Preliminary neutronic analyses on VHTR core design

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Abstract: In the present work, we have focused to design an annular and solid cylindrical prismatic, very high temperature reactor core (VHTR). The fundamental neutronic analyses using the continuous energy Monte Carlo code MVP2.0 and MVPBURN with the nuclear data library of JENDL-4.0 are carried out for the core with power of 100 **MW$_{th}$**. In the study, it was used the advanced TRISO fuel with a solid layer of ZrC deposited over the kernel in which ^{235}U was enriched by 20% of. The preliminary neutronic results are compared between the cores operating at temperature of 850**°C** with and without ZrC additional layer and it shows that the effective neutron multiplication factor in BOC and discharged burnup are increased, while a core lifetime is reduced due to existence of the ZrC layer. Therefore, neutronic feature of an annular prismatic VHTR core with ZrC-containing TRISO fuel is improved for long term operation as higher fuel burnup in effect of inner reflector.

Keyword: VHTR; ZrC-Containing TRISO; neutronic analyses

1 Introduction

In the recent years, the advanced and safety core design have been intensively studied by scientists in universities and research centers in the world. Reactor core design with inherent passive safety feature has been receiving a special attention worldwide because of Fukushima Daiichi nuclear power plant accident in 2011. Very High Temperature gas-cooled Reactor (VHTR) has been studying as one of Gen-IV reactors. VHTRs use an advanced TRISO fuel particles with several coating layers in which the additional ZrC layer is deposited on the fuel kernel. Due to the advanced ZrC-containing TRISO fuel, its mechanical properties do not change at high temperature and the additional ZrC layer acts as a barrier against the diffusive release of fission products [1]. Therefore, the accident likelihood from normal and abnormal operating conditions could be very small due to its high specific capacity of graphite core and inert helium gaseous as a coolant [2]. The principal function of these coating layers is to retain fission products within the particle and to resist high temperature till 1600**°C** [3].

In our previous papers, we had studied the dependence of design parameters of a solid and an annular prismatic HTGR which can remove decay heat by passive ways [4][5]. The dimension of VHTR core was determined from the above dependence. The purpose of the present work is to design a solid and an annular cylindrical, prismatic VHTR cores and to compare the obtained results with those for HTGR cores as well as to perform their preliminary neutronic analyses by changing several parameters in geometry, the operating condition and material.

2 Methodology

2.1 Design concept

Both cores of solid and annular cylindrical VHTRs consist of hexagonal blocks for fuel, control rod and reflectors, and these blocks are piled up cylindrically to form the core. Design, configuration and size of the block is the same as those of the Japanese High Temperature Test Reactor (HTTR) core [6][7][8][9]. A horizontal cross sections of both cores are displayed in Fig.1 and their main specifications are listed in Table 1.

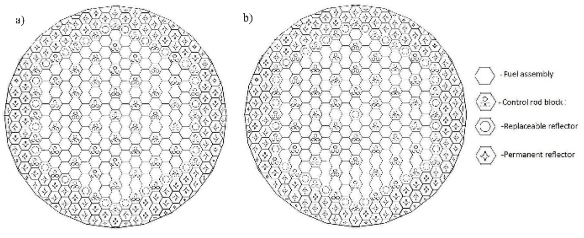

Fig.1 Horizontal cross section of the both proposed reactor core configuration a) solid cylindrical core b) annular cylindrical core.

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Table 1. Main specifications of cores

Specifications	Solid cylindrical VHTR	Annular cylindrical VHTR
Thermal power, $\mathbf{MW_{th}}$	100 [4] [5]	
Core temperature, **ºC**	850 [4] [5]	
Effective height of an active core, **m**	6.38 [4]	6.38 [5]
Equivalent outer radius of an active core, **m**	2.46 [4]	2.47 [5]
Inner reflector radius/pitch, **m**	0 [4]	0.18/0.36 [5]
Top and bottom reflector thickness, **m**	0.58 [4] [5]	
Side reflector thickness, **m**	0.39 [4]	0.87 [5]
Average power density, $\mathbf{W/cm^3}$	0.82	
Coolant material	Helium gas	
Fuel	UO_2	
Fuel enrichment, **wt%**	20	
Total number of fuel blocks	1452	
Number of layers	11	
Total number of CR blocks in core/outer reflector	407/264 [4]	396/264 [5]
Number of inner/outer reflector blocks	0 [4]	11/264 [5]

Dimensions of both cores were determined from parametric conditions which were obtained in our previous works [4][5].

2.2 Fuel design

The main issue of Gen IV reactor operation is the fuel concept. The fuel concept of VHTR considered in the present work is an advanced TRISO which has an additional layer of ZrC on the fuel kernel as shown in Fig.2. Here, the names of constituting layers and radiuses after each layer of TRISO coated fuel particle are also given. We chose ZrC layer thickness as 20 **µm**. This concept was already tested at high temperature up to 1446**ºC** in 500 days under neutron irradiation and both volatile and non-volatile fission products were not released from the advanced TRISO and therefore, its mechanical and safety feature were not degraded at all [1].

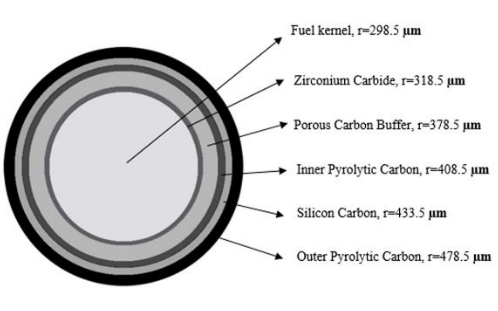

Fig.2 The horizontal cross section of the advanced TRISO particle.

2.3 Neutronic analyses

The neutronic analyses of both cores of the solid and annular cylindrical VHTRs are performed to confirm the possibility of designing a long-life VHTR core with high burnup by using Monte Carlo codes of MVP2.0 [10] and MVPBURN [11] with JENDL4.0 [12] nuclear data library for neutron cross section at arbitrary temperature. In the analyses, the all control rods are withdrawn from the core and their locations are filled with the helium gaseous. We have chosen a packing factor of 0.3 for the coated fuel particles in the graphite matrix. Total packing fraction of all spherical particles probabilistically placed in the spatial region for the STGM including coated fuel particles. The most probable value for the neutron multiplication factor (k_{eff}) is evaluated based on track length, collision and analog estimators with the method of maximum likelihood. The number of histories per batch was 50,000 for all analyses and the number batches was 100 and the first 20 batches were neglected for the statistical treatments. The statistical error of k_{eff} was less than 0.03% for all calculations. This calculation condition was the same with that was used in our previous works [4] [5] and it was chosen after performing many calculations to find the appropriate calculation condition that can give the result with high enough accuracy and small enough error.

3 Results and discussions

The results obtained from the fundamental neutronic analyses for both cores of the solid and annular cylindrical VHTR with power of 100 $\mathbf{MW_{th}}$, operating at temperature of 850**ºC** using the continuous energy Monte Carlo code MVP2.0 [10] and MVPBURN [11] with the nuclear data library of JENDL-4.0 [12] are shown in Table 2 and Fig.3a, 3b and 4a, 4b. In the analyses, it is used the advanced TRISO fuel with a solid layer of ZrC deposited over the kernel in which ^{235}U is enriched by 20% of. The results for the corresponding HTGR cores which use the conventional TRISO particles are also listed for the comparison. There are two different results of annular cylindrical HTGR cores that have TRISO particles without additional ZrC layer as presented in Table 2. These are results used nuclear data library of JENDL-3.3 [4] and JENDL- 4.0 [13], respectively.

Results in Table 2 and Fig.3a, 3b, 4a, 4b show that the effective neutron multiplication factor in BOC and discharged burnup was increased, while core lifetime was reduced due to existence of the ZrC layer on TRISO particle. Since neutronic results are improved due to existence of inner reflector, the next analyses are done for annular reactor cores. The discussion on inner reflector influence was already discussed in our previous work for annular HTGR core with conventional TRISO particles [5].

Table 2. Results from neutronic analyses for cores with and without ZrC additional layer on TRISO particles

Core type	ZrC layer on TRISO	k_{eff} in BOC (error SD (%))	Core life (year)	Burnup at EOC (GWd/t)
Solid cylindrical HTGR core	No [4]	1.4862 (0.0205)	25.4	100.0
	Yes	1.4921 (0.0228)	22.8	106.0
Annular cylindrical HTGR core	No [5]	1.4934 (0.0102)	34.0	144.0
	No [13]	1.4977 (0.0183)	26.4	106.0
	Yes	1.5025 (0.0207)	23.4	108.0

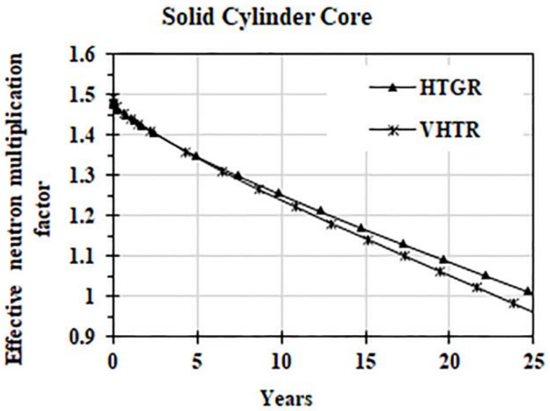

Fig.3a Change in effective neutron multiplication factors of solid cylindrical HTGR and VHTR as time.

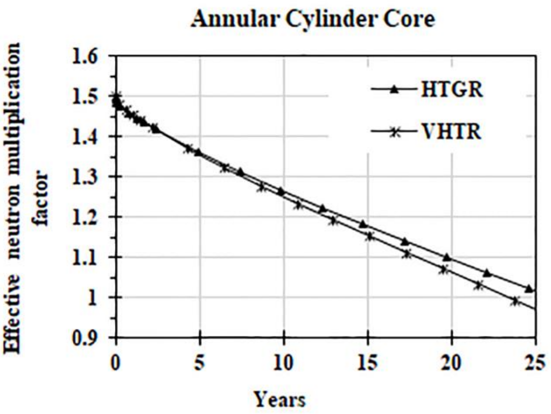

Fig.3b Change in effective neutron multiplication factors of annular cylindrical HTGR and VHTR as time.

Therefore, neutron fluxes and fission reaction rates throughout the annular cylindrical HTGR cores with and without ZrC layer on TRISO particles were compared and discussed to describe these results.

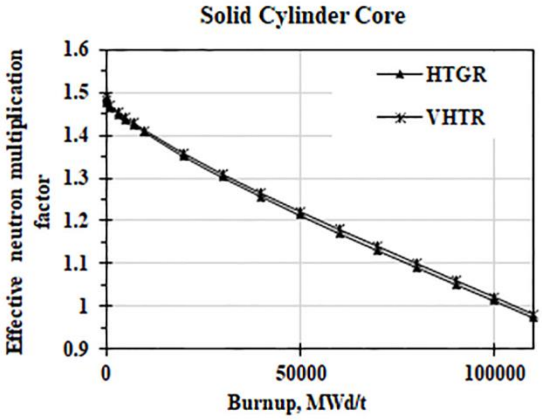

Fig.4a Change in effective neutron multiplication factors of solid cylindrical HTGR and VHTR as fuel burnup.

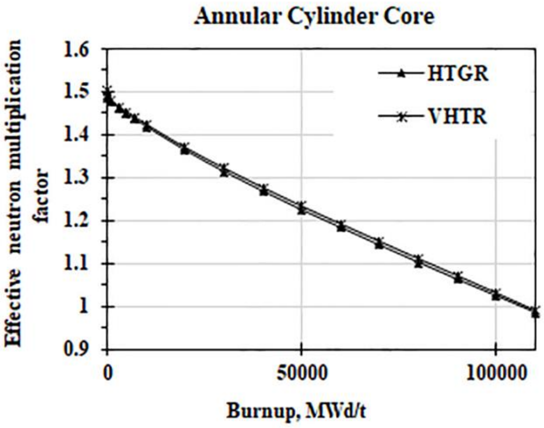

Fig.4b Change in effective neutron multiplication factors of annular cylindrical HTGR and VHTR as fuel burnup.

Neutron fluxes of both cores with and without ZrC additional layer on TRISO particles in BOC and EOC are compared in Fig.5a and 5b. It is shown that neutron flux is increased in all neutron energy region due to existence of additional ZrC layer nearby fuel kernel in both BOC and EOC. The ZrC layer serves here as a scatterer not an absorber. Figure 6a and 6b show the fission reaction rate of ^{235}U throughout the both cores in BOC and EOC. It says that higher fission reaction rate of ^{235}U occurs for core with advanced TRISO fuel particles since the neutron flux are higher due to existence of additional layer of ZrC. So then, the neutron multiplication factor in BOC is increased slightly for VHTR core compared to that for HTGR.

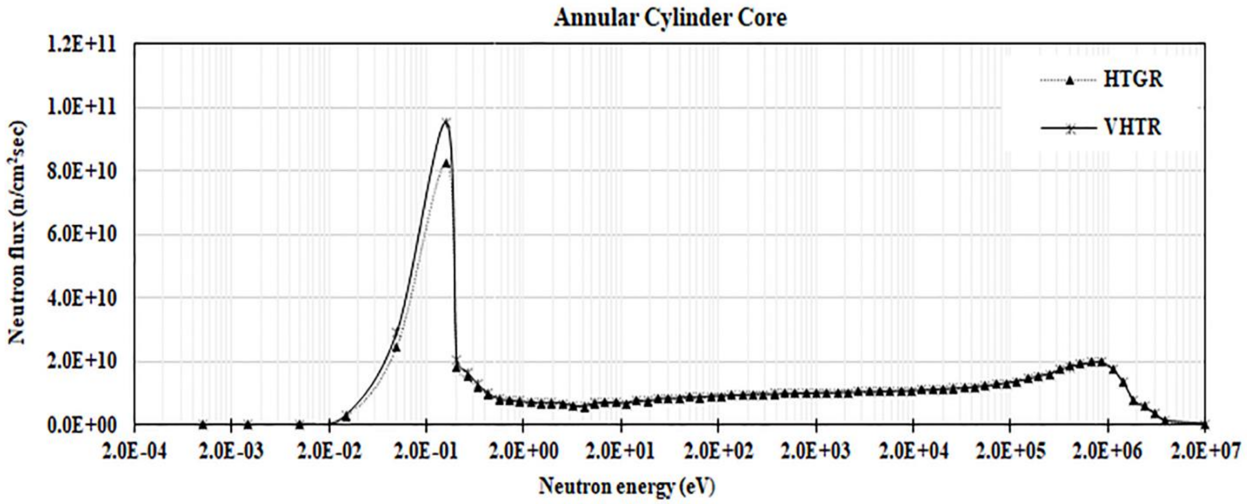

Fig.5a Neutron fluxes of annular HTGR and VHTR at BOC.

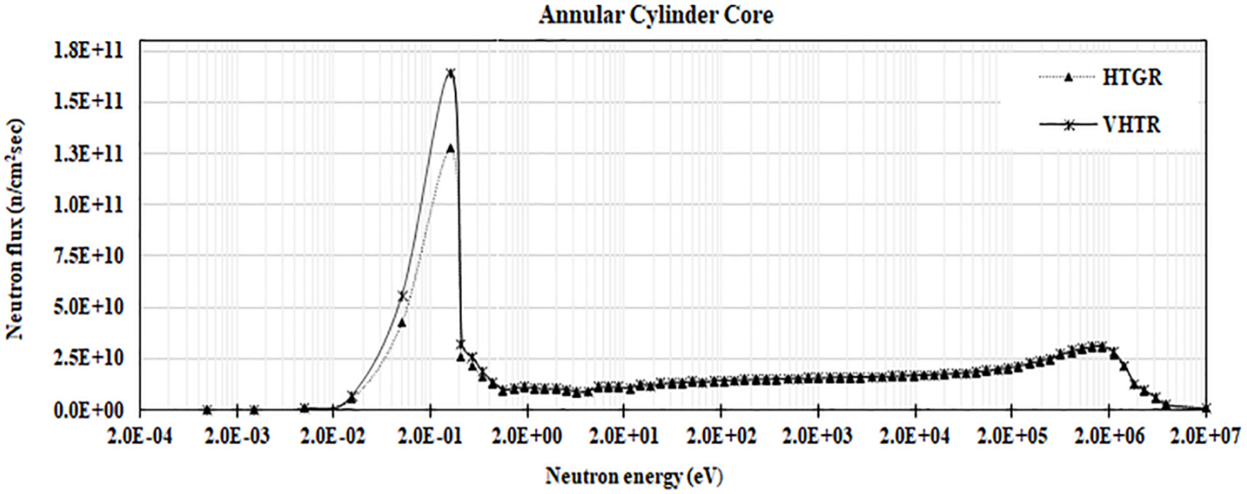

Fig.5b Neutron fluxes of annular HTGR and VHTR at EOC

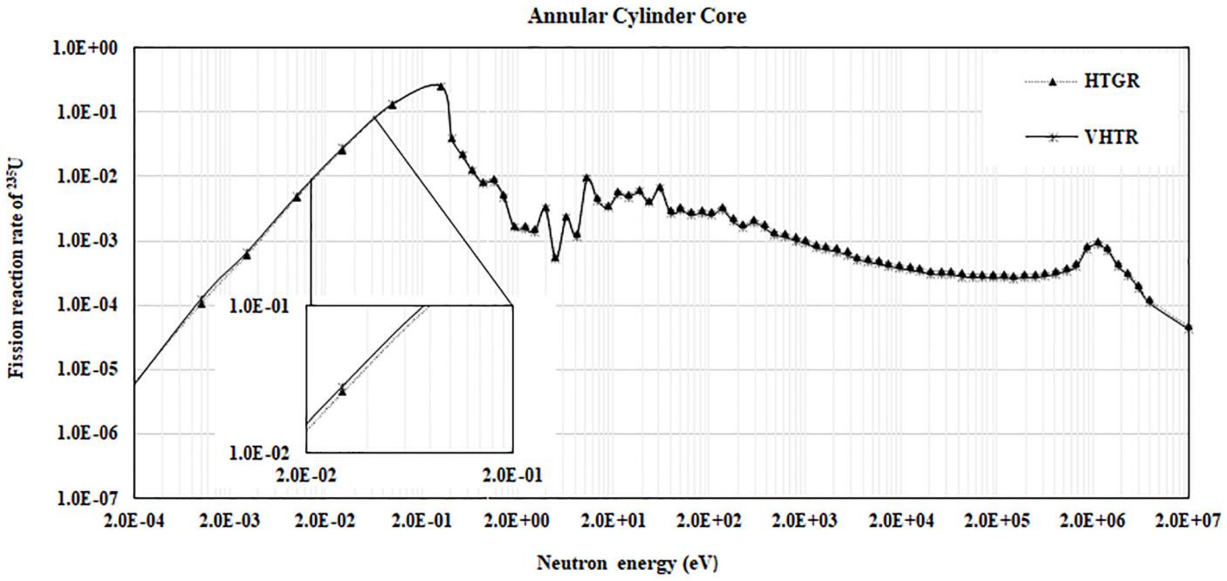

Fig.6a Fission reaction rates of annular HTGR and VHTR at BOC.

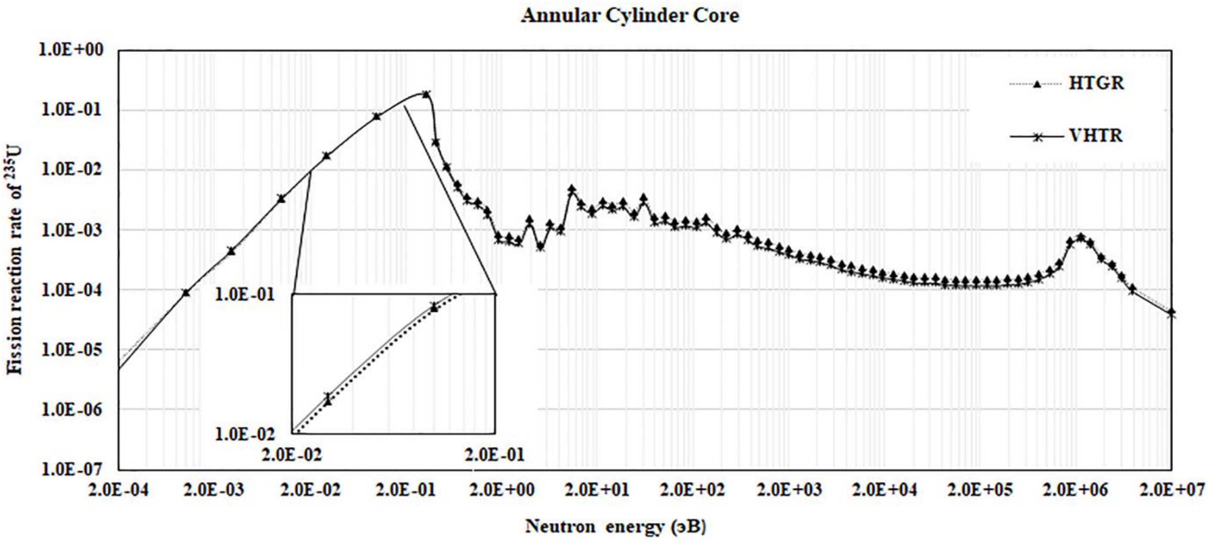

Fig.6b Fission reaction rates of annular HTGR and VHTR at EOC.

However, the fission reaction rate of ^{235}U by thermal neutrons in EOC of VHTR is still little higher since the neutron flux at EOC is slightly larger for VHTR.

So then, the fuel burnup of VHTR is higher than that of HTGR. The core lifetime is reduced considerably due to higher neutron flux for VHTR.

Since the core operating temperature of VHTR is higher than that of HTGR, it is needed to determine the neutronic parameters for the core operating at about 1227°**C** temperature. The effective neutron multiplication factor obtained from the calculation was shown in Fig.7 and it was reduced slightly due to reactivity of fuel Doppler effect.

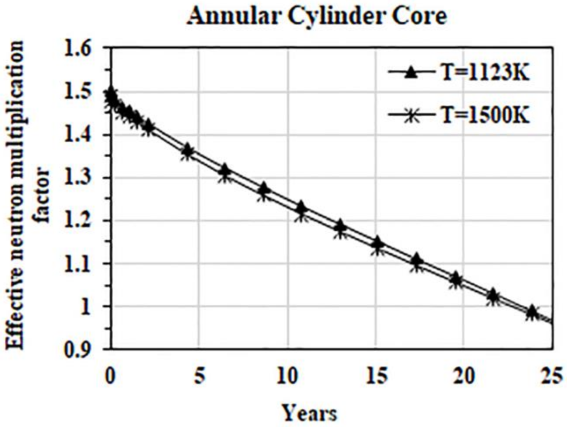

Fig.7 Changes in effective neutron multiplication factor of annular VHTR at different operating temperatures as time.

Next calculation was done to reveal the impact of thicknesses of ZrC layer on the neutronic parameters of the VHTR core by changing it as 10 **μm** and 40 **μm** rather than 20 **μm** results was listed in Table 3 and Fig.8.

Table 3. Results from impact of thicknesses of ZrC layer on the neutronic parameters of the annular prismatic VHTR core

Thicknesses of ZrC layer	k_{eff} in BOC (error SD (%))	Core life (year)	Burnup at EOC (GWd/t)
10 **μm**	1.5010 (0.0187)	24.7	107.0
20 **μm**	1.5025 (0.0207)	23.4	108.0
40 **μm**	1.5072 (0.0213)	20.9	109.2

It is shown that the core with thicker ZrC-TRISO has higher effective neutron multiplication factor at BOC and larger the discharged burnup at EOC while the core lifetime was reduced. It is described by the increases in neutron flux and reaction rate due to thicker ZrC layer.

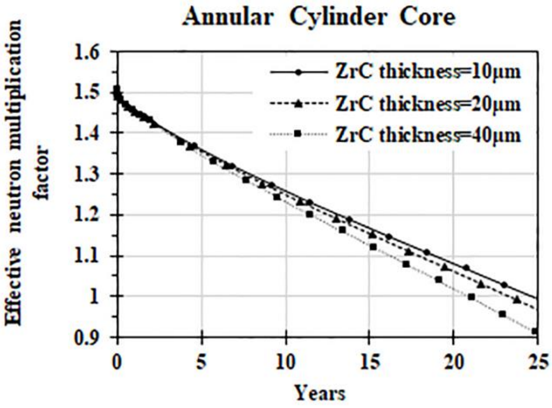

Fig.8 Changes in effective neutron multiplication factor of annular VHTR with different thicknesses of ZrC layer as time.

4 Conclusions

In the present work, we performed the preliminary neutronic analyses for an annular and solid cylindrical prismatic VHTR core with advanced TRISO fuel with a solid layer of ZrC deposited over the kernel and with power of 100 $\mathbf{MW_{th}}$ at operating temperature of 850°**C**. The effective neutron multiplication factor in BOC and discharged burnup were increased, while core lifetime was reduced due to existence of the ZrC layer. Neutronic features of an annular prismatic VHTR core with ZrC-containing TRISO fuel was improved for long term operation as higher fuel burnup in effect of inner reflector. The present work confirms that there is in a dilemma considering either slightly shortened core life or little higher discharged burnup to choose thicker or thinner ZrC layer on neutronic parameters of core. Therefore, it is needed to suppress an excess reactivity and to flatten the reactivity swing during core lifetime by optimizing fuel enrichment throughout the core as well as introducing burnable poison particles in the future work.

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