Concept Design of Pebble Catcher of Pebble Bed HTGR with Fast Pebble Discharge System

Dong Jianling* Kong Xiangwei Song Yingming Yang Yongwei
(INET, Tsinghua University, Beijing 100084, P.R. of CHINA)

ABSTRACT

High temperature gas cooled modular reactor (HTGR) is an advanced reactor. It is passively safe against the loss-of-forced-cooling accident. In order to be passively safe, low mean core power density has to be adopted. This leads to much larger RPV and relevant surroundings comparing with PWR of the same power. Obviously, how to decrease size of RPV and relevant surroundings is a key to make HTGR more economical. One way is to increase the core power density. But this may compromise its inherent safety performance. In 2002, a new method was put forward to solve this problem. The basic idea is: 1) Under normal operation, the reactor core is of high power density; 2) When loss-of-forced cooling accident happens, pebbles are discharged into a pebble catcher by gravity, which make the reactor core in low power density; 3) Pebble catcher should prevent second criticality from happening and decay heat can be safely removed by passive ways.

This paper presents the concept design of a pebble catcher. The result shows that the pebble catcher can prevent the second criticality from happening and decay heat can be removed passively.

INTRODUCTION

High temperature gas cooled reactor (HTGR), such as HTR-10 of China and PBMR of South Africa, is an advanced modular reactor using helium as coolant [1]. The system is passively safe against the loss-of-forced-cooling accident. But to get such a safety feature, low mean core power density, 2MWt/m^3 for HTR-10 and 2.5MWt/m^3 for HTTR of Japan, has been adopted; decay heat has to be continuously removed from the core through the water wall surrounding the RPV during the reactor operation. This leads to much larger RPV and relevant surroundings, so construction and operation cost higher. For example, though the heat power of HTR-10 is only 10MWt, the reactor has a core cavity with diameter of 1.8m and mean height of 1.97m, surrounded by graphite reflectors with thickness of 1.0m. The reactor pressure vessel is much larger than that of PWR of the same thermal power. Therefore, whether the size of RPV and the relevant surroundings can be decreased is a key to make HTGR more economical. One way to decrease the size of the pressure vessel and the relevant surroundings is to increase the core power density. But this may compromise its inherent safety performance.

In references [2] and [3], a new concept was put forward to solve the problem. It can be described as: 1) Under normal operation, the reactor core is of high power density; 2) When the loss-of-forced-cooling accident happens, a fast pebble discharge system is used to passively discharge part or whole of pebbles into a pebble catcher to decrease the core power density so that the decay heat can partly or whole removed outside the core by passive means; 3) The pebble catcher is designed and constructed in such a way that no second criticality could occur and the decay heat produced by discharged pebbles is removed by passively safe means.

The preliminary study has shown that if the diameter of the discharge pipe is ¢500mm, discharge time could be very short [2]. In the case of HTR-10, core cavity has a diameter of 1.8m, mean height of 1.97m, and holds 27000 pebbles, diameter of which is ¢60 mm. In the conical-shaped bottom, the cone angel is 120℃ and diameter of the discharge pipe is ¢500mm, which is 8 times larger than pebble’s diameter. The study shows that discharge time is less than 30s. It also has been proved that when pebbles drop into pebble catchers, the integrity of pebbles can be guaranteed.

In the reactor of high core power density with fast pebble discharge system, a pebble catcher accommodates pebbles discharged from the reactor core when the loss-of-forced-cooling accident happens. In this paper, taking pebble bed

* Correspondent author: dongjl@tsinghua.edu.cn

reactor core of thermal power 50 MW and core power density 10MW/m^3 as an example to describe the concept design of a pebble catcher.

PEBBLE BED REACTOR CORE OF THERMAL POWER 50 MW AND ITS PEBBLE CATCHER

Figure 1 shows the layout of a pebble bed reactor core of thermal power 50 MW. It can be seen from the figure that comparing with the conventional pebble bed HTGR, the reactor has a pebble discharge system and a pebble catcher.

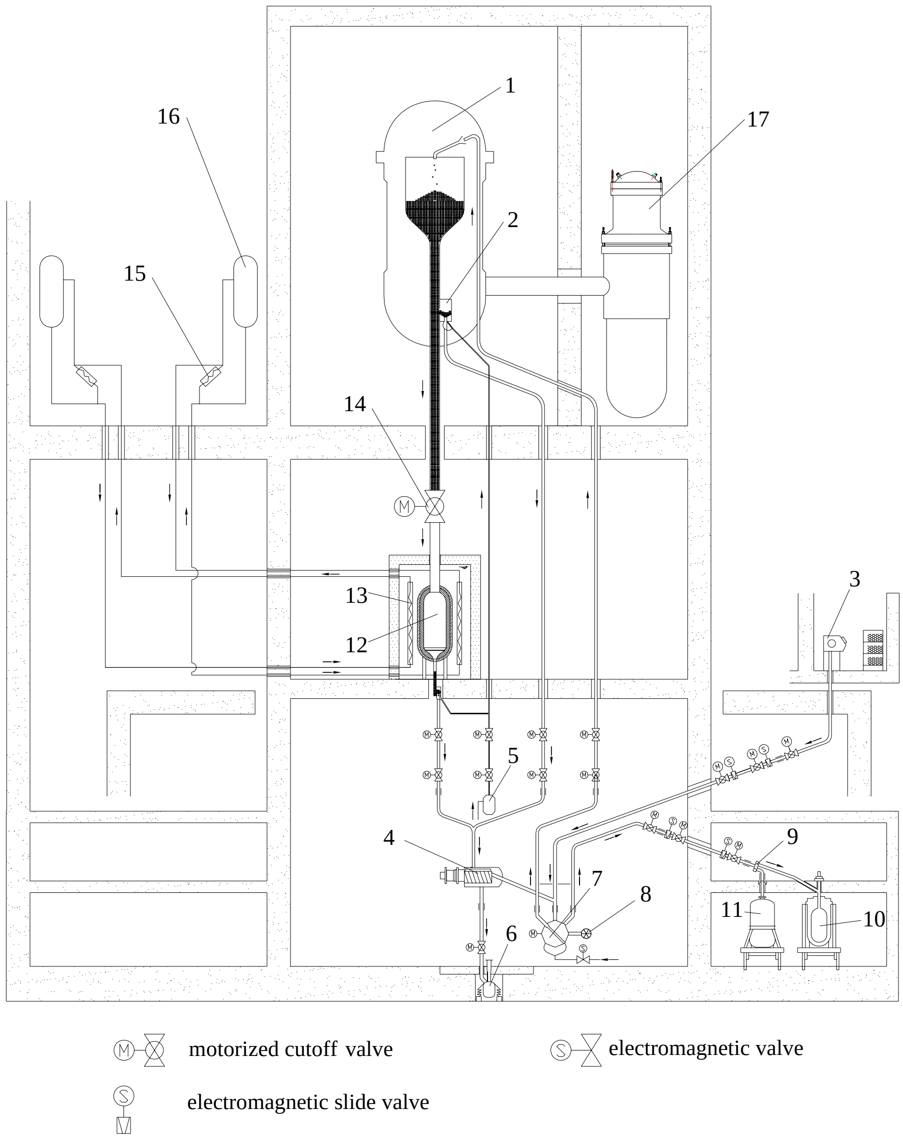

Figure 1 layout of a 50 MW pebble bed reactor with a fast pebble discharge system
1-reactor core; 2-singulizer; 3-glove box; 4-failed fuel separator; 5-pulse air generator; 6-fragment tank; 7-elevator; 8-device for burn-up measurement; 9-distributor; 10-used pebbles storage tank; 11-graphite element container; 12-pebble catcher; 13-heat exchanger; 14-pebble discharge system; 15-air cooler; 16-expanding tank; 17-steam generator

Suppose all pebbles in the core are discharged into the pebble catcher when loss-of-forced-cooling accident occurs, the decay heat in the pebble catcher will be about 3.5MW.

The main function of a pebble catcher is to hold pebbles discharged from the core, absorb neutrons to avoid the second criticality, and remove decay heat from pebbles efficiently to prevent pebbles temperature from exceeding 1600^{o}C, when loss-of-forced-cooling accident occurs.

The pebble catcher system consists of a pebble catcher and a decay heat removal system. A cooling pool surrounds the pebble catcher. In the pool, one of the cooling options is that several heat exchangers are installed in the pool. The heat exchangers are connected to air coolers.

The working principium of the pebble catcher system is: when loss-of-forced-cooling accident happens to the core, heat produced in the core cannot be removed effectively. It makes the core temperature rising. When the temperature is high enough, it triggers a signal to open the ball valve between the core and the pebble catcher (with a dam board to be a redundant system). Due to gravity, pebbles drop from the core into the pebble catcher. There, the pebble catcher absorbs produced neutrons efficiently and prevents second criticality from happening. During the process, temperature of water in the cooling pool surrounding the pebble catcher rises. Temperature difference between inside water and outside water of heat exchangers in the cooling pool makes cooling water inside the heat exchanger flow naturally. Through heat exchange with the air, heat exchangers gradually transfer the decay heat to the air.

PEBBLE CATCHER DESIGN GOALS

According to the functional requirements, constraints on the pebble catcher are as follows:

1） The pebble catcher should prevent second criticality of the discharged pebbles；
2） The pebble catcher should contain the discharged pebbles(size, structure, thermal shock resistance)；
3） The pebble catcher should be as cheaper as possible；
4） The pebble catcher should facilitate long-term coolability using passive means；
5） Interactions between pebble catcher materials and these discharged pebbles should not result in exothermic reaction；
6） The pebble catcher should prevent a seismic hazard；
7） The pebble catcher should be stable for the lifetime of the reactor；
8） The pebble catcher should be easily installed and maintained；
9） The pebble catcher should not adversely affect reactor performance or coolant circulation.

STRUCTURE DESIGN

From figure 1, it can be seen that the pebble catcher locates beneath the reactor pressure vessel. It is a columniform container with two hemispherical closure heads connected to two cross sections of the cylindrical shell. Its total height is 5.0 m, and the two spherical closure heads have diameter of 1.5m.

Due to its functional requirement, a pebble catcher has two layers. The outer layer is used to hold all discharged pebbles and inner layer carbon bricks. It will resist the pebbles' impact and thermal shock from the temperature difference between the water surrounding the container and the inner layer. To a certain extent, outer layer can absorb neutrons leaking from the inner layer, decrease the number of neutrons slowing down by the water, and transfer the decay heat to water effectively.

Now stainless steel is widely used in nuclear engineering for its excellent properties. The core catcher uses stainless steel with about 10% carbon in this kind of steel.

The inner layer is used to absorb neutrons and prevent second criticality. It should be a material having features as follows:

1) It should be a material with a large thermal neutron absorbing cross section;
2) It should be a material that maintains its integrity at high temperature;

3) It should be relatively inexpensive;
4) It should have good heat transfer capability;
5) It must be compatible with outer layer but no reaction with outer layer material;
6) It must be compatible with helium.

A comparison of relevant properties suggests that borated carbon brick is suitable for the inner layer material.

Figure 2 is the sketch of the pebble catcher to show its structure. In this figure, 1 represents metal container of the pebble catcher, 2 represents borated carbon bricks layer.

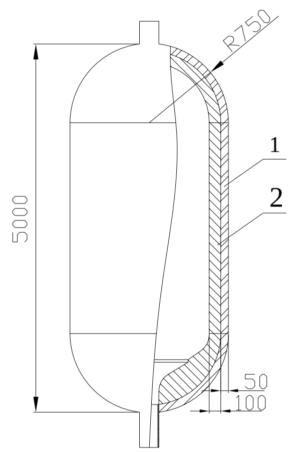

Figure 2 Sketch of a pebble catcher

PHYSICS DESIGN

The structure and size of every part of pebble catcher is shown in figure 2. New pebbles of 27 000 are used in the criticality safety calculation. Calculation results under normal and abnormal conditions are as follows:

1) Under the normal conditions: The pebble discharged into the pebble catcher will have a packing density of 0.61. The thickness of water layer surrounding the pebble catcher is assumed as 300mm. Assume that substance outside water layer is vacuum, then the coefficient $k_{eff} = 0.46554 \pm 0.00160 < 1$, so no second criticality happens. Figure 3 gives the calculation model.

68% confidence: 0.46394 to 0.46715

95% confidence: 0.46236 to 0.46873

99% confidence: 0.46132 to 0.46977

2) Under abnormal conditions, such as earthquake: The maximum of a packing density will be 0.74. The thickness of water layer surrounding the pebble catcher is also assumed as 300mm. The calculation model is same except the packing density. Through calculation, the coefficient $k_{eff} = 0.66067 \pm 0.00212$.

68% confidence: 0.65855 to 0.66279

95% confidence: 0.65646 to 0.66489

99% confidence: 0.65508 to 0.66627

3) Under abnormal conditions, such as earthquake: Packing density is supposed as 0.74. But water thickness is 3000mm. The calculation model is shown in figure 4. After the calculation, it is found that the coefficient $k_{eff} = 0.66067 \pm 0.00212$.

68% confidence: 0.65855 to 0.66279

95% confidence: 0.65646 to 0.66489

99% confidence: 0.65508 to 0.66627

From the calculations, it can be seen that the second criticality cannot happen if the pebble catcher is used.

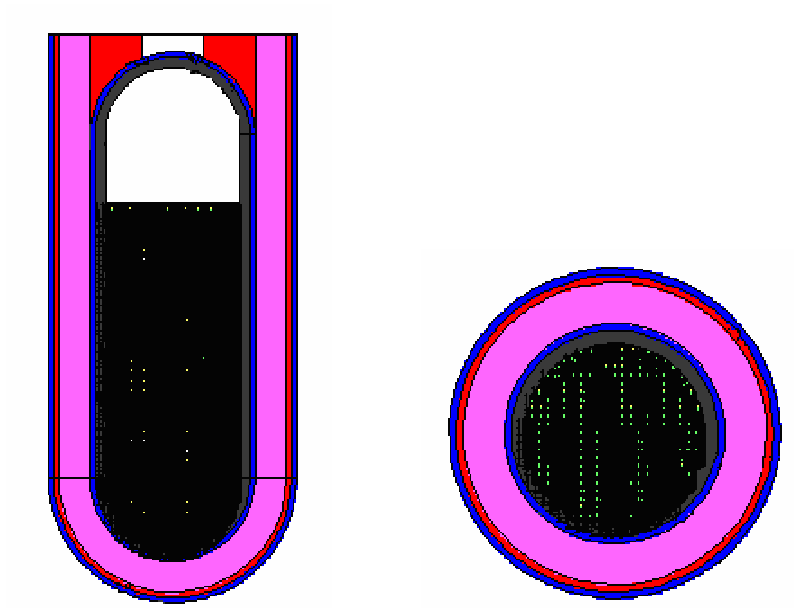

Figure 3 Criticality safety calculation model with packing densities 0.61 and 0.74, respectively, water layer thickness 300mm

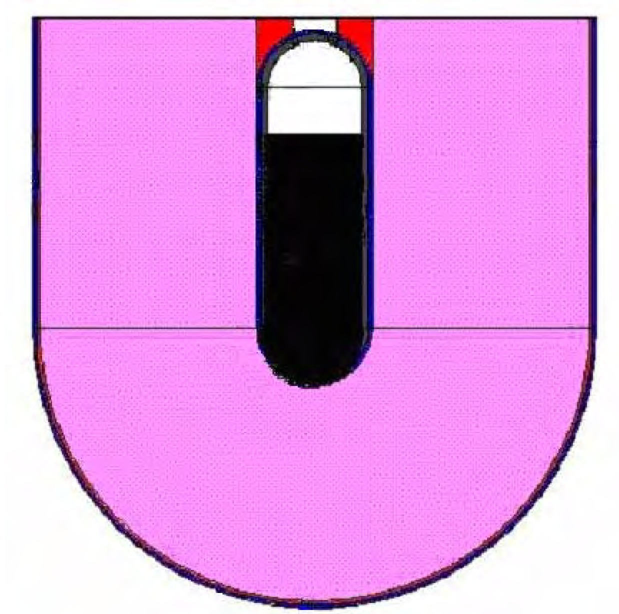

Figure 4 Criticality safety calculation model with packing densities 0.74 and water layer thickness 3000mm

THERMAL ANALYSES

When pebbles are discharged into the pebble catcher, they fill the pebble catcher quickly. According to physical calculations in the above section, no second criticality will happen. But, decay heat of discharged pebbles still exists. If mean power density of HTR-10 is increased from 2MWt/m^3 to 10MWt/m^3, the thermal power is 50MW and decay heat will be about 7% of the normal full operation power, 3.5MWt. If the decay heat cannot be removed in time, the temperature of pebbles will keep increasing. If it rises up to 1600℃, the integrity of pebbles will be damaged.

Heat inside the pebble catcher is transferred to the pebble catcher wall by four means: radiation in the inter-space of the pebbles; conduction between pebbles; heat conduction and heat convection of the helium in the inter-space of the pebbles. The amount of heat transferred is considered as sum of these four means, and finally it is transported to the metal container wall [4].

When the pebble catcher wall is heated, due to the temperature difference between the pebble catcher wall and outside environment, decay heat transfers from pebble catcher to outside.

There are three options to remove the heat from the pebble catcher wall:

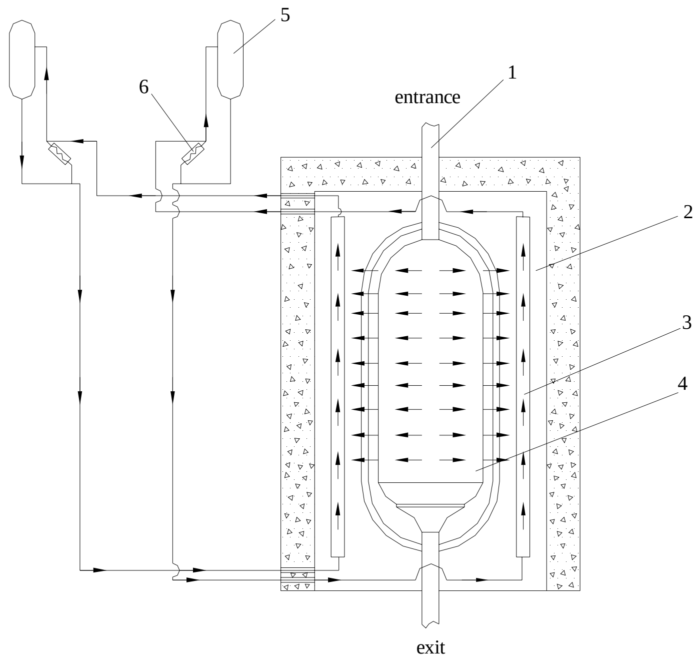

Figure 5 sketch of heat transfer process
1-discharge pipe; 2-annular space; 3-heat exchanger; 4-pebble catcher;
5-expanding water tank; 6-air cooler

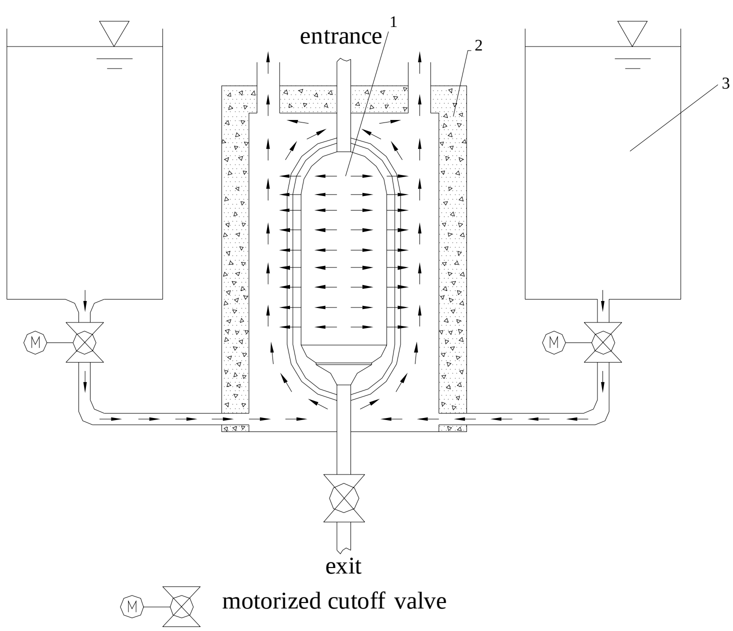

Figure 6 Sketch of water flow and heat transfer in pebble catcher

1-pebble catcher; 2-cooling water pool; 3-cooling water tank

Option 1: In this design, eight heat exchangers are installed in the annular space between pebble catcher cavity wall and the pebble catcher. Each heat exchanger has a heat removal capability of larger than 0.5MW. Temperature of water in heat exchanger rises after being heated. Temperature difference between the inside and the outside of heat exchanger makes cooling water inside the heat exchanger start to flow naturally. Through heat exchange with the air, heat exchanger gradually transfers the decay heat to the air. Figure 5 is the sketch of heat transfer process, the arrows shows how decay heat is transferred out of pebble catcher.

Option 2: A few pebble catchers are connected with the reactor core. Each pebble catcher has the same size and much great height-to-diameter ratio to avoid criticality. The number of pebble catchers is determined by the amount of decay heat and cooling capability of a decay heat removal system.

This option may have advantages as follows:

1) It is easier to prevent second criticality from happening because of their greater height-to-diameter ratio;
2) Thickness of each material layer can be much smaller, which makes heat transfer more easily;
3) It can be designed and manufactured in a modular way, so cost can be reduced.

Option 3: In this option, the pebble catcher is designed with a much greater height-to-diameter ratio; so second criticality will be easily avoided. The pebble catcher is put inside a cooling water pool pressure of which is 0.1 MPa. The cooling water pool is connected with several cooling water tanks. Heat of the surrounding water is cooled by water evaporation into the atmosphere. Adoption of direct evaporation makes cooling capability of heat removal system much better.

Under normal conditions, the cooling water tank and cooling water pool have the same height of water surface. When loss-of-forced-cooling accident happens, decay heat is transferred from the pebble catcher to ambient water. The temperature of the water will increase. After the water absorbs enough energy, the temperature will reach the boiling point at 0.1MPa and begin to boil. So much vapor is produced that it will take away enough heat from pebble catcher to keep the temperature of pebble well below 1600℃. As ambient water surrounding the pebble catcher vaporizes, the water surface of cooling water pool will drop. Pressure difference between the surfaces of cooling water pool and the cooling water tank makes water flow into cooling water pool from cooling water tank naturally. If there is enough water in cooling water tanks and the pool, decay heat from pebble catcher can be removed.

But in this design option, selection of the height-to-diameter ratio should be restricted. To make pebble flow smoothly, the inner diameter of a pebble catcher should be no less than 300mm. Figure 6 illustrates the principium of the decay heat removal system.

COMPARISON BETWEEN PEBBLE CATCHER AND REACTOR CORE

In order to estimate the economics, comparison between pebble catcher and reactor core is conducted. The results are shown in table 1.

Table 1 Comparison between pebble catcher and the core

Difference	Pebble catcher	Core
Structure	There is no graphite reflector in a pebble catcher. Neutrons are absorbed by borated carbon bricks layer	Graphite reflector is installed outside the core cavity to slow down fast neutrons. And outside of the layer, borated carbon bricks is used to absorb neutrons
	In a pebble catcher, there are no tunnels for control rods, material test equipments and helium channels.	In graphite reflector, tunnels are manufactured for control rods, material test equipments and helium channels. The core is cooled by helium

	Control rods are not needed	Control rods are needed for fission of the fuel
	Pebble catcher isn't connected with steam generator	The core is connected to steam generator to transport heat
	Pebble catcher has a greater height-to-diameter ratio to avoid second criticality	The core is designed to have small height-to-diameter ratio for criticality
	Pebble catcher has less test equipments	To ensure core's safety, more test equipments are installed to measure and detect neutron flux and temperature field than a pebble catcher
	A concrete pool holds cooling water and functions as a radiation shield to neutrons	The core is protected through borated carbon bricks and concrete layer is a final radiation shield
	Much smaller size than the core	Core is much greater
Cost	Cheap	Expensive
Criticality Safety	Pebble catcher is designed to avoid second criticality	Criticality is a basic requirement to core design
Decay Heat Removal	Decay heat is transferred from pebble catcher to outside environment, Then through the heat exchanger or direct evaporation, it is finally transported to the air	Decay heat is removed by water wall outside the core When loss-of-forced-cooling accident happens，decay heat passes the graphite reflector、borated carbon bricks to the RPV，then it is transported from the RPV to water wall by radiation and natural convection. The water in water wall transfers decay heat to air naturally

It can be seen that the pebble catcher is much simple comparing with the reactor core, from the table.

CONCLUSIONS

From the aspect of safety, the preliminary study above shows that the pebble catcher can prevent second criticality from happening. It is also feasible for decay heat produced by discharged pebbles to be effectively transferred to annular space, and be released into air through natural convection of cooling water in the heat exchanger.

From the aspect of economy, concept of pebble catcher is beneficial to high power density gas cooled reactor. Construction and operation of a pebble catcher is much cheaper than of the core.

REFERENCES

[1] Wu Zongxin, Zhang Zuoyi, "High Temperature Gas Cooled Reactor", Chapter 5, Advanced Nuclear System and High Temperature Gas Cooled Reactor, Tsinghua University Press, Beijing 2004.

[2] Dong Jianling, Zhou Si Cong, Yu Suyuan, "Calculation of pebbles discharge time of pebble bed based HTGR with fast pebble discharge system", *Proceedings of ICONE 13, Beijing, China, 2005*.

[3] Dong Jianling, Yu Suyuan, "Concept of pebble bed based HTGR with fast pebbles discharge system", *Proceedings of 2th Topic Meeting on High Temperature Reactor Technology, Beijing, China, 2004.*

[4] Liu Jie, Gao Zuying (1999), "The effective conductivities of pebble bed in high temperature gas cooled reactor and its application to SANA benchmark experiments", *Chinese Journal of Nuclear Science and Engineering, Vol. 19, No.4, pp.303-308.*