DESIGN OF CHINESE MODULAR HIGH-TEMPERATURE GAS-COOLED REACTOR HTR-PM

Zuoyi Zhang, Zongxin Wu, Yuanhui Xu, Yuliang Sun, Fu Li
Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, China

ABSTRACT: Modular high-temperature gas-cooled reactor (MHTGR) has distinct advantages in the sense of the inherent safety, economy property, high electricity efficiency, potential usage for hydrogen production, and etc. Chinese design of MHTGR, named as High Temperature Gas-Cooled Reactor-Pebble bed Module (HTR-PM), based on the technology and experiences of the HTR-10, is under the standard design phase. And the HTR-PM demonstration plant is planned to finish the construction in 2010. The main philosophy of HTR-PM project is safety, standard, economy, and proven technology. The works in the categories of market, organization, project and technology is done in predefined order. And the biggest challenge for the HTR-PM is to ensure the economical competition while maintaining the inherent safety. As a result of optimization and compromise, a design of 450MWth annular pebble bed core is presented in this paper.

KEYWORD: MHTGR, annular core, pebble bed, HTR-10, HTR-PM

0. CURRENT STATUS OF HTR

Starting from the gas-cooled reactor in 1950s and advanced gas-cooled reactor in 1960s, and the high-temperature reactor Dragon in 1964, the high-temperature gas-cooled reactors have developed for nearly 50 years. And the concept of modular high temperature gas-cooled reactor (MHTGR), which is much safer than its ancestor and other type of reactors, was proposed more than 20 years ago, and was realized and verified by 10MW high-temperature gas-cooled test reactor (HTR-10) designed in China in 2000. Therefore the MHTGR is a mature reactor now.

And MHTGR is very excellent in the safety, market flexibility. For safety, MHTGR eliminates the possibility of core melt and radioactive release to the environment, provides an inherent safety solution. The market flexibility is realized by the small power size of each module, multiple modules in one plant, batch and standard construction of each module, higher output temperature, possibility for many processing heat application including hydrogen production. Therefore MHTGR is very attractive and competitive in the world, many research and engineering projects are planned and ongoing, for example, the South African PBMR project, USA-Russia GT-MHR project, USA NGNP (Next generation Nuclear Power) in Idaho, HTTR in Japan, Korean HTGR plan, and Chinese High Temperature Gas-Cooled Reactor-Pebble bed Module (HTR-PM) demonstration project.

It is especially urgent for China to develop and construct new nuclear power plants. The economy grows continuously, the energy demand increases continuously, the shortage of electricity, oil and coal becomes serious and serious, the environment pressure (green house gas and air pollution) increases continuously, thus nuclear power becomes inevitable for China [1]. Because of the distinguished advantages of MHTGR in safety, and the success of HTR-10 project [2], HTR-PM project becomes urgent, practical, feasible for China [3,4]. And this is also the main topic of this paper.

1. THE PHILOSOPHY OF HTR-PM PROJECT

The main philosophy of HTR-PM project is safety, standard, economy and proven technology.

The “safety” requirement means the HTR-PM will comply with the inherent safety principles of MHTGR, which must remove the decay heat passively from the core under any designed accident condition, and keep the maximum fuel temperature below 1600°C so as to contain nearly all fission products inside the SiC layer of TRISO coated fuel. Therefore it eliminates the possibility of core melt and large release of radioactive into environment.

The “standard” requirement means that the design of the HTR-PM nuclear power plant, especially the nuclear island, must be standardized and modularization, so multiple modules can be constructed in a batch and standardized way in one site or in many sites. The standard design of HTR-PM try to solve this problem as discussed later.

The “economy” requirement means that the designed power plant must be competitive with other type of energy sources, including the current PWR, while providing more safety margin and application flexibility. This is the most serious challenge for us.

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

The work done and been doing on HTR-PM project can be divided into four categories, namely the market, organization, project, and technology.

The market category concerns the market requirement and the market chance. Now China is eagerly searching the new energy sources for its rapid economy growth, the nuclear energy has big chance to develop. In current stage, cheap and safe electricity is the main object for nuclear energy, in future, the hydrogen production, the sea-water desalination may become main stream. Although mature PWR is the main stream for the new Chinese nuclear power plants, as the Chinese national policy and world trend, but MHTGR is very attractive for its safety, higher electricity efficiency and possibility for hydrogen production. And through HTR-10, China has achieved full intelligence property and know-how of the high temperature reactor. So Chinese government agrees to support HTR-PM project in the sense of both the policy and finance. Therefore HTR-PM is suitable for the Chinese market, and finds its position in Chinese market, that is the supplement of PWR for electricity production in current stage and main source for hydrogen production in future.

In the organization category, a development team includes all aspects of Chinese nuclear industry is set up to push forward the HTR-PM project, including the research, design, construction, manufacture, operation, and utility. The kernel of this team is Institute of Nuclear and New Energy Technology (INET) of Tsinghua University, which owns the experience and experts to design, construct, operate the HTR-10, and is responsible for the research, design and technology development of the nuclear island of HTR-PM. The second level of this team is a future Architecture and Engineering (AE) company for HTR-PM which is responsible for the engineering design, main components supply, all issues about the construction. This future AE company is set up just for short time, and is a joint venture company between Chinese Nuclear Industry Construction Company, which is responsible for the construction of all Chinese nuclear power plants, and Tsinghua University, which can provide HTR design technology. This AE company will be responsible to combination of design, manufacturer, construction, utility together to provide a complete HTR-PM power plant to utility. Another part of the team is the future utility company. This company will be a joint venture company among a Chinese electricity company, namely Huaneng Group Company, and nuclear industry company, namely the Chinese Nuclear Industry Construction Company, and 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 HTR-PM. This utility company will be responsible for the issues of marketing, financial, site selection, and etc.

For project category, 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 line of project is outlined. One is the reactor itself, including the site selection, standard design, experiment verification, safety review, demonstration plant, and future batch construction of HTR-PM. Another line of project is for the nuclear fuel plant, which is very different from the fuel plant for PWR. This work is outlined as, to expand the size of the plant, to stabilize the production technics, to produce fuel elements for physical critical of demonstration nuclear power plant, and produce more fuel elements for operation of demonstration plant and future power plants. The long term development project concerns the development of new technology, including helium turbine (prototype will be tested in HTR-10), hydrogen production technology (technology developing in laboratory), gas fast reactor technology, very high temperature gas-cooled reactor technology, and etc.

For technology category, the main work is to finish the HTR-PM standard design which is based on the enveloping or reference site condition. This idea of standard design is like the standard design of ABWR done by GE company. The purpose of standard design to hurry up the design process and improve the design quality. According to Chinese rules, the design of nuclear power plant must follow the stages of: 1) preliminary feasibility study which chooses the site, outlines the conceptual scheme, analyzes the economic feature, forms the utility company, outlines the financial source, 2) feasibility study which includes the site seismic and geology report, site choice safety analysis report, environment impact analysis report and project feasibility study report itself, 3) preliminary design aimed at to get the construction license, 4) final construction design. As a new type of nuclear power plant, the first two stages are too lengthy and the government permission must be obtained one by one. Therefore the standard design which uses the enveloping site condition and reaches the depth of preliminary design can make the design of the HTR-PM more detailed and at early stage. From another viewpoint, MHTGR requires the standardization of the design in nature because a power plant may contains tens of reactor modules, each module must be standardized. Based on the standard design, only the design of some BOP system will be modified or reified according to specified site parameters. Therefore the standard design can speed up the process of the design, safety review, construction and commissioning of the power plant.

2. TECHNIQUE DATA ABOUT HTR-PM

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

The pebble bed core is chosen because of the long history of research on pebble bed core in China, the experience obtained in HTR-10, the online fueling and de-fueling feature of pebble bed core, and the success of the design of HTR-MODUL [5].

The annular core is chosen in order to further improve the economy performance of the HTR-PM. Annular core with inner graphite zone can greatly reduce the maximum fuel temperature under loss of coolant and loss of pressure accident [6], thus can increase the power level of each reactor module, and reduce the construction cost per unit of output power, while maintaining the inherent safety. The solution of movable graphite ball zone and fixed graphite column is compared and balanced for the inner graphite zone, according to the safety margin, the reactor power level, the engineering feasibility, and the component cost. The fixed graphite column can provide more advantages for the safety margin and thermo-hydraulic design, but the cost to replace this inner graphite column will be very high, or even impractical because of the lack of enough irradiation data of graphite and thus the lack of the confidence of the replacement solution. The movable graphite zone solution is more reasonable, after some technique challenges is solved, for example, how to setup and maintain the boundary between the fuel ball zone and graphite ball zone, how to mix the hot helium out from the fuel zone and cold helium out from the graphite zone, how to provide enough reactivity to shutdown the reactor from outer reflector of larger core, how to ensure the enough life time for the reflector graphite for whole reactor life time, and etc. But the confidence to solve the problems concerning the movable graphite balls is higher than to solve the replacement problem of fixed graphite column. As a result, the annular core with inner movable graphite balls zone is selected for HTR-PM project, at least at current stage.

Now, the steam turbine, whose parameters and manufacture technics are used and proven in coal plant, is chosen. The main purpose of the demonstration HTR-PM power plant is to demonstrate the standard nuclear island and the technology to connect the nuclear island and conventional island, so a practical, existing and proven steam turbine is the best choice. When new technologies such as gas turbine become mature, HTR-PM can directly adopt them in future, if the nuclear island is safe and mature.

As a result, Fig.1. presents the draft schematic about 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. In the steam generator, secondary feed water is heated and live steam of 535ºC at 13.5MPa is generated to drive the turbine-generator system. Re-heat is foreseen. The re-heater is designed above the steam generator tubes. And another proposal to use re-heater outside the reactor vessel are under discuss and review.

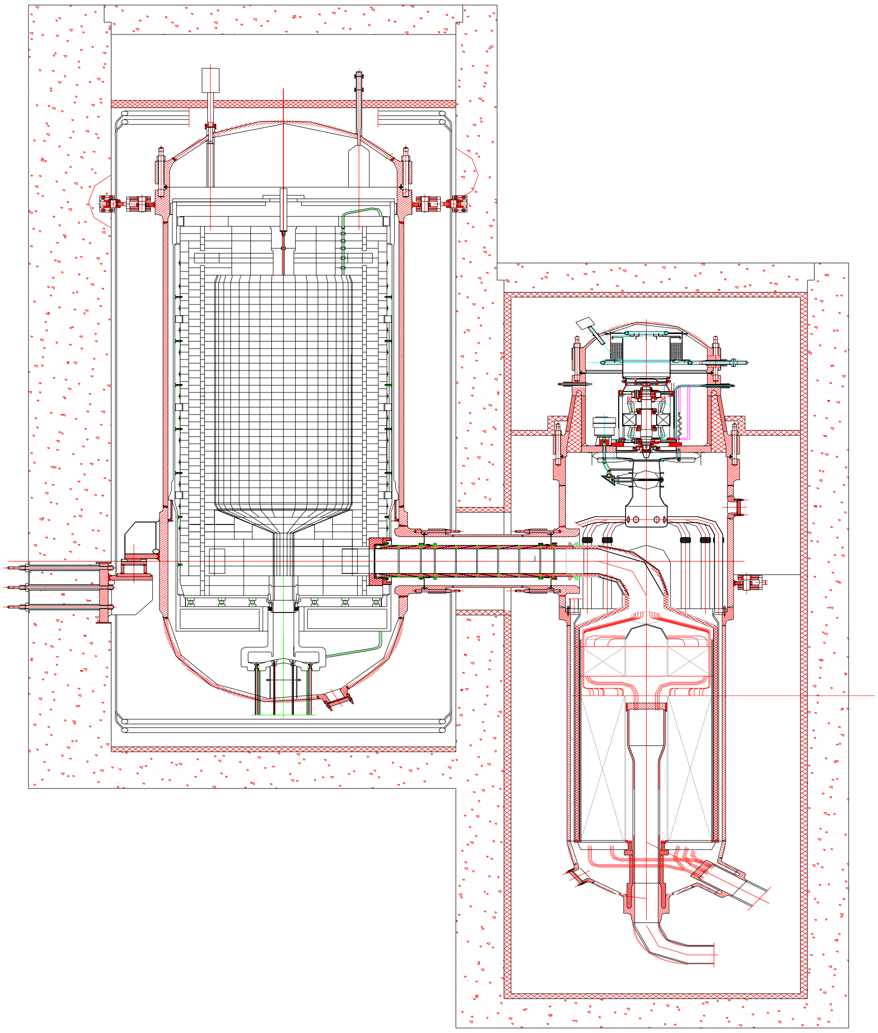

FIGURE 1 Primary system of HTR-PM

In summary, the HTR-PM design has the following key technical features:

- Spherical fuel elements with TRISO coated particles are used, which have proven capability of fission product retention under 1600ºC in accident cases.
- A two-zone core design is adopted, with one central movable column of graphite spheres surrounded by pebble fuel elements.
- The active reactor core shall be surrounded by ceramic materials of graphite and carbon bricks, which are high temperature resistant.
- Decay heat in the fuel elements shall dissipate by means of heat conduction and radiation to the outside of reactor pressure vessel, and then taken away to the ultimate heat sink by water cooling panels on the surface of the primary concrete cell. Therefore, no coolant flow through the reactor core shall be necessary for decay heat removal in case of loss of coolant flow or loss of pressure accidents. Maximum accident fuel temperature shall be limited to 1600ºC.

- Spherical fuel elements shall be charged and discharged in a so-called “multi-pass” mode, which means that before the fuel elements reached the discharge burn-up, they will go through the reactor core several times.
- Two independent reactor shutdown systems are foreseen. Both systems shall be designed in the side reflector graphite blocks. The neutron absorber elements shall fall into the designated channels in side reflectors by gravity when called-upon.
- The reactor core and the steam generator are housed in two steel pressure vessels which are connected by a connecting vessel. Inside the connecting vessel, the hot gas duct is designed. All the pressure retaining components, which comprise the primary pressure boundary, are in touch with the cold helium of the reactor inlet temperature.
- At a complete loss of pressure accident, the primary helium inventory shall be allowed to be released into the atmosphere. Then the helium release channel shall be closed and the reactor building shall be vented and serves as the last barrier to radioactivity release.
- Several of HTR-PM modular reactors can be built at one site to satisfy the power capacity demand of utility. Some auxiliary systems and facilities shall be shared among the modules.

Table 1 gives some key design parameters of HTR-PM. Its rated thermal power is 450MW, and the generator power output is 190MW. The active reactor core has a height of 11m and an outside diameter of 4m. The central movable graphite ball column has a diameter of 2.2m, so that the annular fuel pebble bed is in fact 0.9m in width. Fuel elements are 6cm in diameter. Every spherical fuel element contains 7g heavy metal with an enrichment of nearly 8.8%. The overall height of the reactor pressure vessel is 25m and the inner diameter of the vessel is 6.7m. The reactor is designed for 40 years of operational life with a load factor of 85%.

TABLE 1 HTR-PM main design parameters

Design parameters	units	Designed Value
Reactor thermal power	MW	450
Designed operational life time	year	40
Expected load factor	%	85
Fuel Elements		
Diameter of fuel elements	mm	60
Nuclear fuel		UO_2
U-235 enrichment of fresh fuel	%	8.8
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 (10 times)
Number of fuel balls discharged each day		8,036

Number of fresh fuel balls required each day		803
Number of graphite balls discharged each day		3,485
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	1100
Average power density of fuel zone	MW/m^3	4.67
Reactivity Control		
Number of control rods		18
Number of absorber ball units		18
Graphite Reflector		
Height of graphite structure	m	15.2
Nominal diameter	m	5.5
Height of core cavity	m	11.4
Carbon brick		
Height of carbon structure	m	16.6
Outer diameter	m	6.0
Core barrier		
Height	m	19.1
Inner diameter	m	6.3
Reactor Pressure vessel		
Inner diameter	m	6.7
Height	m	25.4
Wall thickness	mm	146~250
Coolant		
Primary helium pressure	MPa	7.0
Helium temperature at reactor outlet	ºC	750
Helium temperature at reactor inlet	ºC	250
Primary helium flow rate	kg/s	172
Maximum fuel temperature under normal operation	ºC	1035
Maximum fuel temperature under accident	ºC	1471
Steam Cycle		
Main steam flow rate	t/h	543
Feed water temperature	ºC	205.3
Main steam pressure at turbine inlet	MPa	13.5
Main steam temperature at turbine inlet	ºC	535
Generator power	MW	190

3. CONCLUSION REMARKS

After the physical criticality of HTR-10 in year 2000, the HTR-PM began the conceptual study and design. Aimed at finishing the construction of HTR-PM demonstration plant in 2010, 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 appropriate site, setup utility company, querying the manufacture of large component, carrying out some verification experiments, all these thing are doing in predefined order.

The biggest challenge for the HTR-PM is to improve the economy features while maintaining the inherent safety. Through the optimization design, a 450MWth pebble bed annular core design is presented in this paper, which adopts a movable graphite ball zone in the core center, and use standard steam turbine proven in coal plant as the conventional island. There are still some technique and engineering problems required to be solved in next two 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 hot helium out form the fuel zone and the cold helium out from the graphite zone, and etc.

REFERENCES

[1] Wang Dazhong, Lu Yingyun, Roles and prospect of nuclear power in China’s energy supply strategy, Nuclear Engineering and Design, v218 (2002), p3

[2] Zongxin. Wu, Dengcai. Lin and Daxin. Zhong, The design features of the HTR-10, Nuclear Engineering and Design, v218 (2002), p25

[3] Z. Zhang and S. Yu, Future HTGR developments in China after the criticality of the HTR-10, Nuclear Engineering and Design, v218 (2002), p249

[4] Y. Xu,The Chinese Point and Status, Proceedings of the Conference on High Temperature Reactors, Petten, NL, April 22-24, 2002

[5] H.Reutler, G.H.Lohnert. The Modular High-Temperature Reactor. Nuclear Technology, Vol. 62 (July 1983), 22-30.

[6] Fu Li, Xingqing Jing, Comparison of fuel loading pattern in HTR-PM, HTR-2004, Beijing, Sept.22-25, 2004