulties, this first demonstration project is orientated toward electricity generation. As the first demonstration plant sharing the site with several PWRs, we do not insist on legally eliminating the off-site emergency response, but we aim to prove that it can be technically eliminated. The construction of PWRs on the same site helps to share the infrastructure capital costs, thus supporting the first demonstration plant for the HTR-PM.

4. Safety and economics

Decay heat removal is the key issue in nuclear safety. Failure in decay heat removal caused the reactor core to overheat and melt down in both the Three Mile Island and Fukushima Daiichi nuclear accidents. In the Chernobyl accident, after the initial explosion that was caused by the fission power increment, the resulting sequences were mostly related to the failure of the decay heat removal system. For an LWR, it is essential to develop a highly reliable emergency cooling system guaranteed by a reliable electricity and water supply.

Inherently safe nuclear technology can be innovatively found, based on these physical ideas: When we employ three measures—① using the more heat-resistant and substantial silicon carbide (SiC) as the fuel cladding; ② significantly lowering the volumetric power density of the reactor core; and ③ "dividing 1 into *N*," or dividing one large reactor into identical small reactor modules—then the reactor core can be designed such that the decay heat can never heat up the reactor core to the temperature limit. Based on the law of energy conservation, the decay heat in the reactor core can only be removed by heat conduction and radiation, which depend on material properties; heat convection is not necessary. After studying for more than 30 years in the international nuclear community, we have constructed the world's first commercial-scale reactor of this kind. Regarding the fuel element of the HTR-PM, it can be proved that the maximum fuel temperature limit is 1600–1800 °C for maintaining the coated fuel particle integrity. The average power density in normal operations is 3.3 $MW·m^3$, which is 1/30 of that in a PWR. The thermal power of one reactor module is chosen to be 250 MW_{th}, which provides a sufficient margin. Fig. 5 gives the reactor fuel peaking temperature during a loss-of-coolant depressurized accident, which does not depend on any engineering safety facility. The above-mentioned safety characteristics can be proved by repeatable full-plant safety demonstration tests, without affecting further operation.

The innovations for the inherent safety of the HTR-PM are easy to understand according to physical laws. However, two challenges still remain: ① How can we construct and operate the HTR-PM? and ② what are the economics of the HTR-PM? The key problem is how a small HTR-PM can compete with an LWR plant, which is 10 times bigger.

We use the idea of "combining *N* into 1." We have finished a concept design of a 660 MW_e multi-module HTR-PM nuclear power plant, which includes 6 HTR-PM reactor modules connecting to a steam turbine. Each reactor module has the same design as the HTR-PM demonstration plant, with an independent safety system and shared non-safety auxiliary systems. The footprint of a multi-module HTR-PM plant is not significantly different from that of a PWR plant generating the same power. Fig. 6 shows a 2 × 600 MW_e HTR-PM nuclear power plant for cogeneration.

To date, supply contracts have been signed for all the components of the HTR-PM project. From the actual contract costs, we can compare the detailed capital costs of a 2 × 600 MW_e multi-module HTR-PM plant with those of a real 2 × 600 MW_e PWR plant constructed at the same time in China. Using the capital costs of the HTR-PM plant as evaluated by the government in 2014, the total price of a 2 × 600 MW_e multi-module HTR-PM plant is about 110%–120% of the price of the PWR. The electricity price to the grid thus increases from 0.4 CNY·$(kW·h)^{-1}$ to 0.48 CNY·$(kW·h)^{-1}$, which is still much lower than the costs of gas, wind power, and solar power in the Chinese market. The costs of the RPV and reactor internals are very small, about 2% of the total plant costs. Therefore, assuming that the other costs of the plant are unchanged, even if the costs of the RPV and reactor internals increase to 10 times their original value, the increase of the total plant costs can be limited to within 20%. This is the reason behind the above economic evaluation results; details can be found in Ref. [7].

To realize the dream of inherent safety, the philosophy of "dividing 1 into *N*" is adopted, and to limit the cost increase, the philosophy of "combining *N* into 1" is preferred.

5. Concluding remarks

The Fukushima Daiichi nuclear accident, caused by an earthquake and a tsunami, raised the question of humanity's capability for using nuclear fission power in a safe way. Scientists around the globe have created many ingenious solutions to answer the question of safety; however, the real challenge is how to verify these solutions and ensure that they survive the very long path from conceptual stage to market. Based on experience in the nuclear engineering field, this path should include fundamental research, concept development, R&D of key technologies, the construction of a test reactor, and finally the construction of a full-scale commercial demonstration plant. This process may take two or three decades and cost billions of US dollars. Supported by the Chinese National Science and Technology Major Projects, the scientists at Tsinghua University fully cooperate with the industry and with the global nuclear community, and are now in the final stage of this process. We understand the hardships that must be experienced and the challenges that come before success. And we will continue to accomplish the HTR-PM project in order to provide a technologically and commercially innovative reactor for the nuclear power development of China and the world.

The HTR-PM is not yet a proven technology. For this reason, it is believed that the LWR will continue to be the mainstream technology of nuclear power, and that its safety will be continually improved.

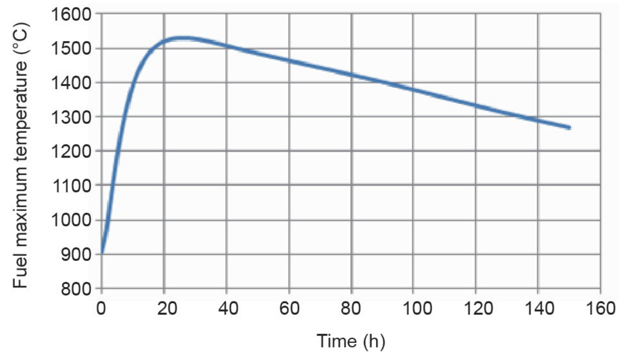


Fig. 5. The fuel peaking temperature of the HTR-PM during a loss-of-coolant depressurized accident.

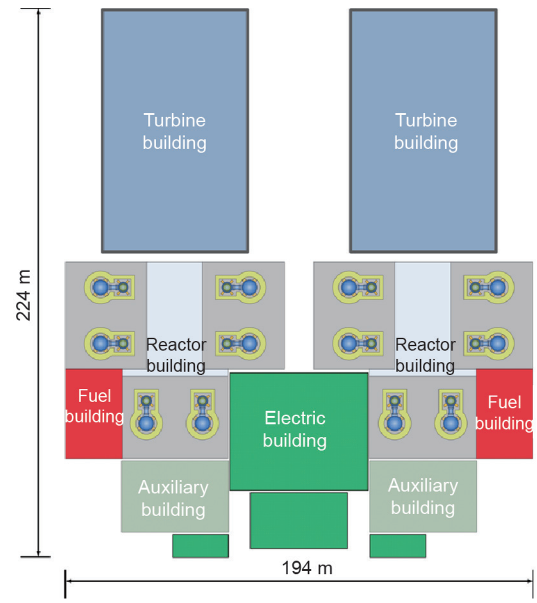


Fig. 6. The 2 × 600 MW_e HTR-PM multi-modules plant.

Acknowledgements

The HTR-PM is a team work. In China, it is the effort of two generations of scientists. Without the HTR-10 test reactor, there would be no HTR-PM later on. It has been contributed to by different government organizations, industry partners, and team

members. Around the world, many scientists from Germany, the US, Japan, South Africa, and more have also devoted their whole lives to this technology and have contributed a lot. To construct the world's first demonstration power plant of the modular high-temperature gas-cooled reactor is a common dream for many nuclear scientists. The HTR-PM in China is based on all the work that been done worldwide. The first author of this paper has been the director of INET since 2001 and later the HTR-PM chief scientist. He, as well as the other authors, tries to express the engineering and technology of this project from a special viewpoint.

Compliance with ethics guidelines

Zuoyi Zhang, Yujie Dong, Fu Li, Zhengming Zhang, Haitao Wang, Xiaojin Huang, Hong Li, Bing Liu, Xinxin Wu, Hong Wang, Xingzhong Diao, Haiquan Zhang, and Jinhua Wang declare that they have no conflict of interest or financial conflicts to disclose.

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