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Design aspects of the Chinese modular high-temperature gas-cooled reactor HTR-PM

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Abstract

The modular high-temperature gas-cooled reactor (MHTGR) has distinct advantages in terms of inherent safety, economics potential, high efficiency, potential usage for hydrogen production, etc. The Chinese design of the MHTGR, named as high-temperature gas-cooled reactor-pebble bed module (HTR-PM), based on the technology and experience of the HTR-10, is currently in the conceptual phase. The HTR-PM demonstration plant is planned to be finished by 2012. The main philosophy of the HTR-PM project can be pinned down as: (1) safety, (2) standardization, (3) economy, and (4) proven technology. The work in the categories of marketing, organization, project and technology is done in predefined order. The biggest challenge for the HTR-PM is to ensure its economical viability while maintaining its inherent safety. A design of a 450 MWth annular pebble bed core connected with steam turbine is aimed for and presented in this paper.

1. Current HTR status in China

Starting from the gas-cooled reactors in the 1950s and the advanced gas-cooled reactor in the 1960s and the high-temperature reactor “Dragon” in 1964, the high-temperature gas-cooled reactors (HTGR) have been developed for nearly 50 years. The concept of the modular high-temperature gas-cooled reactor (MHTGR, such as HTR-MODUL designed in Germany and MHTGR designed in US), which is only employing by inherent characteristics to ensure safety, was proposed more than 20 years ago.

Hence, the MHTGR is not only excellent in its safety performance, but it is also very market flexible. Therefore, the MHTGR is very attractive and competitive in the world, many research and engineering projects are planned and are ongoing, for example, the South African PBMR project, the US–Russia GT-MHR project, the US NGNP (Next Generation Nuclear Power) in Idaho, the HTTR in Japan, the French HTGR program, and the Chinese high-temperature gas-cooled reactor-pebble bed module (HTR-PM) demonstration project.

Especially for China it is urgent to develop and construct new nuclear power plants. The economy grows enormously, thus the energy demand increases continuously. Hence, the shortage of electricity, oil and coal becomes more and more serious, the environment pressure (green house gas and air pollution) increases tremendously. Thus, nuclear power becomes inevitable for China (Wang and Lu, 2002).

The condition of high-temperature gas-cooled reactor in China is inspiring. Supported by the Chinese national high-technology program, the 10 MW high-temperature gas-cooled test reactor (HTR-10) (Wu et al., 2002), whose design began in 1992 and construction commenced in 1995, reached its criticality in December 2000, and its full power operation in January 2003. During the operation of the HTR-10, five safety verification experiments were carried out on the HTR-10 in October of 2003, which verified and demonstrated many inherent safety features of the MHTGR. Therefore, the HTR-10 is an ideal test bed for future HTR design.

Based on the success of the HTR-10, a HTR-10GT project, which will connect a small helium gas turbine to the HTR-10 to develop and test gas turbine technology, began its study in 2002, and is planed to be finished in 2007. The project is supported by the second phase of the National High Technology Program. The gas turbine technology may be adopted by the HTR-PM in the future, when gas turbine technology becomes mature, and when the nuclear island of the HTR-PM is standard and mature also. Aimed at future usage of an HTR, research and development of hydrogen production using high temperature from an HTR

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is under research. Parallel to the development of reactor design, work to improve the fuel element manufacture technology and to expand its production capacity is also carried out.

Based on the technologies and experience obtained from the HTR-10, a larger, commercial MHTGR nuclear power plant, namely the HTR-PM (Zhang and Yu, 2002; Xu, 2002), aimed to complete a demonstration plant in 2012, entered its conceptual design phase in the year 2002, planned to finish the design in 2006. This HTR-PM project will be done in a market way, the government will only support its technology development. For us the HTR-PM project is practical and feasible, and its design philosophy and technical detail will be presented in this paper.

2. The overall philosophy of the HTR-PM project

2.1. The overall HTR-PM project

The HTR-PM power plants are intended to be a series of commercial plants, starting from a demonstration plant. Therefore, all the project activities including investment, design, construction and operation will follow market rules, i.e. the HTR-PM must be competitive. These points are especially important under the market economy system of today's China.

The investment for the HTR-PM project will come from the market, i.e. from the future utility company. Of course, for the development of some new technology in the stage of demonstration plant, the financial support from government is necessary and appreciated, and the Chinese central government agrees to support the technology development activities.

Work on the HTR-PM project can be divided into four categories, namely: the technical design, marketing, project, and organization. Concerning the technical design, the main work is to find and optimize an HTR-PM standard design which is based on the enveloping or reference site conditions.

The marketing concerns the market requirement and the market chance. Now China is eagerly searching for new energy sources for its rapid economy growth; nuclear energy has a big chance to develop. At present a viable and safe electricity supply is the main object for nuclear energy, in the future, hydrogen production, sea-water desalination, etc. may become important. Although mature PWRs are the work horses for the new Chinese nuclear power plants—this is the result of the Chinese national policy and the world trend—but the MHTGR is also very attractive due to its safety, its higher electricity generation efficiency and its possibility for direct hydrogen production. Therefore, the HTR-PM can meet the market requirement in short term and in long term.

In respect to the project, a roadmap for the demonstration plant is set up, a long-term roadmap of the HTR-PM is in the preliminary stage. For the demonstration plant, two parallel lines of the projects are outlined. One is the reactor itself, including the site selection, standard design, experimental verification, safety review, demonstration plant, and future batch construction of HTR-PMs. Another line of project is for the nuclear fuel plant. The long-term development project concerns the development of new technologies, including helium turbine (a prototype will be tested in the HTR-10GT), hydrogen production technology (technology developing in laboratory), gas-cooled fast reactor technology, very high-temperature gas-cooled reactor technology, etc.

In the organization category, a development team which includes all aspects of Chinese nuclear industry is set up to push forward the HTR-PM project, including research, design, construction, manufacturing and operation. The kernel of this team is the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University, which has the experience and the experts to design, to construct and operate the HTR-10. It is responsible for research, design and technology development of the nuclear island of the HTR-PM. The second level of this team is a future architecture and engineering (AE) company for the HTR-PM which is responsible for the engineering design, main components supply and all issues concerning the construction. Another part of the team is the future utility company. This company will be a joint venture company among a Chinese electricity company, namely China Huaneng Group, and a nuclear industry company, namely the Chinese Nuclear Engineering and Construction Corporation (CNECC), Tsinghua University and other local investors located near the final site of the HTR-PM power plant. Maybe the shares of the stock will be expanded further to combine more positive strength for the HTR-PM. This utility company will be responsible for all issues of marketing, financial, site selection, etc.

2.2. Demonstration plant

For the time being, all work is aimed to finish the demonstration plant in 2010. For the demonstration plant, three parallel lines of the project are being followed. One is the standard design of the HTR-PM, one is the site selection of the demonstration plant, and the third one is the fuel plant for the HTR-PM.

The standard design of the HTR-PM envelops all possible site conditions in China. This idea of standard design is like the standard design of the ABWR by GE or the KONVOI by Siemens. The purpose of standard design is to accelerate the design process and to improve the design quality. According to Chinese rules the design of a nuclear power plant must follow the stages of: (1) preliminary feasibility study for the choosing the site, outlining the conceptual scheme, analyzing the economic feature, forming the utility company, outlining the financial source, (2) Completion of the feasibility study which includes the site seismic and geology report, the site selection safety analysis report, the environment impact analysis report and the project feasibility study report itself, (3) preliminary design aimed at getting the construction license, (4) final construction design. This procedure is suitable for construction of mature plants which rely on demonstration plants or reference plants. For the HTR-PM this will take too much time, since a preliminary design of a commercial HTR-PM demonstration plant—from the starting point of the HTR-10—need much time and resources, especially if the engineering design can be finished only after completion of the site selection and the feasibility study. Therefore, a standard design which uses enveloping site conditions and reaches the depth of preliminary design will make the final design of the HTR-PM very detailed even at an early stage.

From another viewpoint, the HTR-PM requires the standardization of the design in nature because a power plant may contain tens of reactor modules, each module being standardized by its very nature. Based on the standard design, only the design of some BOP system will be modified according to specified site parameters. Therefore, the standard design will speed up the process of the design, the safety review, the construction and the commissioning of the power plant.

The standard design of the HTR-PM, started in the beginning of 2004, is planned to be finished in the mid of 2006. In the meantime, the selection of a site for the HTR-PM demonstration plant is done in parallel. Sites located in Shandong province and Anhui province are the candidates. A combination of actual site parameters and of the HTR-PM standard design will add up the preliminary design of the HTR-PM demonstration plant. The construction of the HTR-PM demonstration plant is planned to begin in 2008 and to be finished in 2012.

The work for the fuel plant is aimed to expand the capacity of the plant, to stabilize the mass production processes, to produce fuel elements for initial loading of demonstration nuclear power plant, and to produce enough fuel elements for the operation of the demonstration plant and for future power plants.

2.3. Philosophy of design

The main philosophy of the HTR-PM project is safety, standardization, economy and proven technology. The “safety” requirement means the HTR-PM will comply with the inherent safety principles of the MHTGR, which must be able to remove the decay heat passively from the core under any designed accident conditions, and should keep the maximum fuel temperature below 1600 °C in all cases so as to contain all fission products inside the SiC layer of the TRISO coated fuel, and assure the low fuel temperature (lower than 1100 °C) under normal operation and large negative temperature coefficient. Therefore, it eliminates the possibility of large releases of radioactive into the environment for all possible accidents by far in the hypothetical regime.

The “standardization” requirement means that the design of the HTR-PM nuclear power plant, both the standard design and the demonstration plant design, must be standardized and modularized, so that multiple modules can be constructed batchwise in a standardized way and be assembled in every site. The reactor power of each module must be fixed in the standard design phase, and be proven in the demonstration plant. The standard design of the HTR-PM must be suitable for most nuclear power plant site condition within China, if transportation of large components permits it. Also, construction costs and economic viability must be demonstrated in the demonstration plant.

The “economy” requirement means that the designed power plant must be competitive with other types of energy sources, including the current PWR, albeit providing more safety and application flexibility. This is the most serious challenge. The construction cost target for the nth-of-a-kind (NOAK) equilibrium plant is 1300 USD/kWe in order to be competitive in China.

The “proven technology” requirement means that the HTR-PM will adopt as much as possible proven technologies. According to this guideline, the HTR-PM design will take the HTR-10 as a prototype reactor as far as even possible, including system configuration, layout, fuel element technology, design, manufacture and construction experience of the HTR-10, take the HTR-MODUL design as a reference and starting point, and use the proven, high efficient, conventional steam turbine used in coal fired plants as the best solution of the conventional island.

3. Design of HTR-PM

3.1. Main technical consideration

3.1.1. Reactor power

Economy of the HTR-PM is a very serious challenge. Although the construction cost can be reduced through batch construction and modular construction, but only a certain degree of cost reduction can be achieved if the safety principle and safety standard of the MHGTR maintain the same; for example, the cost for the pressure vessel.

Another way to improve the MHGTR economy features is to increase the reactor power, as shown in the MHGTR development trend since 1980s, for example, the designed reactor power of American MHTGR follows the trend of 200, 350, 450, and finally to 600 MW of the GT-MHR, and the designed reactor power of South African PBMR also follows the trend of 224, 265, 302, and 400 MW, respectively.

For the HTR-PM demonstration plant, the economy features are very important features to be demonstrated for the success of future commercial plants.

Table 1
comparison of movable and fixed graphite column configurations

Technique issues	Movable graphite column configuration	Fixed graphite column configuration
Reactivity control worth	Control rods will be shadowed by absorb ball unit, control margin is smaller	Control rods in side reflector, absorb balls units in center column, control margin is adequate
Maximum fuel temperature under normal operation (°C)	1050	900
Maximum fuel temperature under accident conditions (°C)	1520	1500
Replacement of central graphite column	Not required	Required, difficult to realize
Replacement of side reflector	May not be required	May be required
Main problem	Gas mixing of about 600 K	The cost to replace the central graphite blocks

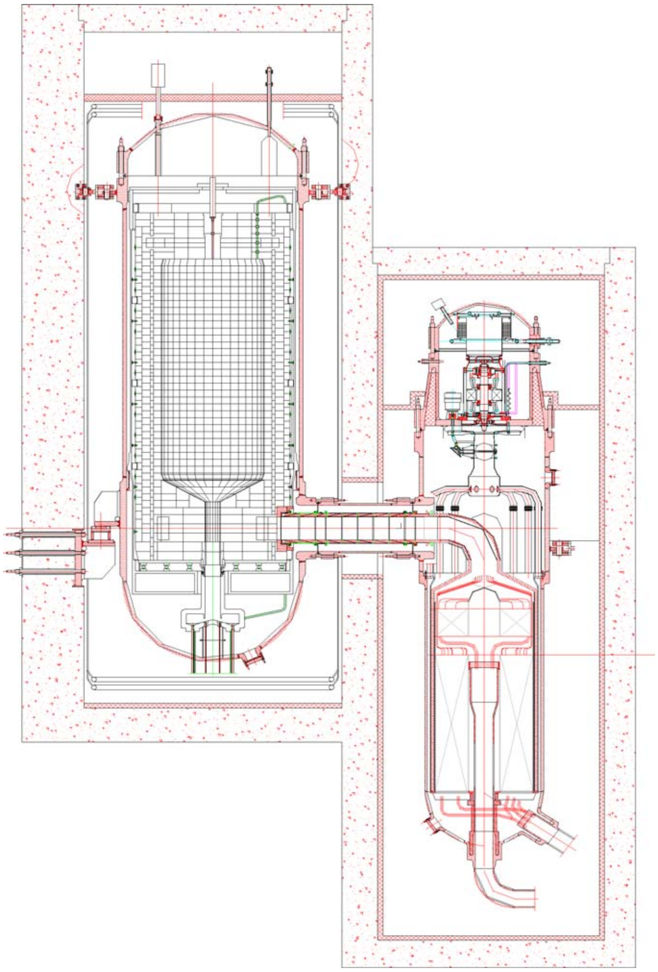

Fig. 1. Primary system of the HTR-PM.

Therefore, the reactor power of the demonstration plant and the standard design must aim at the final commercial plant, must reach the final target in one step, and the design of the nuclear island must be fixed. Other systems, for example conventional island, the BOP systems, can use the state-of-the-art mature technology. These performance indexes, for example, the electricity efficiency, the configuration of multiple reactor modules coupling with one large steam turbine, can be improved in the future. Currently, the reactor thermal power of the HTR-PM is set to 450 MW, very well knowing the enormous technological hurdles to be overcome. Also we are thinking about the possibility to further increase the reactor power.

For a 450 MW pebble bed HTR-PM core, a single zone core configuration in the HTR-MODUL (Reutler and Lohnert, 1983) is impossible; an annular core with two-zones whose inner zone is filled with graphite is inevitable.

3.1.2. Annular core

There are two types of annular core configurations. One configuration contains movable graphite column, whose inner zone of the core is filled with dummy graphite balls. The other configuration contains fixed graphite column, whose inner zone is made up of fixed graphite blocks.

These two configurations have their own advantages and disadvantages as shown in Table 1. It can be shown from Table 1 that the fixed graphite column configuration has distinguished advantages in the thermo-hydraulic performance and the maximum fuel temperature after loss of coolant and loss of pressure accident. The main problem of the fixed column configuration is how to replace the inner graphite block in the mid of the reactor lifetime, how much cost must be paid for the replacement, this will take long time to verify its feasibility. Therefore, current design adopts the movable graphite column configuration, and research and design on the fixed graphite column configuration will continue.

3.1.3. Power generation system

The Brayton cycle (gas turbine) which can provide higher efficiency is an advanced technology from our viewpoint, but the uncertainty to adopt the Brayton cycle in the HTR-PM

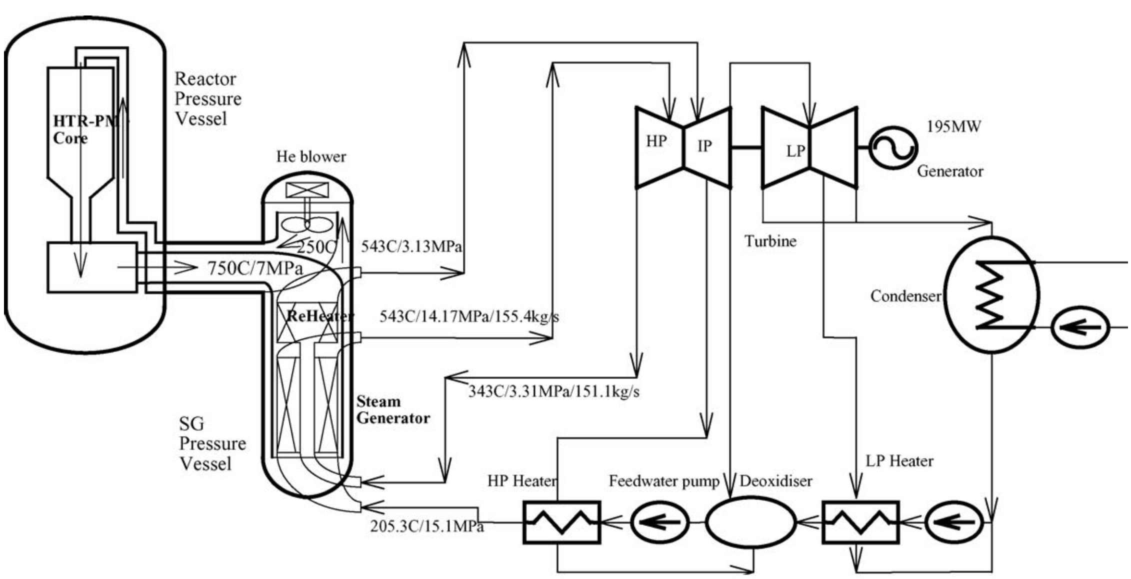

Fig. 2. Flow diagram of the HTR-PM steam turbine cycle.

Table 2
HTR-PM main design parameters

Design parameters (units)	Designed value
Reactor thermal power (MW)	458
Designed operational life time (year)	60
Expected load factor (%)	85
Fuel elements	
Diameter of fuel elements (mm)	60
Nuclear fuel	UO_2
U-235 enrichment of fresh fuel (%)	9.08
Heavy metal loading per fuel element (g)	7
Number of fuel balls	520,000
Number of graphite balls	225,530
Average discharge burn-up (MWD/tU)	80,000
Fuel loading scheme	Multi-pass (six times)
Average time of fuel elements in core (EFPD)	647
Number of fuel balls discharged each day	4,821
Number of fresh fuel balls required each day	804
Number of graphite balls discharged each day	2,091
Nuclear design parameter	
Diameter of central graphite column (cm)	220
Inner/outer diameter of fuel zone (cm)	220/400
Average height of active core (cm)	1,100
Average power density of fuel zone (MW/m^3)	4.75
Maximum power density of fuel zone (MW/m^3)	12.85
Average output power per fuel ball (kW)	0.881
Neutron leakage from the core (%)	15.08
Reactivity control	
Number of control rods	18
Number of absorber ball units	18
Worth of control rods (%)	5.25
Worth of absorb ball units (%)	11.32
Worth of control rods and absorb ball units (%)	14.08
Coolant	
Primary helium pressure (MPa)	7.0
Helium temperature at reactor outlet (°C)	750
Helium temperature at reactor inlet (°C)	250
Primary helium flow rate (kg/s)	176
Maximum fuel temperature under normal operation (°C)	1055
Maximum fuel temperature under accidents (°C)	1520
Reactor pressure vessel	
Inner diameter (m)	6.7
Height (m)	24
Wall thickness (mm)	146–250
Steam cycle	
Main steam flow rate (kg/s)	155.4
Feed water temperature (°C)	205.3
Main steam pressure at turbine inlet (MPa)	13.5
Main steam temperature at turbine inlet (°C)	538
Generator power (MW)	195

demonstration plant is too high. So, the demonstration plant will adopt the steam turbine (ranking cycle). The gas turbine will be tested and verified in the HTR-10GT project, it could be used in the HTR-PM in the future.

Now the HTR-PM demonstration plant will adopt a mature sub-critical steam turbine proven in coal-fired plants, aims to demonstrate the feasibility and maturity of the reactor itself, the connection technology between the nuclear island and conventional island, and the adoptability of new power generation system in future. New power generation systems under consideration include the configuration of several reactor modules connected to one turbine, adoption of super-critical steam turbine, adoption of super-super-critical steam turbine. All choices will depend upon the Chinese state-of-the-art of the standard and mature turbine technology.

The re-heater is another technical issue. The efficiency gain from re-heater is obvious, the structure complexity and safety impact arising from the re-heater is also obvious. The existing steam turbine in China requires a re-heater. So the re-heater is included in the conceptual design. The configuration without re-heater and the configuration with re-heater outside the reactor primary loop are also under consideration. But according to our philosophy of proven technology, the reactor and the reactor power are the most important issue, others will adopt mature and proven technology, including re-heater issue.

3.2. *Technical data of HTR-PM*

As a result of optimization and balance between the safety and economy features of the HTR-PM, the main technical features of the HTR-PM can be described as: pebble bed core, annular active zone with an inner dynamical graphite balls zone and a conventional steam turbine.

As a result, Fig. 1 presents a sketch of the primary system of the HTR-PM reactor, with the reactor unit and the steam generator unit being arranged in the so-called “side-by-side” way. The main helium circulator sits above the steam generator. Fig. 2 presents the flow diagram of the HTR-PM steam cycle, the secondary feed water is heated and live steam of 538 °C at 13.5 MPa is generated to drive the turbine-generator system.

Table 2 gives some key design parameters of HTR-PM. Its rated thermal power is 458 MW, and the generator power output is 195 MW. The reactor active zone has a height of 11 m and an outside diameter of 4 m. The central movable graphite ball column has a diameter of 2.2 m, so that the annular fuel pebble bed is in fact 0.9 m in width. Fuel elements are 6 cm in diameter. Every spherical fuel element contains 7 g heavy metal with an enrichment of nearly 9.08%. The overall height of the reactor pressure vessel is 24 m and the inner diameter of the vessel is 6.7 m. The reactor is designed for 60 years of operational life with a load factor of 85%.

4. Conclusion remarks

After the criticality of HTR-10 in year 2000, the INET began the conceptual study and design for the HTR-PM. Aimed at finishing the construction of the HTR-PM demonstration plant in 2012, the urgent task is to finish the standard design of HTR-PM based on enveloping site parameters in the mid of 2006, in the meantime, choosing an appropriate site, setting up an utility company, enquiring the manufacture of large components, carrying out some verification experiments. All these are being done in predefined order.

The biggest challenge for the HTR-PM is to prove the economy features while maintaining the inherent safety. Through the optimization design, a 450 MWth pebble bed annular core design is presented in this paper, which adopts a movable graphite ball zone in the core center, and uses a standard steam turbine proven in coal plants as the conventional island. There are still many technical and engineering problems required to be solved in the next 2 years, such as how to maintain the boundary between fuel ball zone and graphite ball zone, how to ensure the reflector graphite withstanding the whole reactor life time, how to mix the outlet hot helium from the fuel zone and the cold helium from the graphite zone, etc.

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