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ARTICLE

Conceptual Study for a Demonstration High Temperature Gas-Cooled Reactor (HTGR)

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The core nuclear design was performed for a demonstration High Temperature Gas-Cooled Reactor (HTR-F) with 260MW thermal power with the aim of starting operation in the late 2030s. The design policy of the HTR-F is to use existing technology that does not require new demonstration tests, enabling operation in the late 2030s. Therefore, the core nuclear design of the HTR-F was based on the proven technologies of the High Temperature Engineering Test Reactor (HTTR) and the Small-sized HTGR System (HTR50S), which was conceptually designed by improving HTTR technology. In the core design of the HTR-F, to achieve higher output than HTTR and HTR50S, the number of fuel block layers was increased and the fuel regions expanded by making the annular core, and the nuclear characteristics of the new core were investigated through whole-core burnup calculations. Additionally, the placement and size adjustment of burnable poisons (BP) were used to further suppress the effective multiplication factor. As a result, the core became an annular core with 12layers of fuel blocks, the effective multiplication factor was suppressed to 1.05 or less throughout the burn period, and a burnup of 45GWd/t was achieved.

KEYWORDS: demonstration HTGR, annular core, nuclear characteristics, whole-core burnup calculations

I. Introduction

Recently, a High Temperature Gas-cooled Reactor (HTGR) has been receiving particular attention worldwide as one of the Generation IV nuclear reactor systems because of its excellent safety features and its use as a heat source for hydrogen production, etc. In Japan, the Basic Policy for the Realization of GX (Green Transformation)[1] was released by the government in 2023, with decarbonization as one of its objectives. In the policy, the demonstration HTGR is planned to start operation in the late 2030s as shown in **Fig. 1**, which shows the Japan's future milestones of next-generation advanced reactor. Under these circumstances, the University of Fukui has started the conceptual design of the HTGR (HTR-F), which also meets the requirements of the demonstration HTGR. In this paper, the preliminary nuclear and thermal design of the HTR-F is carried out.

II. Outline of the Reactor Core

1. Design Philosophy

The design of the HTR-F shall be based on the High Temperature Engineering Test Reactor (HTTR)[2] technology, which is a proven HTGR technology, in order to enable the start of operation in the late 2030s. Therefore, the fuel, control rods (CRs), graphite blocks, etc. of the HTR-F shall be the same as those of the HTTR. **Table 1** shows the major specifications of the HTR-F and HTTR.

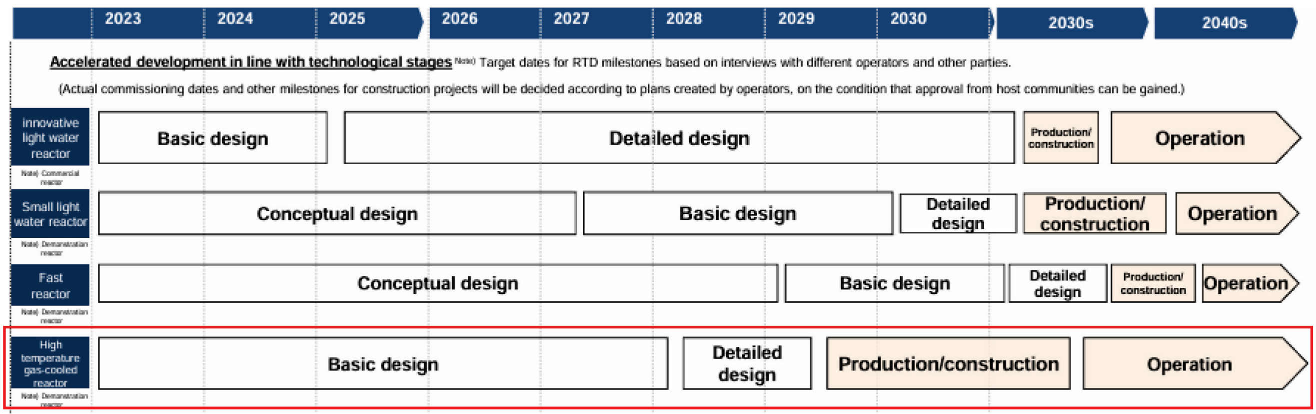

Fig. 1 Japan's future milestones of next-generation advanced reactor

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Table 1 Major specifications of HTR-F and HTTR

Items	Values	
	HTR-F	HTTR
Power (MWt)	260	30
Inlet coolant temp. (ºC)	325	395
Outlet coolant temp. (ºC)	750	850
Equivalent core diameter (m)	4.3	2.3
Core height (m)	7.0	2.9
Power density (MW/m^3)	4.3	2.5
Uranium enrichment (wt%)	6.7, 9.8	3.3-9.9
Number of fuel enrichment	2	12
Number of CRs	42	32

2. Core Structure

The core is constructed by stacking three kinds of hexagonal blocks, which are fuel blocks, CR guide blocks and replaceable reflector blocks. They are surrounded by permanent reflectors made of graphite. All these hexagonal blocks are made of high-purity graphite, and are the same size: 360 mm in across flats and 580 mm in height.

The diameter of the core is determined 7.6 m or less by considering the fabricability of the pressure vessel, the dimensions of the reflector area outside the radial direction of the core, and the dimensions of the core restraint mechanism. The core shape is determined in consideration of the ability to safely remove decay heat in the event of an accident.

In general, the construction of a commercial reactor should be realized only by scaling up the demonstration reactor without requiring new technology development as much as possible to reduce development risks. In other words, the thermal power of the demonstration reactor should be about half that of the commercial reactor so that the technologies of the components, structures, systems, cores, and fuels of the commercial reactor can be demonstrated and the manufacturability and install-ability can be foreseen.[3]

Since the Gas Turbine High Temperature Reactor (GTHTR300),[4] a commercial HTGR for which Japan Atomic Energy Agency conducted a conceptual design, has a thermal power of 600MW, the thermal power of the HTR-F should be approximately 300 MW. In addition, the thermal power scale targeted for the demonstration HTGR is in the range of 200 to 300 MW in discussions related to the establishment of research and development items and basic infrastructure required for the development of next-generation innovative reactors by the Ministry of Education, Culture, Sports, Science and Technology-Japan (MEXT).[5] Based on these considerations, the thermal power of the HTR-F should be in the range of 250 to 300 MW.

The HTR50S (50MW small-sized high temperature gas cooled reactor)[6] is a HTGR with thermal power of 50MW and its conceptual design was performed based on the proven technology of the HTTR. The HTR50S was designed to safely remove decay heat by radial radiation and heat transfer in a loss-of-coolant accident. The fuel region for radial direction in the HTR50S core consists of three fuel block layers and its average power density is 4.3 MW/m^3. Thus, the HTR-F core also consists of three fuel block layers in the radial direction of the fuel region, and the average power density is 4.3 MW/m^3, which is the same as that of the HTR50S, to safely remove decay heat in the accident. The upper limit of the reactor pressure vessel size is set to be 7.6 m from the viewpoint of fabricability based on conceptual design of the GTHTR300, and the equivalent diameter of the core is set to be about 4.3 m, considering the dimensions of the reflector area and core restraint mechanism outside the core radial direction. In order to achieve a thermal power of 250 to 300MW under these conditions, the reactor core shape of the HTR-F is decided to be an annular type with 78 fuel columns consisting of 12 stacked fuel blocks. **Figure 2** shows the horizontal cross-sectional view of the reactor core of the HTR-F. The fuel region of the reactor core is divided into eight regions according to the distance from the center of the core.

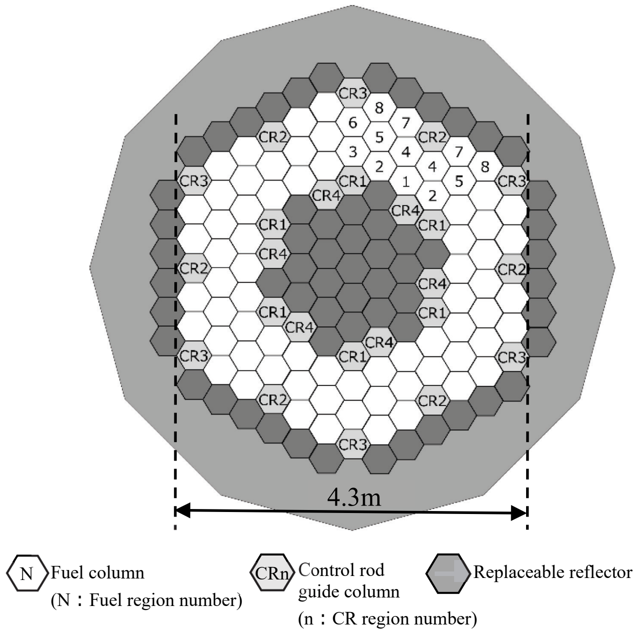

Fig.2 Horizontal cross-sectional view of the reactor core

3. Fuel and Burnable Poison

Figure 3 shows the configuration of the HTR-F fuel, whose specifications are the same as the HTTR. The fuel compact contains about 13,000 coated fuel particles, which have the function of preventing the release of fission products from the fuels to the coolant. The fuel rod consists of 14 fuel compacts enclosed in a graphite sleeve made of IG-110. Two kinds of fuel enrichments are used to ensure a uniform power distribution in the radial direction. The fuels with 6.7 wt% and 9.8 wt% enrichment is loaded in fuel regions 1-3 and 4-8, respectively.

Rod-type burnable poisons (BP) are used to reduce the effective multiplication factor during the burnup period. The rod-type BP is made of boron carbide, with a boron concentration of 1.2 wt% and a diameter of 2.4 cm. One or two rod-type BPs are loaded in each fuel block so that the distance between the rod-type BPs in adjacent fuel blocks are not close.

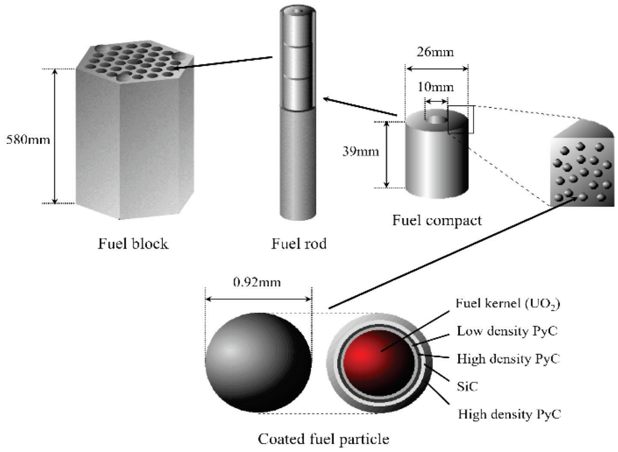

Fig. 3 Fuel configuration of the HTR-F

4. Control Rod

The CRs are inserted into the core from the upper region of the reactor core to the bottom of the fuel region through vertical holes placed in the CR guide columns. Figure 2 shows the CR arrangement and there are total of 42 CRs: 18 pairs of 36 CRs (CR1, CR2 and CR3) and 6 CRs alone (CR4).

Ⅲ. Design Requirements and Targets

1. Nuclear and Thermal Characteristics

The nuclear characteristics is confirmed, including reactor shutdown margin, excess reactivity, average discharge burnup, maximum fuel temperature under normal operation and temperature coefficient of reactivity.

(1) Shutdown Margin

The shutdown margin must be more than 1 %Δk/k and it is determined by the following equation.

$$\rho_0 = (1-k)/k \quad (1)$$

where ρ_0 is shutdown margin and k is the effective multiplication factor when all CRs are fully inserted into the core under room temperature conditions, except for one CR with the maximum reactivity.

(2) Excess Reactivity

The target value of the effective multiplication factor is set to be less than 1.05 during the burnup period, as in the conceptual design of the GTHTR300, to reduce the insertion depth of the CRs in to the core.

(3) Burnup

The target value of the average discharged fuel burnup is set to the same level as the 45 GWd/t of the current light water reactors.

(4) Temperature Coefficient of Reactivity

The temperature coefficient of reactivity must be a negative value during the burnup period to provide negative reactivity feed-back characteristics. The temperature coefficient of reactivity is calculated by following equation,

$$TC = \Delta\rho/\Delta T \quad (2)$$

where *TC* is the temperature coefficient of reactivity. $\Delta\rho$ represents the change in reactivity when the temperature of the core is increased by ΔT.

(5) Fuel Temperature and Power Distribution

The maximum fuel temperature must not exceed 1600 ºC to prevent fuel failure under any anticipated operational occurrence conditions.[2)] To satisfy this requirement, the fuel temperature limit for normal operation condition is determined in the same way as the HTTR design and is specified as 1493ºC.[7)]

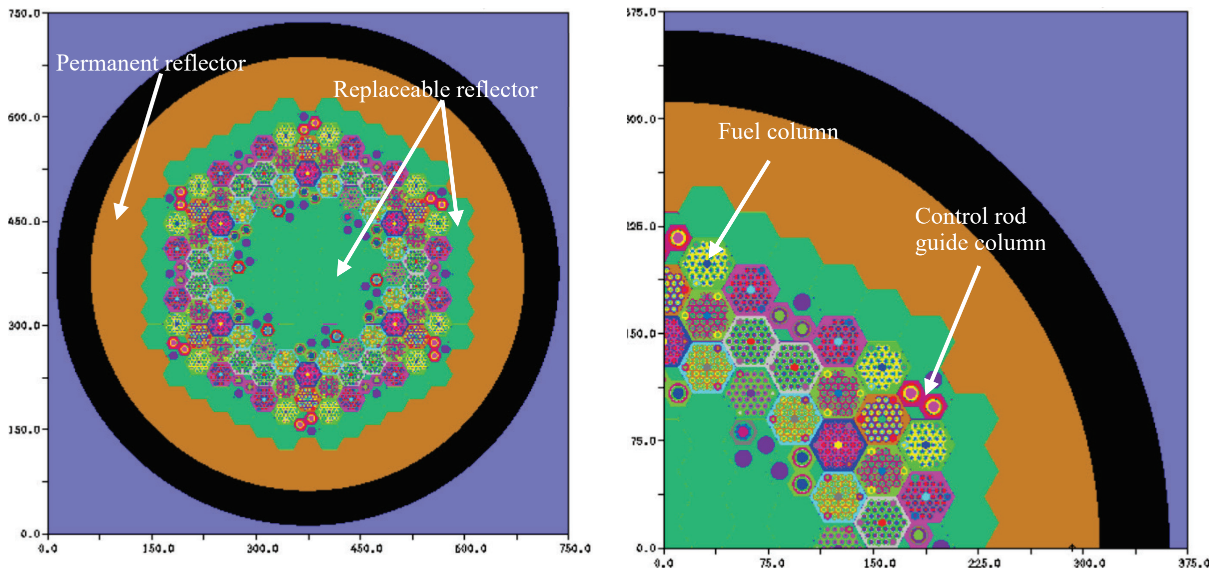

Fig.4 Horizontal cross section of 3D whole core model of HTR-F

2. Calculation Method

The whole-core burnup calculations are performed using a Continuous-Energy Monte Carlo Burn-up Code MVP-BURN[8)] and the neutron cross-section set based on the Japanese Evaluated Nuclear Data Library-4.0 (JENDL-4.0).[9)] **Figure 4** shows the horizontal cross section of the 3D whole core model of the HTR-F drawn by the CGVIEW, which is a program to draw cross-sectional views of MVP-BURN calculation geometry. For that model, the axial direction is modeled to the upper and lower reflectors, and the radial direction is modeled to the fixed reflector. The total number of histories for the MVP-BURN calculation is decided so that the statistical error (3σ) of effective multiplication factor is less than 0.1%.

The temperature of the inner surface of the fuel compact are calculated by calculating the temperature of the coolant flowing downwards in the core and the heat transfer to the graphite block, compact, etc. with the calculation results of the power distribution[10)] in the core at each burnup step.

IV. Results

1. Shutdown Margin

In Eq. (1), since k is 0.981, the reactor shutdown margin is determined to be 1.94 %Δk/k, exceeding the design requirement of 1 %Δk/k even if the CR of CR2 as shown in Fig. 2, which has the maximum reactivity worth is completely withdrawn.

2. Excess Reactivity

Figure 5 shows the calculation results of the effective multiplication factor. The maximum value is 1.049, which occurs at 20 GWd/t. The multiplication factor is less than 1.05 during the burnup period, which satisfies the target value, and the excess reactivity is maintained small.

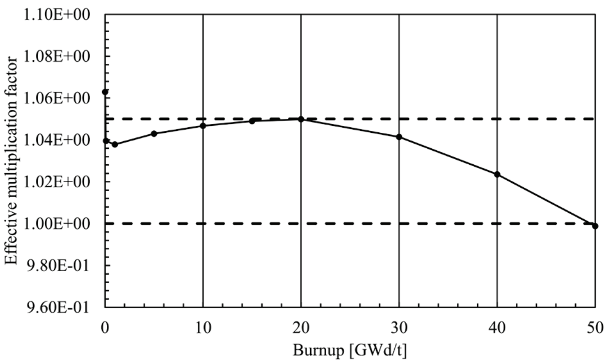

Fig.5 Change in the excess reactivity in rated power operation state

3. Burnup

The discharged fuel burnup is defined as the period when the effective multiplication factor is greater than 1.0 in **Fig. 5**, and its value is 45 GWd/t, which satisfies the target value.

4. Temperature Coefficient of Reactivity

Figure 6 shows the calculation result of the temperature coefficient of reactivity satisfying the design requirement of negative value during the burnup period. However, these results are obtained when the temperature of the entire core, including the fuel and reflector, is raised by 100°C. In the future, it will be necessary to investigate cases where the temperature increase is applied only to the fuel, only to the reflector, or other specific regions individually.

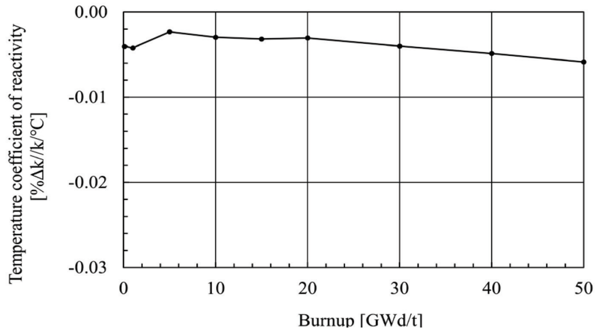

Fig. 6 Burnup change of temperature coefficient of reactivity

5. Fuel Temperature and Power Distribution

Figures 7, **8** and **9** show the calculation results of fuel temperature and the power distributions at beginning of life (BOL), middle of life (MOL) and end of life (EOL). By using two different enrichment fuels, the power density is approximately uniform in the radial direction through the burn period. Since the uranium enrichment is uniform in the axial direction of the core, the power density becomes higher in the central region of the core during BOL and MOL. Therefore, the relative uranium enrichment becomes higher in the upper and lower regions of the core during EOL. In addition, because the coolant flows from the top of the core, the temperature in the upper region becomes lower than that in the lower region, which is considered to result in a higher power density in the upper part of the core. The maximum fuel temperature during normal operation conditions considering systematic random factor,[10)] which is an engineering safety factor to account for design uncertainties, is 1301°C, occurring in the 4th layer of the fuel region 7 at BOL. However, since these are the results with the CR fully withdrawn, the calculated temperatures are lower than the actual temperatures with the CR inserted during operation. In a more detailed study to be conducted in the future, it will be necessary to calculate the maximum fuel temperature with the CR inserted during operation and confirm that the temperature is lower than 1493°C and satisfies the design requirements.

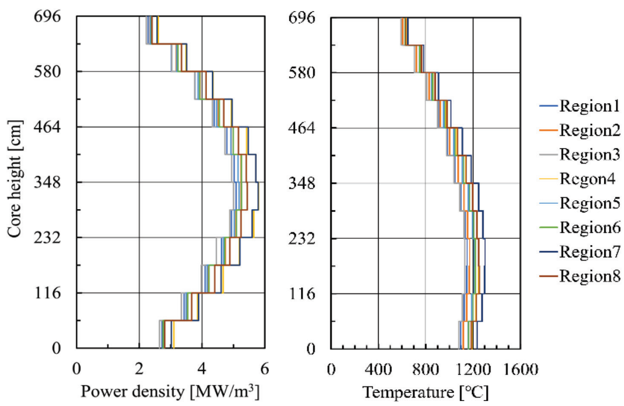

Fig. 7 Calculation results of power density and temperature at BOL

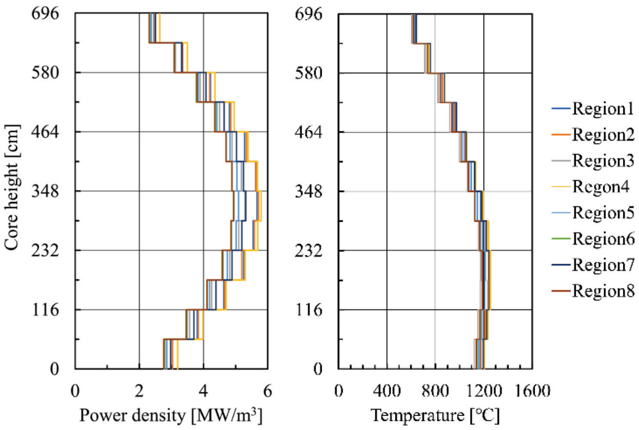

Fig. 8 Calculation results of power density and temperature at MOL

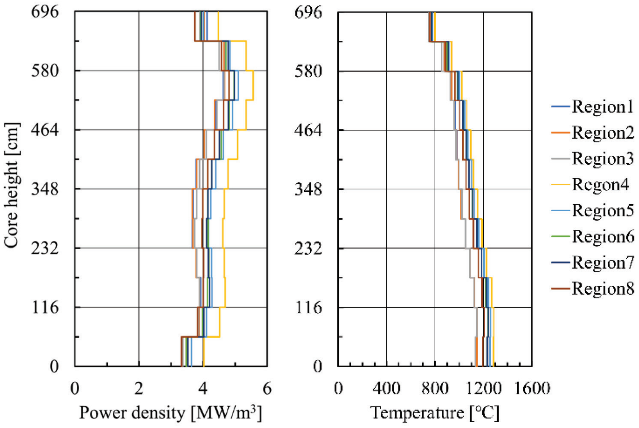

Fig. 9 Calculation results of power density and temperature at EOL

V. Conclusion

A preliminary nuclear thermal design of the HTR-F, a demonstration-scale HTGR reactor, was performed. The HTR-F has a thermal power of 260 MW, and an annular core was adopted so that decay heat can be safely removed even in the event of an accident.

The reactor shutdown margin under one-rod stack and room temperature conditions is 1.94 %Δk/k, which satisfies the design requirement of more than 1%Δk/k. By loading each fuel block with rod-type BPs whose concentration and shape are adjusted, the effective multiplication factor is less than 1.05 during the burnup period, and the excess reactivity is maintained small. The discharged fuel burnup of 45 GWd/t is achieved, which is equivalent to the burnup of current light water reactors. The power density in the radial direction could be homogenized by using two kinds of enrichment. The maximum fuel temperature calculated using the homogenized power distribution is 1301°C with CR fully withdrawn, which is below the target value of 1493°C during the burn period.

These results provide sufficient prospect for the feasibility of HTR-F. Based on the results of this study, the University of Fukui plans to conduct the conceptual design of the HTR-F and research and development of high burnup and high power HTGRs.

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