Comparative study on core designs of an annular, prismatic HTGR for passive decay heat removal

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Abstract: In the present work, we have designed annular cores of HTGRs in which the number of inner reflector blocks were one, seven and nineteen. The power of these reactors was the same as 100 $\mathbf{MW_t}$, as well as the number of fuel blocks in core and core size were the same. Then the fundamental neutronic analyses of those uniform cores for criticality and burn-up were performed using the continuous energy Monte Carlo code MVP2.0 and MVPBURN with the nuclear data library of JENDL-4.0. Next, calculations by introducing uniformly distributed burnable poison particles to suppress the excess reactivity and to flatten the reactivity swing and power peaking factor (PPF) during core operation were performed and obtained the optimal condition.

Keyword: prismatic HTGR; inner reflector; nuclear energy, core design

1 Introduction

High temperature gas-cooled reactors (HTGRs) are capable of providing high temperature heat (1000^{o}**C**) for various industrial technologies and electricity generation. Therefore, safety feature of HTGR is provided by TRISO fuel which has high temperature resistant ceramic layers, large heat capacity of graphite core, and inert helium gaseous as a coolant. So, the reactor core temperature rises gradually and the accident probability could be very low. Since HTGRs use TRISO fuel particles, the reactor can safely operate during normal and abnormal conditions by keeping the fission products inside TRISO particles. The TRISO fuel discharged burnup is higher than that for Gen II, III reactors which is significant for uranium economy [1].

In our previous works, we performed core design of an annular, prismatic HTGR for passive decay heat removal with power of 100 $\mathbf{MW_t}$ and the fundamental neutronic analyses were carried out as well as the results were compared with those for solid cylindrical reactor core [2][3]. The annular core has one inner reflector block per layer. Those calculations were performed using the continuous energy Monte Carlo codes of MVP2.0 [4] and MVP-BURN [5] with the nuclear data library of JENDL-3.3 [6]. Our center has just received the new version of nuclear data library JENDL-4.0 [7] in the beginning of this year. The objective of this work is as followings: a) it is needed to upgrade the neutronic results for the above-mentioned annular HTGR core using the JENDL-4.0 [7]; b) to reveal the influence of inner reflector thickness on neutronic parameters of the core without changing reactor power and the number of fuel blocks; c) to perform the analyses for suppression of an excess reactivity and for flattening reactivity swing of the uniform core during operation by introducing burnable poison particles (BPP_s) into the annular cores.

2 Design concept

The annular HTGR cores with different number of inner reflector blocks consist of several types of prismatic hexagonal blocks as fuel blocks, control rod (CR) blocks and reflector blocks which are piled up as cylindrical core. The configuration of the all blocks was the same as that of the Japanese High Temperature Test Reactor (HTTR) core [8-12]. Horizontal cross sections of the cores and their constituting blocks were displayed in Fig.1 and Fig.2. The design parameter relationship of annular HTGR core for passive decay heat removal was determined by performing decay heat transfer analyses by using COMSOL multiphysics software [2][3]. Core

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dimensions were estimated from the design parameter relationship. Since the reactor core is composed of fixed-size hexagonal blocks of HTTR

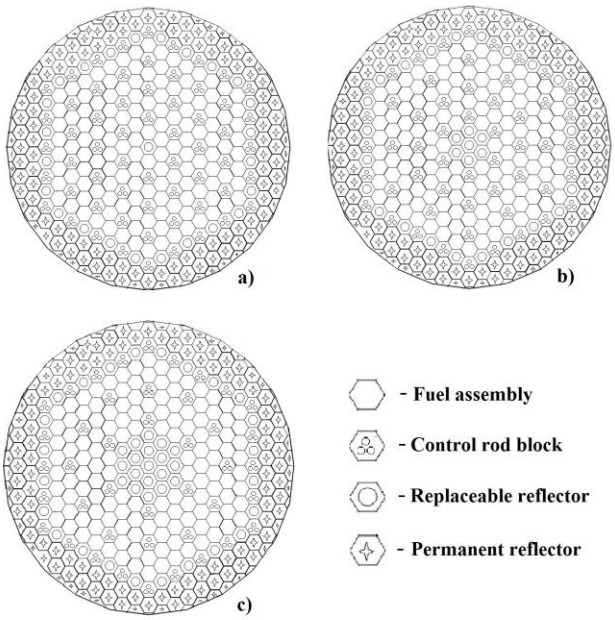

Fig.1 Horizontal cross sectional view of the annular reactor cores with: a) one inner reflector block. b) seven inner reflector blocks c) nineteen inner reflector blocks.

Table 1. Main specifications of annular cores

Thermal power, MW_{th}		100	
Core temperature, °C		850	
Inner reflector radius/pitch, m	0.18/0.36	0.5/1.08	0.8/2.52
Core outer radius/height obtained from heat transfer analyses, m	2.5/6.24	2.53/6.32	2.58/6.45
Equivalent outer radius/height of an active core, m	2.47/6.38	2.47/6.38	2.47/6.38
Average power density, W/cm^3		0.82	
Fuel		UO_2	
Enrichment, wt%		20%	
Coolant material		Helium gas	
Reflector thickness, m: Top/bottom/ Side		0.58/0.58/0.87	
Number of fuel blocks		1452	
Number of layers		11	
Number of CR blocks in one layer:			
Core	36	30	18
Reflector	24	24	24
Number of inner/outer reflector blocks	1/24	7/24	19/24

(Pitch - 36 **cm**, height – 58 **cm**) [8-12], the real dimensions of the core would be different from the ones estimated from heat transfer calculations. These dimensions were listed in Table 1 together with other main specifications of the cores.

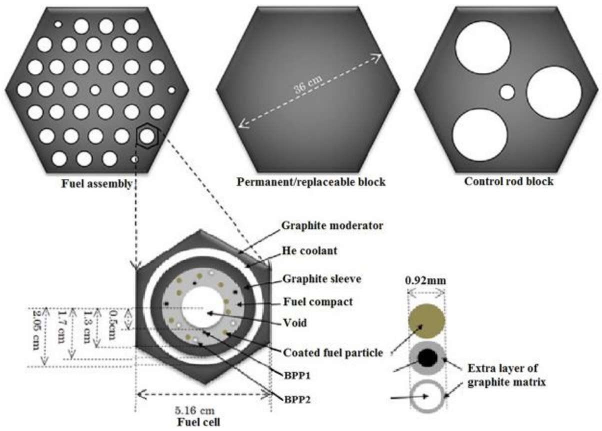

Fig.2 Configurations of blocks and fuel cell with two different BPPs.

3 Neutronic analyses

The fundamental neutronic analyses of the annular cores with different number of inner reflector blocks were performed using Monte Carlo codes of MVP2.0[4] and MVPBURN [5] with nuclear data library of JENDL4.0 [7] for reaction cross section at arbitrary temperature. All calculations were performed for whole-core, and the CRs were completely withdrawn from the core and replaced by helium gaseous. A packing factor for the coated fuel particles in the graphite matrix was chosen as 0.3. The most probable value of neutron multiplication factor (k_{eff}) was evaluated based on track length, collision, and analog estimators with the method of maximum likelihood [9]. The number of histories per batch was 50,000 for all cases and the number of batches was 100. The first 20 batches were neglected for the statistical treatments.

3.1 Influence of inner reflector

To reveal the influence of inner reflector thickness on neutronic parameters of the core without changing reactor power and the number of fuel blocks, the number of inner reflector blocks were increased from one to 7 and 19 and the criticality and fuel burnup analyses were conducted. The main results were compared in Table 2 and Fig.3.

It is shown that the effective neutron multiplication factor of the annular core with thicker inner reflector, the maximum of core reactivity during operation as well as discharged fuel burnup were decreased.

Table 2. Results from neutronic analyses of the proposed reactors

N	Radius of inner reflector, m	k_{eff} at BOC (% error)	Max Δk/k (%)	Core life (year)	Burnup at EOC, GWd/T
1	0.18	1.4977 (0.0183)	33.23	26.4	106.0
7	0.5	1.4789 (0.0182)	32.38	25.3	103.0
19	0.82	1.4467 (0.0215)	30.88	24.7	99.2

Note:

N	Number of inner replaceable reflector blocks per layer
BOC/EOC	Beginning/ending of cycle

The reason for these reductions of neutronic parameters could be described by neutron flux throughout the cores and reaction rates in inner reflector and core region at BOC and EOC.

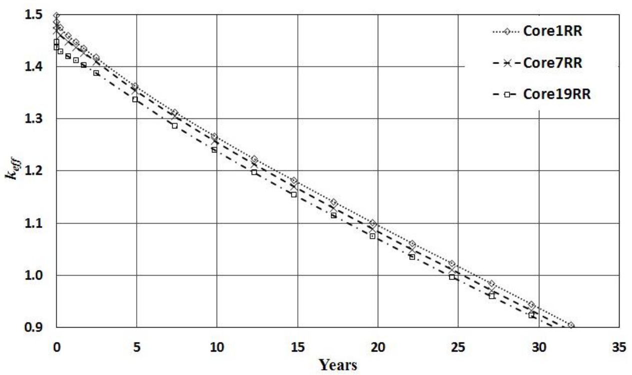

Fig.3 Change in effective neutron multiplication factors of the annular reactors as time.

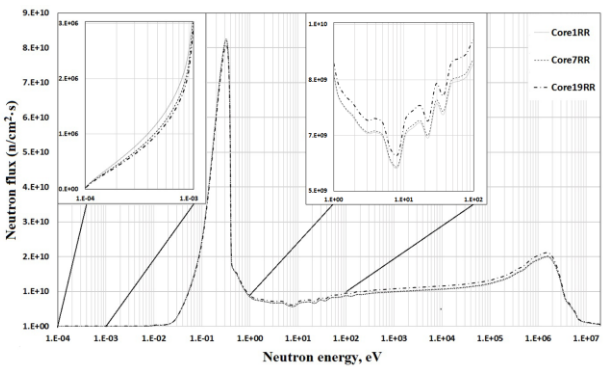

Fig.4 Neutron fluxes of the annular reactor cores with different number of inner reflector blocks at BOC.

The neutron fluxes of the annular reactor cores with different number of inner reflector blocks at BOC are shown in Fig.4. The thermal neutron flux (10^{-5} – 0.1 **eV**) of the annular reactor core with one inner reflector block is larger than that of other cores with thicker inner reflector blocks while the fast flux is smaller for the core with thinner inner reflector blocks.

Generally, the neutron migration length in graphite at 20 **ºC** is approximately 62 **cm** [13]. The thermal neutron diffusion coefficient does not depend on temperature, but the capture cross section is a function of temperature. Since annular HTGR core operation temperature is 850 **ºC**, the migration length of thermal neutron there could be less than 62 **cm**. Thus, the scattering probability of neutrons back into the core from the inner reflector could be decreased for cores with 7 and 19 inner reflector blocks per layer because its thickness becomes larger than the neutron migration length in it. Reaction rate ratios of capture to scattering in inner reflector region of the annular reactor cores at BOC are shown in Fig.5. The ratio in 10^{-5} **eV** – 100 **keV** energy region is higher for the core with thicker inner reflector while that in fast energy region is larger for the core with 7 inner reflector blocks per layer.

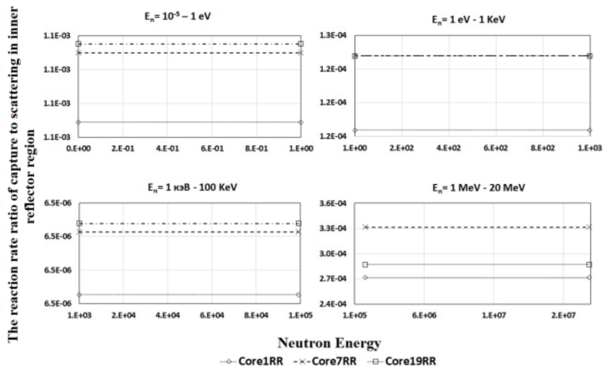

Fig.5 The reaction rate ratio of capture to scattering in inner reflector region of the annular reactor cores at BOC.

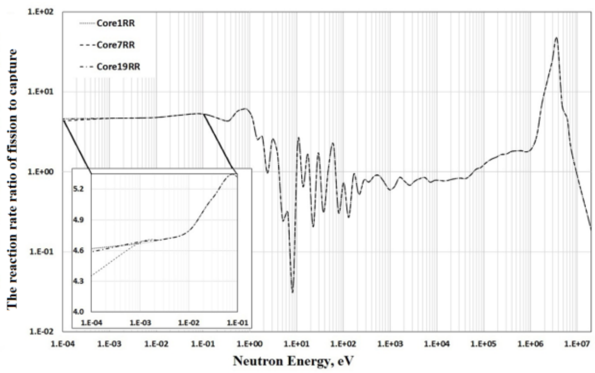

Fig.6 The reaction rate ratio of fission to capture throughout the core of various annular reactors at BOC.

As seen in Fig.6 the reaction rate ratio of fission to capture throughout the core with one inner reflector block at BOC is greater in energy region of 10^{-5} – 0.1 **eV**. Therefore, since the configuration of these three cores are not exactly the same by keeping the same number of fuel blocks as 1452, the ratios of interfacing surface area of fuel blocks and inner reflector blocks of the three annular cores are not equal as listed in Table 3. This ratio is smaller for the core with 7 inner reflector blocks so the thermal fission rate for this core at BOC was the smallest as shown in Fig.6.

Table 3. Ratio of interfacing surface area of fuel blocks and inner reflector blocks of the three annular cores

Reactor cores	$S_{fuel}/S_{inner\ reflector}$
Core1RR	1
Core7RR	0.67
Core19RR	0.80

It could say that since the thermal neutron flux is larger for the core with one inner reflector block (Fig.4), and the scattering rate in inner reflector region is greater than the capture rate there (Fig.5), the more fission reactions inducing by more scattered neutrons from the inner reflector (Fig.6) could be occurred throughout the core. So, the effective neutron multiplication factor at BOC for the reactor core with thinner inner reflector could be greater than that for the core with thicker inner reflector.

The reaction rate ratio of fission to capture throughout the cores at EOC was shown in Fig.7. Here, the trend of the reaction rate ratio shown in Fig.6 is similar with that in Fig.7, so that the fuel burnup and core lifetime are higher for the core with thinner inner reflector.

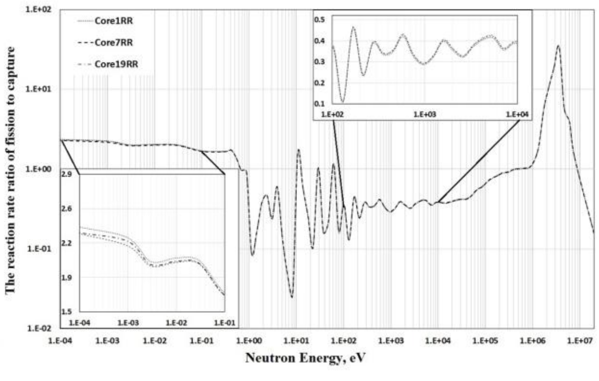

Fig.7 The reaction rate ratio of fission to capture throughout the core with various annular reactors at EOC.

3.2 Suppressing of the excess reactivity

As seen in the previous section, the excess reactivity (**Δk/k**) at BOC was very high. There are many ways to reduce excess reactivity during reactor operation and in our previous work of solid cylindrical reactor core [14], BPPs were used in the proposed reactor design to minimize the excess reactivity and to control long-term reactivity during the burnup period. Moreover, it was shown that two different BPPs as B_4C and Gd_2O_3 were more efficient to flatten the reactivity swing as time [14]. So then these BPPs were also used in the annular reactor cores to suppress the excess reactivity. There are two main parameters which determine the BPP's content and size; diameter and volume ratio of fuel to BPP. They are free parameters which are changeable to optimize the concentration of BPPs in a core. The initial guess of the both parameters were chosen as the same as that used for the previous work [14] which are the diameter of 0.02 **cm** for B_4C and Gd_2O_3 and the volume ratio of fuel to BPPs of 140 and 490 for B_4C and Gd_2O_3, respectively. The BPPs were uniformly distributed and the fuel enrichment throughout the core was also the same in everywhere. However, these initial parameters were not the optimal ones, the more neutronic analyses using MVP2.0, MVPBURN with JENDL4.0 library were conducted to find the optimal parameters by changing their values. The neutronic results together with BPP's parameters were presented in Table 4 and the effective neutron multiplication factors were displayed in Fig.8 as well as power peaking factors (PPFs) were depicted in Fig.9.

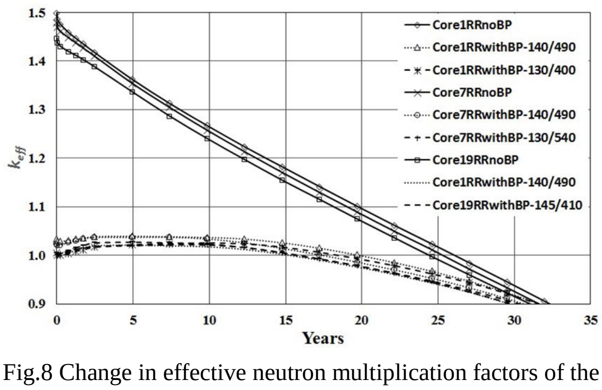

Fig.8 Change in effective neutron multiplication factors of the uniform cores of the proposed reactors without and with two BPPs as time.

The neutronic results say that the optimal parameters for BPP's content really depends on the core configuration, design and size, and it is possible to reduce the maximum excess reactivity from about 30 **% Δk/k** to 2 **% Δk/k** while maximum of the PPFs were increased slightly by introducing two different uniformly distributed BPPs into core.

Table 4. Specification of the optimized BPPs and calculations results for the annular reactor cores

N	BPPs: BPP_1 BPP_2	d_{BPP} (cm)	V_{fuel}/ V_{BPP}	Packing fraction of all particles, % (percentage of each particles, fuel, BPP_1, BPP_2)	k_{eff} at BOC (% error)	Max Δk/k (%)	Max PPF	Core life (year)	Burnup at EOC, GWd/T
1	NA	-	-	0.3000 (100 0 0)	1.4977 (0.0183)	33.23	2.87	26.4	106.0
	B_4C Gd_2O_3	0.02 0.02	140 490	0.3733 (80.37 15.27 4.36)	1.0337 (0.0312)	3.82	2.94	20.0	80.8
	B_4C Gd_2O_3	0.02 0.02	130 400	0.3813 (78.67 16.10 5.23)	1.0053 (0.0333)	2.49	3.05	18.4	74.8
7	NA	-	-	0.3000 (100 0 0)	1.4789 (0.0182)	32.38	3.02	25.3	103.0
	B_4C Gd_2O_3	0.02 0.02	140 490	0.3733 (80.37 15.27 4.36)	1.0238 (0.0302)	3.55	3.79	17.2	70.1
	B_4C Gd_2O_3	0.02 0.02	130 540	0.3762 (79.75 16.32 3.93)	1.0047 (0.07)	2.14	3.93	15.7	64.0
19	NA	-	-	0.3000 (100 0 0)	1.4467 (0.0215)	30.88	2.58	24.7	99.2
	B_4C Gd_2O_3	0.02 0.02	140 490	0.3733 (80.37 15.27 4.36)	1.0010 (0.0312)	0.10	2.52	0.02	1.0
	B_4C Gd_2O_3	0.02 0.02	145 410	0.3745 (80.11 14.69 5.20)	1.0051 (0.0233)	2.66	3.20	16.1	64.4

Note:
d_{BPP}- BPP particle diameter
V_{fuel}/V_{BPP}- volume ratio of fuel and BPPs in proposed cores

We have tried many calculations to reduce the maximum excess reactivity during operation less than 1**$**, but it was difficult by distributing fuel and BPPs uniformly throughout the cores. It would be performed the neutronic calculations by changing fuel enrichment and concentrations of the BPPs in the future.

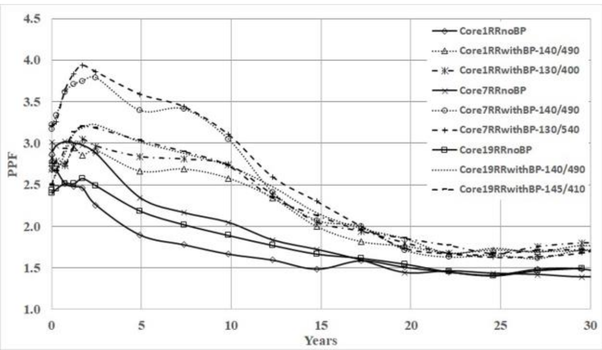

Fig.9 Change in PPFs of the uniform cores of the proposed reactors without and with two BPPs as time.

4 Conclusions

In this work, we have designed the annular HTGR cores with power of 100 $\mathbf{MW_t}$ in which the number of inner reflector blocks were one, 7 and 19 without changing the number of fuel blocks. Then the following conclusions were made using the obtained results:

1. It is shown that the annular core with thinner inner reflector has longer core life and higher fuel burnup.
2. The excess reactivity of the cores was successfully suppressed by introducing two different BPP_s into the cores. The optimal parameters of BPP_s were different for each core.
3. It is needed to perform the neutronic analyses for non-uniform cores to flatten the reactivity swing and PPF_s as time.

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References

[1] DAVID, A.: Modular High Temperature Gas-Cooled Reactor Safety Basis and Approach: INL/EXT-13-30872, 2001.

[2] ODMAA, S., JAMYANSUREN, T., TORU, O., NOROV, N., and MUNKHBAT, B.: Design parameters in an annular, prismatic HTGR for passive decay heat removal. Annals of Nuclear Energy, 2018,:441-448.

[3] ODMAA, S., JAMYANSUREN, T., and NOROV, N.: Core design analyses of an annular, prismatic HTGR for passive decay heat removal. Scientific Transaction of the National University of Mongolia, 2017, 25(478): 34-40. In Mongolian

[4] NAGAYA, Y., *et al.*: MVP/GMVP II: general-purpose Monte Carlo code for neutron and photon transport calculations based on continuous energy and multigroup methods. JAERI-1348. Japan: Japan Atomic Energy Research Institute, 2005.

[5] OKUMURA, K., *et al.*: MVP-BURN user's manual. Japan: Atomic Energy Agency, 2005.

[6] SHIBATA, K., *et al.*: "Japanese Evaluated Nuclear Data Library Version 3 Revision-3: JENDL-3.3," J. Nucl. Sci. Technol. 39, 1125(2002)

[7] SHIBATA, K., *et al.*: "JENDL-4.0: A New Library for Nuclear Science and Engineering," J. Nucl. Sci. Technol. 48(1), 1-30(2011).

[8] HAYASHI, K., *et al.*: Assessment of fuel integrity of HTTR and its permissible design limit. JAERI-M-89-162. Japan: JAERI; 1989

[9] SAITO, S., *et al.*: Design and safety consideration in the HTTR. Energy 1991; 16(1/2): 449-458.

[10] SAITO, S., *et al.*: Design of HTTR. JAERI-1332. Japan: Japan Atomic Energy Research Institute; 1994.

[11] SHIOZOWA, S., *et al.*: Overview of HTTR design features. Nucl. Eng. and Design 2004; 233: 11-21.

[12] Evaluation of HTGR Performance: Benchmark Analysis Related to Initial Testing of the HTTR and HTR-10, IAEA-TECDOC 1382. IAEA: Vienna; 2003.

[13] LAMARSH, J.R.: Introduction to Nuclear Reactor Theory. Textbook. American Nuclear Society. 2001

[14] ODMAA, S., and OBARA, T.: Neutronic and thermo-hydraulic analyses of a small, long-life HTGR for passive decay-heat removal. Journal of Nuclear Science and Technology, 52, Issue 12, 2015, pp1519-1529. http://dx.doi.org/10. 1080/00223131.2015.1017546