Strategic Study of CAE 2019 Vol. 21 No. 1
DOI 10.15302/J-SSCAE-2019.01.003

Development Strategy of High Temperature Gas Cooled Reactor in China

Zhang Zuoyi , Wu Zongxin, Wang Dazhong, Tong Jiejuan

Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, China

Abstract: High temperature gas cooled reactor (HTGR) together with its successor, the very high temperature reactor, is one of the six nuclear energy systems identified and selected by the Generation IV International Forum for further development. The paper briefly summarizes the technical characteristics of HTGR and reviews the recent research and development status of HTGR technology at home and abroad. It also discusses the strategic positioning of HTGR in China and looks ahead to the HTGR technology development road map in China. China has gone through the stages such as tracking, stepping over, and independent innovation in the past years, and now is in the front-runner status with respect to the commercial-level HTGR nuclear power plant. On this basis, China is working on the design of 600 MW pebble bed HTGR (HTR-PM600), so as to further promote industrialization of the HTGR technology and stay ahead in this field.

Keywords: high temperature gas cooled reactor; very high temperature; technology road map

1 Introduction

High temperature gas cooled reactors (HTGRs) are typically characterized by a helium coolant, graphite moderator, and fully ceramic-coated particle fuel elements. Such reactors are expected to operate in the reactor outlet temperature range of 700–1000 °C.

Recent HTGR designs have been referred to as modular HTGRs [1]. The modular HTGR concept emerged in the 1980s based on lessons learned from the Three Mile Island accident. Such designs are intended to achieve revolutionary improvements in nuclear safety by practically eliminating the possibility of core melt under any conditions. To achieve this safety enhancement, such HTGRs utilize smaller reactors as modules, where each module has power ranging from 200 to 600 MWt, and establish high-temperature resistance capabilities by utilizing coated particle fuel elements. Thus, heat in the cores can be naturally removed from the reactors, even under conditions with no emergency cooling. Overall, excellent safety is the most important feature of modular HTGRs.

High-temperature operation is another important feature of modular HTGRs. High temperatures are favorable for not only highly efficient power generation, but also combined heat and power (CHP) generation. Given that HTGR outlet temperatures range from 700 to 750 °C, steam-cycled power generation can be implemented with subcritical, supercritical, or even ultra-supercritical parameters with an expected efficiency range of 40%–48%. By diverting steam from the turbine to run in CHP generation mode, such reactors can satisfy the required temperature range of 100–400 °C for industrial and civil heating purposes.

Recent HTGR developments have moved toward the consensus that the majority of current HTGR designs, including structural materials, can remain largely intact while improving outlet temperature up to 800–1000 °C for additional applications of nuclear heat. Among potential applications, hydrogen production via thermal

---

Received date: December 18, 2018; **Revised date:** January 10, 2019

Corresponding author: Zhang Zuoyi, Professor from Institute of Nuclear and New Energy Technology, Tsinghua University. Major research field is theory, technology, application and development of advanced reactors. E-mail: zyzhang@tsinghua.edu.cn

Funding program: CAE Advisory Project “Strategic Research on Development of New-Generation Nuclear Materials” (2016-ZD-06)

Chinese version: Strategic Study of CAE 2019, 21 (1): 012–019

Cited item: Zhang Zuoyi et al. Development Strategy of High Temperature Gas Cooled Reactor in China. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2019.01.003

decomposition of water is very attractive because hydrogen plays a crucial role in numerous current systems. Hydrogen is not only an important raw material for many industrial applications, such as synthetic ammonia and methanol production, petroleum refining, metallurgy, coal liquefaction, and gasification, but also regarded as one of the best clean energy carriers for future energy solutions. HTGR is considered the best reactor technology for nuclear hydrogen production to satisfy production demands at an industrial scale.

2 Overview of HTGR technology

Gas-cooled reactors were originally developed to produce nuclear materials for military purposes. So far, the evolution of this technology can be considered to include early gas-cooled reactors (Magnox), evolutionary gas-cooled reactors (AGR), HTGRs, and modular HTGRs [2].

Currently, the family of modular HTGRs has two members, namely the pebble bed and prism reactors. Pebble bed reactors are characterized by the use of spherical fuel elements called pebbles. Pebbles are piled up to form a bed, which serves as the reactor core. Unlike the fixed core of a prism reactor, a pebble bed core “flows” at a very slow speed as pebbles continuously move from the top to the bottom during operation. When pebbles reach the exit, they are checked for burnup. Pebbles with insufficient burnup are sent back to continue the next cycle, whereas pebbles with satisfactory burnup are discharged as spent fuel, facilitating online refueling without reactor shutdown. Online refueling is of great importance for a reactor to achieve high availability. It is also beneficial for making reactor power distribution and burnup distribution more even. As little compensation reactivity is required, reactor control is simpler.

Pebble bed reactor technology was first invented by Prof. R. Schulton [2] at the Julich Center. Significant related research and development has been conducted in Germany, including the construction of the 15 MWe AVR experimental reactor and 300 MWe THTR industrial demonstration reactor. In 2000, the HTR-10 experimental reactor entered operation at Tsinghua University with support from the Chinese 863 Program [3]. HTR-10 is now the first pebble bed modular HTGR experimental reactor in the world to utilize a side-by-side configuration.

Prism reactors were mainly developed in the US and Japan. The Peach Bottom experimental reactor and Fort St. Vrain industrial demonstration reactor were constructed in the US and the high-temperature engineering test reactor (HTTR) was constructed in Japan. Prism and pebble bed reactors differ significantly in the appearance of their fuel elements. However, the essential technologies (i.e., fully ceramic-coated particle fuel, helium coolant, and graphite moderator) are the same. Since the 1980s, both types of reactors have gradually turned toward the development of modular HTGR systems.

Excellent inherent safety is the prominent characteristic of modular HTGRs. It is internationally agreed that such HTGRs can satisfy the advanced requirements of Generation IV nuclear energy systems. In 2003, the roadmap report for Generation IV nuclear energy system included very-high-temperature reactors (VHTRs) as one of six candidate technologies [4]. Seven years later, in 2010, the revised roadmap report changed VHTR to V/HTR (very-high-temperature and high-temperature reactor) to cover the temperature range of 700–1000 ℃.

Fig. 1 illustrates the structure of a spherical fuel element (pebble). A UO_2 kernel is coated with several layers of different materials (e.g., pyrolysis carbon (PyC) and silicon carbide (SiC)) to form a coated fuel particle with a diameter of approximately 0.92 mm. A spherical fuel element with a diameter of approximately 60 mm is composed of 12 000 coated particles and a graphite base material.

Fig. 2 presents a structural schematic of the nuclear steam supply system (NSSS) of the HTR-PM reactor, which is a demonstration project of HTGR nuclear power plant (NPP) in China. The cylindrical core, which is approximately 3 m in diameter and 11 m in height, consists of 420 000 fuel pebbles and is surrounded by graphite reflectors. The closed circuit of primary coolant starts at the top of the core. Cold helium is heated as it flows through the core from top to bottom. It then enters the steam generator via the inner flow path of the coaxial connection structure. After being cooled in the steam generator, the helium is then driven back to the core via the outer flow path of the coaxial connection structure by the helium circulator, which is installed on the top of the generator. In addition to the coolant cycle, new fuel elements are introduced into the core from the top of the reactor vessel. When pebbles are discharged from the bottom of the vessel, their burnup status is checked. Pebbles with insufficient burnup depth are conveyed back to the core from the top as new fuel elements.

A reactor and a steam generator form a single HTGR reactor module. In the HTR-PM reactor, each module has a rated power level of 250 MWt. Two modules in the HTR-PM reactor jointly serve a single steam generator with a capacity of 210 MWe. As stated by Routler and Lohnert, who were the inventors of the modular HTGR concept [1], the concept of a module refers to the expectation that multiple reactor modules can be connected to a single unit when necessary.

When adopting such reactors for applications requiring higher temperatures, it is necessary to replace steam generators with intermediate heat exchangers that are tolerant to even higher temperatures. The reactors would maintain most of their current design, including fuels, reflectors, metal internals, and pipe/vessel materials. Recent radiation experiment results have demonstrated the feasibility of long-term operation in the temperature range of 1250–1350 °C for current coated fuel particles. Considering the influence of temperature inhomogeneity, an expected average temperature of 1000 °C for outlet helium is reasonable.

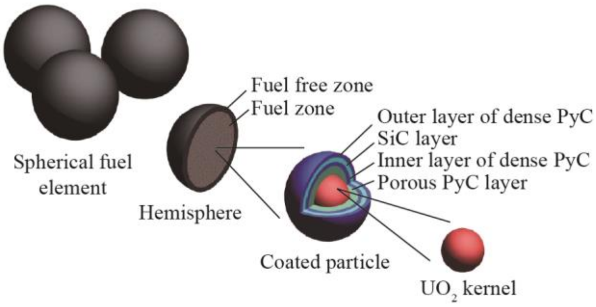


Fig. 1. Spherical fuel element for the HTR-PM reactor [5].

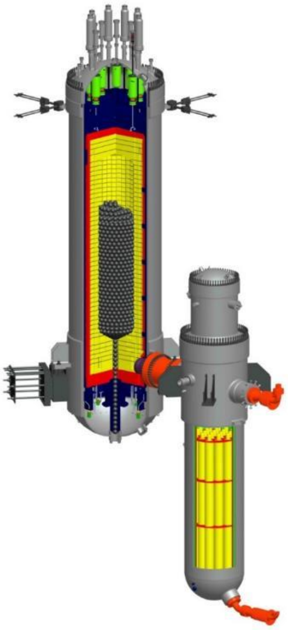


Fig. 2. NSSS module of a modular HTGR [5].

3 Recent HTGR developments

Pebble bed HTGRs were first studied and developed in Germany in the 1960s to the 1990s. During the same period, the US developed prism HTGRs. When Siemens proposed the concept of modular HTGRs in the early 1980s [1], global development moved in the direction of modular HTGRs. Most studies were undertaken in Germany, the US, Japan, Russia, South Africa, and China. Some of these studies provided sufficient design details for constructing initial demonstration projects, including the HTR-Modul and MHTGR reactors. The HTR-Modul reactor, which was designed by Siemens from 1980 to 1995, was a pebble bed HTGR rated at 200 MWt. The MHTGR reactor was developed by GA as a typical prism design rated at 350 MWt. China constructed a 10 MWt experimental reactor at Tsinghua University (HTR-10) [4] and is currently constructing its first industrial demonstration project for an NPP utilizing pebble bed modular HTGR technology in Shidao Bay, Shandong (HTR-PM). The HTR-PM project is designed to include two reactor modules, each with a rated power of 250 MWt.

3.1 Recent research and development (R&D) around the world

3.1.1 US

HTGR development in the US over the past few decades has been characterized by the Next Generation Nuclear Plant (NGNP) and X-energy projects. The US has been an active and important member of the Generation IV Nuclear Energy System Forum (GIF) since 2000.

The NGNP project was initiated by the US DOE in 2006. It was originally intended to promote the commercialization of HTGR technology in the areas of power generation, hydrogen production, and process heat application. The NGNP announced a target for constructing its first demonstration project of a modular HTGR in 2021. However, owing to cost-sharing issues between the government and industry, progress on the demonstration project has stalled since 2010. Recent efforts have mainly focused on basic scientific and research issues (i.e., tri-structural isotropic (TRISO) coated particle fuel, graphite, and high temperature-resistant materials (Inconel 617)). However, we believe that the US has the capacity to continue the construction of demonstration plants at any time.

X-energy (www.x-energy.com) was founded in 2009. In contrast to traditional technology choices in the US, X-energy is dedicated to the development of pebble bed HTGRs utilizing “intrinsically safe and proliferation-resistant TRISO fuel.” The Xe-100 reactor, which is the main development project of X-energy, is rated at 200 MWt with both pebble bed and modular characteristics. In addition to R&D funding from the government (e.g., five-year support from the US Department of Energy at $53 million in 2016), X-energy has received significant private capital investment ($38.5 million). The only TRISO fuel fabrication facility in US developed by X-energy began operation in 2018.

3.1.2 Japan [6]

Japan started construction on the small HTTR in the 1990s. The rated thermal power of the HTTR is 30 MW, the helium outlet temperature is 950 ℃, and the inlet temperature is 395 ℃. The HTTR began operation in November of 1998 and was mainly utilized for studies on high-temperature process heating, materials, fuel, and safety tests.

The Japanese government’s attitude is firm in supporting the technical development of HTGRs. They have included HTGRs as a part of their long-term R&D plan. In Japan, HTGR development programs are organized and largely funded by the Japan Science and Technology (S&T) Agency and implemented by the Japan Atomic Energy Institute in cooperation with relevant private enterprises, including Fuji Electric, Mitsubishi Heavy Industries, Hitachi, and Toshiba.

3.1.3 GIF

The US and other countries have proposed a development plan for fourth-generation nuclear energy systems and formed a cooperative international endeavor called the GIF to conduct the research and development required to establish the feasibility and performance capabilities of next-generation nuclear energy systems. The first 10 countries included the US, Japan, France, Britain, and South Korea. China officially joined the forum in 2006 and has participated in the implementation of nearly all of the candidate nuclear power systems.

Thus far, HTGR/VHTR systems have the largest number of participating countries among the six types of candidate systems. Since the United Kingdom joined the HTGR family in 2018, this type of system has had nine full member countries, namely China, the European Union, France, Japan, South Korea, Switzerland, the US, Australia, and the UK.

There is no doubt that China has become the main promoter of HTGR/VHTR technology. For example, there are several cooperative research groups operating under the HTGR/VHTR family, namely the hydrogen production (HP), fuel and fuel cycle (FFC), material (MAT), and computational methods validation and benchmarking (CMVB) groups. These cooperative research activities are very active and support the HTGR/VHTR family in a move toward the maturity of technology. These groups have also attracted significant attention from the other five system families based on the common technologies among different systems. Chinese scientists and technicians have contributed significantly to these cooperative research groups and have begun to play more important roles (i.e., chairpersons of cooperative research groups).

3.2 Recent R&D status in China

R&D related to HTGR technology in China began in the late 1970s and was mainly carried out by the Institute of Nuclear Research of Tsinghua University (INET). The history of this R&D can be divided into three main phases.

Early exploration (1974–1990): Basic R&D and feasibility studies were the main tasks conducted during this stage. The fact that the HTGR program was finally recognized as a key project under the National High Technology Research and Development Program (863 Program) is the most valuable takeaway from this stage.

Experimental reactor construction (1990–2003): In this stage, Tsinghua University began to construct the first HTGR experimental reactor in China, namely the HTR-10 reactor, which began operation in 2000.

Construction of a demonstration project for the commercial HTGR NPP (2003–2020): In addition to operational studies and safety tests carried out on the HTR-10 reactor and supported by the 863 Program, some early studies on key technologies with the goal of constructing an industrial-scale demonstration NPP were performed under the framework of the National Nuclear Energy Development Plan. Therefore, with support from the National Major S&T Projects (2006–2020), the 200 MW HTGR NPP project in Shidao Bay (HTR-PM) entered construction [7–9].

In summary, the HTR-PM is part of a project called the "Large Advanced Pressurized Water Reactor and HTGR NPP," which is the sixth overall national project. As stated in [6], the HTR-PM project has the following goals:

"Based on experience gained from a 10 MW experimental HTGR, to solve key technical problems for industrial-level applications and engineering verification, as well as to develop plant-scale manufacturing technology for high-performance fuel elements based on new R&D, a 200 MW modular HTGR NPP with independent intellectual property rights will be constructed for commercial demonstration purposes. Simultaneously, basic R&D for new technologies, such as direct cycle power generation utilizing helium gas turbines and nuclear hydrogen production, will be conducted as a foundation for the future technology of Generation IV nuclear energy systems."

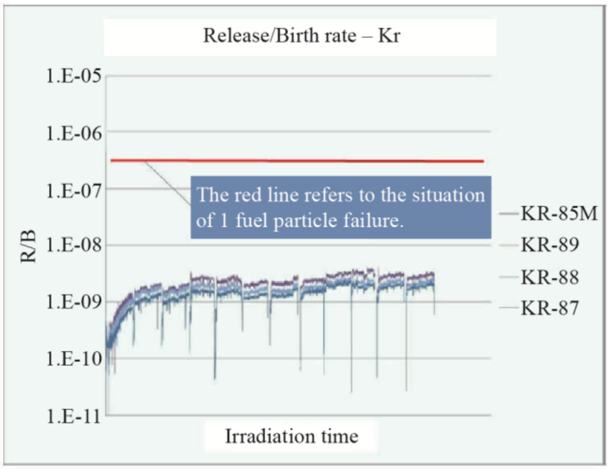
3.2.1 Construction of the HTR-PM

The HTR-PM officially began construction on December 9th of 2012 with the first concrete pouring for the nuclear island. All civil engineering works were completed in 2015. System and component installation was completed in 2018. On-site commissioning is currently underway.

3.2.2 Spherical fuel element manufacturing

INET has devoted its R&D efforts to creating high-performance spherical fuel elements for more than 30 years. To finalize the related machines and processes for mass manufacturing in a reliable manner, INET established a pilot production line at Tsinghua University with a capacity of 100 000 elements per year. Next, the set of manufacturing technology was adopted to construct a commercial factory in Baotou, China. The factory in Baotou was designed with a manufacturing capacity of 300 000 elements per year. Construction began in March of 2013 and formal production began in August of 2016. By the end of 2018, the factory had already completed well-qualified production of approximately 630 000 spherical fuel elements.

To verify the manufacturing technology and product quality of spherical fuel elements in terms of industrial standards and quality assurance requirements, five balls were randomly selected from the products mentioned above and sent to the PETTEN reactor in the Netherlands for irradiation testing. Irradiation testing began in September of 2012 and ended at the end of December of 2014. The test results revealed that all the coated particles (approximately 60 000 particles in the five spherical elements) were in perfect condition. None was damaged during the test, and the quality set a new global standard. Some test results are presented in Fig. 3 based on the use of Krypton as a marker for the release of fission products.



The red line refers to the situation of 1 fuel particle failure.

Fig. 3. Irradiation test results for HTR-PM spherical fuel elements

Following irradiation testing, the fuel elements were sent to the Institute of Transuranium Elements in Karlsruhe, Germany for a series of extreme temperature tests in 2016. The test conditions are summarized in Table 1.

Table 1. Extreme temperature tests of HTR-PM spherical fuel elements following irradiation tests.

Element No.	Temperature Tests
1	150 h, 1620 °C 450 h, 1620 °C
2	150 h, 1620 °C 150 h, 1700 °C 150 h, 1800 °C
4	150 h, 1620 °C 150 h, 1650 °C 150 h, 1700 °C

These tests verified the perfect quality of the HTR-PM fuel elements because all the coated particles were observed to be intact after experiencing extreme irradiation and heating conditions. With a 95% confidence level, these test results are at least one order of magnitude greater than the threshold currently adopted by HTR-PM safety analysis. Therefore, such fuel elements should fully support the possible development space for HTGRs.

3.2.3 HTGR key technology R&D, and engineering verification

To support R&D, and the construction of the HTR-PM project, with aid from the National S&T Major Projects, INET constructed a special engineering laboratory dedicated to the comprehensive verification of the main systems and components of the reactor, including the main helium blower, control-rod-driven mechanism, reactor shutdown mechanism based on absorption balls, fuel handling system, tube assembly of the steam generator, and digital main control room. These prototype items were developed, manufactured, and tested at the same sizes as the real components.

In 2014, the Ministry of S&T of China organized a mid-term examination for all National S&T major projects. In the examination report on the HTR-PM project, it was stated that “predictable difficulties regarding key technologies and major component manufacturing have been overcome, which can support the construction of the demonstration project, and the technical performance meets the predefined implementation plan.”

Fig. 4 summarizes the technical readiness evaluation results for the HTR-PM project as of the end of 2017. It can be observed that all key technologies are approaching the end of their development.

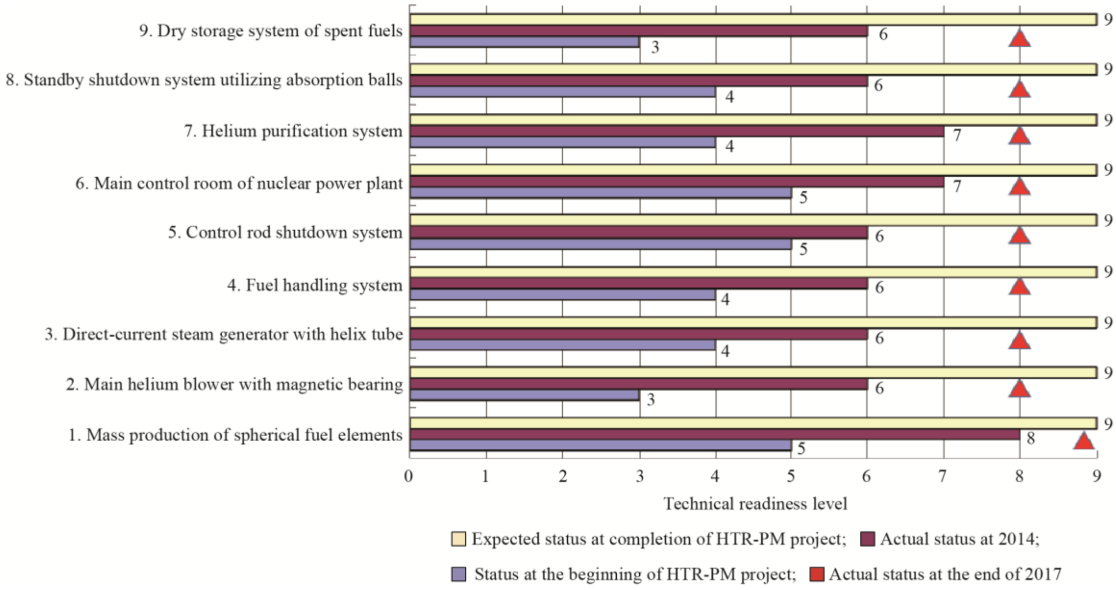


Fig. 4. Technical readiness level evaluation for the HTR-PM key technological items.

3.2.4. Major component manufacturing

The HTR-PM project consists of various components and systems, nine of which are referred to as core

DOI 10.15302/J-SSCAE-2019.01.003

components and systems. These nine items are the reactor pressure vessel, main helium blower, steam generator, metallic internals of the core, control rods, absorption ball system, fuel handling system, helium purification system, and spent fuel storage system.

As most of these important components are first-of-a-kind (FOAK) in the world, significant challenges were posed not only to the R&D teams, but also on the manufacturers. Based on years of intensive efforts from all parties, by the end of 2018, these components were largely completed. In March and September of 2016, the two reactor vessels were completed and installed. In May of 2018, the first set of fuel charging systems was installed. In October of 2018, both reactor core internals were installed. In December of 2018, the steam generators and main helium blowers completed their last inspections and were ready for shipment.

3.2.5 Collaborative innovation mechanisms

Among the various achievements of the HTR-PM project to date, the collaborative innovation mechanisms adopted during the implementation of the project are regarded as being worthy of special attention. It was concluded that these mechanisms provided numerous beneficial features, including sustainable innovation, deep multidisciplinary cross-cutting, and harmony of design, R&D, and manufacturing.

The owner of the HTR-PM project is a union of three stakeholders: China Huaneng Group, China National Nuclear Industry Corporation (formerly China Nuclear Construction Corporation), and Tsinghua University. Chinergy was specifically established to play the important role of engineering, procurement, and construction (EPC). INET of Tsinghua University acted as the chief designer for the general design, main system/component R&D, and detailed engineering design. Additionally, various suppliers, including Shanghai Electric, Haerbin Electric, and Jiangsu Yinhuan, were organized under the framework of the National Major S&T Project.

3.2.6 International market exploration

Many researchers agree that HTGRs have the capability to satisfy the demands of different countries, especially inland countries lacking conventional energy sources. This capability is based on several distinct advantages of HTGRs, including excellent inherent safety, better universality of site conditions, high efficiency of electricity production, small power levels per reactor, easy expansion into large NPPs utilizing standard modules, capability for nuclear hydrogen production and high-temperature process heat applications, and good non-proliferation features because spent fuel is suitable for direct disposal. Based on its leading progress in the construction of HTGRs, China has gained widespread international recognition.

In November of 2017, Ms. Liu Yandong, the Vice Premier of China, officially announced the unveiling of the Sino-Indonesian Joint Laboratory for HTGR technology. This joint lab is operated as a special project under the Intergovernmental Cooperative for S&T Innovation.

In March of 2017, as witnessed by President Xi Jinping and King Salman of the Kingdom of Saudi Arabia, a cooperation agreement for joint research on HGTR project feasibility in Saudi Arabia was signed. Under this agreement, China and Saudi Arabia would work together to develop a systematic solution for HTGR projects in Saudi Arabia, including investment and construction, intellectual property cooperation, and the localization of industrial supply chains. This research was intended to provide decision making support not only for the government of Saudi Arabia, but also for the implementation of the Belt and Road initiative. By the time of writing of this paper, the joint feasibility study on HTGRs in Saudi Arabia had already begun.

In 2018, an HTGR program in Jordan completed several rounds of negotiation and a site survey. A cooperation framework agreement was signed by the China National Nuclear Corporation and Jordan Atomic Energy Commission on June 29th of 2018. This agreement marked the beginning of a joint feasibility study on the construction of an HGTR at a selected site in Jordan. This study is expected to be completed by the end of 2020.

Additionally, the DBD company and INET became shortlisted candidates for the Advanced Modular Reactor Program Phase I in the UK. This program was organized by the Department of Commerce of the UK. Many believe that the UK officially joining the Generation IV Forum in 2018 was an important signal for the development of HTGR technology in the UK.

4 Follow-up development and deployment of HTGRs in China

HTGR technology in China experienced a series of developmental phases, including tracking, overtaking, and independent innovation. China recently took the leading position in the field of commercial-scale NPPs based on modular HTGR technology. China has started R&D for a 600 MW modular HTGR NPP to promote the industrialization of HTGR technology and maintain a leading edge in this field.

The overall technical objectives of the 600 MW modular HTGR are defined as follows. The HTGR should satisfy the international requirements for Generation IV nuclear energy systems in terms of safety with the ability for cogeneration considering domestic and international markets. It should also have economic competitiveness and adapt the technologies proven by demonstration projects to a larger scale.

A preliminary design for the 600 MW modular HTGR called HTR-PM600 was recently released. In this system, six NSSS modules are utilized to serve a single steam turbine generator at a rated power of 650 MWe. These NSSS modules are identical to the two modules currently utilized in the HTR-PM project. A steam extraction interface is provided on the turbine generator side. This interface is capable of steam extraction at different temperatures and pressures, allowing it to satisfy the conditions of process heat applications.

According to the R&D schedule, a standard design solution for HTR-PM600 should be released before 2020 based on the successful construction and operation of the HTR-PM reactor. It is anticipated that the first HTR-PM600 NPP project will be ready for construction at the end of the 13th Five Year Plan of China, which will conclude in 2025. These activities will help to set the stage for 600 MW HTGRs with standardized technology and improve the competitiveness of HTGRs around the world.

5 Market forecast analysis of HTGRs in China

5.1 Efficient electricity generation

An NPP adopting HTR-PM600 technology maintains excellent safety features for avoiding core melt accidents. Under the most stringent safety requirements now and in the future, HTGR NPPs could satisfy radioactive dose limits at the boundaries of sites under accident conditions and could provide the technological possibility to eliminate offsite emergency planning. Therefore, based on the increasingly stringent requirements for environmental protection, HTGR NPPs are promising candidates for replacing old fire plants for electricity generation because they are insensitive to site conditions and can make full use of existing turbine generators, cooling towers, and significant infrastructure.

5.2 Cogeneration

China’s large- and medium-size cities rely heavily on coal-fired plants to generate electricity and provide heating during the winter. A few cities have adopted natural gas cogeneration. If four to six HTR-PM600 NPPs could be deployed at a site approximately 30 to 50 km from a city, a regional cogeneration center could be established. It could not only cover approximately 100 million square meters of direct heating area based on steam extraction, but also provide electrical heating for another 100 million square meters. In seasons without heating requirements, all energy could be utilized to generate electricity. Preliminary studies have shown that such a system would provide greater economic competitiveness and environmental benefits compared with natural gas cogeneration.

5.3 Nuclear hydrogen production

HTGRs may be the best solution for large-scale hydrogen production. Experts and scientists believe that the maturity of nuclear hydrogen production technology will bring about significant innovations in the energy sector. Considering iron and steel making as example processes, one HTR-PM600 reactor unit could satisfy the hydrogen demands for producing approximately 1.8 million tonnes of steel per year.

Additionally, because the proportion of transportation energy in China’s primary energy consumption already exceeds 20%, the hydrogen energy demand for transportation is significant, which creates additional space for HTGR development and deployment.

6 Roadmap suggestions for HTGR development in China

China began its R&D for HTGRs from the inception of such systems and has mastered all the key technologies gradually and systematically based on tremendous efforts. Although China is currently leading the field, development must continue. To promote the development of HTGR technology and maintain a leading position in the world, we propose the following roadmap for future development.

In terms of projects, resources should be focused on completing the HTR-PM project and attempting to operate it successfully before 2020. In the meantime, the 2 × 600 MW HTGR NPP demo project should enter the standard design phase and strive for readiness for construction by 2020. International market negotiations should be actively encouraged because an increasing number of countries are arriving at the consensus that HTGRs are promising.

DOI 10.15302/J-SSCAE-2019.01.003

In terms of R&D, we strongly suggest summarizing lessons learned from the HTR-PM design and construction to support design optimization and standardization. Some R&D works should also be scheduled and deployed in advance, such as graphite manufacturing localization and intermediate heat exchanger development. It is also important to begin R&D for very-high-temperature conditions (i.e., 950 ℃), as well as trial operation at very high temperatures for experimental reactors.

In terms of nuclear hydrogen production, research on key technologies has made significant progress based on support from the National Major S&T Projects Program. Prototype research on key components is currently underway. It is anticipated that nuclear hydrogen production could approach the stage of pilot production and validation during the 14th Five Year Plan of China. Subsequent objectives would include a demonstration project for the nuclear-hydrogen-metallurgy process that will be initiated during the 15th Five Year Plan. It is expected that before 2030, China will realize a helium turbine generation cycle for HTGRs and the engineering application of nuclear hydrogen production utilizing HTGRs.

7 Conclusions

A 200 MWe demonstration HTGR NPP project (HTR-PM) is currently under construction and has entered the phase of engineering commissioning in Shidao Bay, Rongcheng City, Shandong Province. As the first NPP with modular HTGRs installed, it is currently the closest project to commercialization among Generation IV technologies and has attracted significant global attention.

In addition to contributions from the perspective of promoting HTGR technology itself, we wish to acknowledge the precious lessons and experiences we have gained over the past years, including the HTR-PM entering the R&D planning and implementation phases, establishing partnerships in industry, working with regulators for safety reviews, and balancing safety and economy. We believe these lessons and experiences will be valuable for our international peers, particularly our experiences regarding FOAK manufacturing. The success of the HTR-PM project is not only a success for the nuclear industry, but also an important step toward significant technology upgrades in related industries.

Based on primary energy shortages, HTGRs have been studied in China to supplement the electricity production market, where pressurized water reactor NPPs are sure to play a dominant role. HTGRs are likely to become a mainstay in the nuclear heating market. A new HTGR design called HTR-PM600 will make full use of the technologies that have been proven by the HTR-PM demonstration project. Assuming that major systems/components will be retained as they are, additional modules can be installed to satisfy the market demands for larger capacity. We believe that this expansion, once realized, will have a significant impact on the industrialization of new nuclear technology.

References

[1] Reutler H, Lohnert H. Advantages of going modular in HTRs [J]. Nuclear Engineering and Design, 1984, 78(2):129–136.

[2] Kugeler K, Zhang Z Y. Modular high-temperature gas-cooled reactor power plant [M]. Beijing: Springer and Tsinghua University Press, 2019.

[3] Wu Z X, Lin D C, Zhong D X. The design features of the HTR-10 [J]. Nuclear Engineering and Design, 2002; 218(1–3): 25–32.

[4] US DOE Nuclear Energy Research Advisory Committee, Generation IV International Forum. A technology roadmap for generation IV nuclear energy systems [R]. USA: US DOE Nuclear Energy Research Advisory Committee, Generation IV International Forum, 2002.

[5] Zhang Z Y, Yuan K. Technology and industrialization development of high temperature gas cooled reactor in China [J]. Modern Physics, 2018, 30(4) 4–10. Chinese.

[6] Project Team of Chinese Academy of Engineering on “Rethinking the Development of Nuclear Energy in China”. Rethinking the development of nuclear energy in China [J]. Beijing: Tsinghua University Press, 2015. Chinese.

[7] Zhang Z Y, Sun Y L. Economic potential of modular reactor nuclear power plants based on the Chinese HTR-PM project [J]. Nuclear Engineering and Design, 2007, 237(23): 2265–2274.

[8] Zhang Z, Wu Z, Wang D. Current status and technical description of Chinese 2 × 250 MWth HTR-PM demonstration plant [J]. Nuclear Engineering and Design, 2009, 239(7): 1212–1219.

[9] Zhang Z Y, Dong Y J, Li F, et al. The Shandong Shidao Bay 200 MWe high-temperature gas-cooled reactor pebble-bed module (HTR-PM) demonstration power plant: An engineering and technological innovation [J]. Engineering, 2016, 2(1): 112–118.