Neutronic Aspect Assessment on the use of ZrC Triso-Coated Particle (TRIZO) in a High-Temperature Gas-cooled Reactor (HTGR)

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Abstract. Neutronic calculation has been performed to high-temperature gas-cooled reactor (HTGR) that uses ZrC Triso-coated particle (TRIZO). TRIZO is the most reliable alternative to replace the SiC coating on coated fuel particles because of its superiority in resistance to high temperatures and resistance during the irradiation process. Neutronic aspect analysis of HTGR was carried out by calculating the k-inf and k-eff values on ZrC and SiC coating layers. The materials used were based on the Tri-isotropic (TRISO) coated particle standard used in HTTR 30 MWt, with uranium dioxide and thorium dioxide fuels based. The neutronic aspect with different fuels use ZrC coating layer is also investigated. The calculation shows similar behavior between thorium dioxide and uranium dioxide fuel with ZrC and SiC coating layer. The k-inf and k-eff with ZrC coating layer are lower than the SiC coating layer in both fuels. This value is related to the number of ZrC’s capture cross-section. Comparison between thorium dioxide and uranium dioxide fuel shows that thorium dioxide fuel has higher k-eff and k-inf with ZrC coating layer.

1. Introduction
High-temperature gas-cooled reactors (HTGR) are one of the promising candidates for Generation IV Nuclear Energy Systems. As an advanced type power reactor, HTGR has high thermal efficiency and a passive inherent safety system. This superior characteristic because HTGR uses heat-resistant materials and combined with helium as a coolant, causing the temperature to reach 900˚C. The coated fuel particle provides high thermal efficiency and the ability to have better retention of fission products. There are two forms of fuel elements that use the tri structural-isotropic (TRISO) concept, they are prismatic and pebble. In prismatic design, TRISO particles are compacted to increase the density of TRISO particles so that reactor efficiency and temperature will be increased. The prismatic element form is used in the High-Temperature Test Reactor (HTTR). HTTR is a helium gas graphite-cooled reactor with an output temperature of 950˚C and a 30 MWt thermal output operated by the Japan Atomic Energy Agency as a research reactor. This reactor was built to improve the basis of HTGR technology and conduct various irradiation tests for more innovative fundamental research.

The TRISO concept, which is a unique fuel design from HTGR, is a three-layer radial structure and a micro-spherical kernel-shaped fuel to obtain uniform (isotropic) properties. These layers are inner pyrolytic carbon (IPyC), silicon carbide (SiC), and outer pyrolytic carbon (OPyC). SiC layer is the
primary layer which has a function as a pressure barrier and diffusion barrier to prevent the release of gas and metallic fission products. Some alternative has been aimed to improve the performance of TRISO. One of the options is to replace SiC with ZrC. The weakness of the SiC layer seems at very high temperatures. The crystalline material formed in the SiC layer tends to decompose, and the silicon element evaporates then leaves the porous carbon structure. Internal gas pressure will be released because the remaining PyC layer is unable to endure the pressure. The investigation shows that fuel failure starts around 2200˚C, and almost all coated particles fail at 2600˚C. The failure is the reason for consideration to replace SiC with ZrC. ZrC has many superior characteristics compared to SiC including better resistance to pressure vessel failure, better performance against chemical corrosion by fission products including Palladium (Pd), and better retention of fission products especially at temperatures above 1600˚C [7]. The purpose of this paper is to compare the use of ZrC on HTGR with k-eff and k-inf parameter.

2. Description of the reactor

The High-Temperature Gas-cooled Reactor (HTGR) is a helium-cooled reactor with graphite moderator. The design is close to High-Temperature Engineering Test Reactor (HTTR). The primary design parameter is provided in Table 1. The thermal power output is 30 MWt, and the coolant outlet temperature is allowed to be 950˚C for high temperature conditions [5].

| Table 1. Parameter design of fuel pin in the reactor |
| Parameter                     | Specification          |
|-------------------------------|------------------------|
| Power                         | 30 MWt                 |
| Outlet Temperature            | 950˚C                  |
| Inlet Temperature             | 395˚C                  |
| Primary Pressure Coolant      | 4 MPa                  |
| Type of Structure             | Graphite               |
| Core Equivalent Diameter      | 2.3 m                  |
| Core Effective Height         | 2.9 m                  |
| Average Power Density         | 2.5 W/cm³              |
| Fuel                          | Thorium Dioxide, Uranium Dioxide |
| Enrichment U235               | 2-7 %                  |
| Burn-up Period                | 660 days               |
| Coolant                       | Helium                 |

3. Results and Discussion

The parameters used to comprehend the effect of replaced SiC with ZrC are multiplication factor (k-eff) and infinite factor (k-inf). Both are comparisons of the number of neutrons in one generation with previous generations. The fuel compact consists of coated fuel particles (CFPs) and graphite matrix. The geometry of compact is a hollows cylinder of 1.0 cm inner diameter, 2.6 cm outer diameter, and 3.9 cm in height. The highest and lowest enrichments are 9.9% and 3.4%, respectively [8].

The infinite multiplication factor (k-inf) for uranium dioxide with ZrC coating layer have been calculated as shown in figure 1.
Figure 1. Infinite multiplication factor (k-inf) uranium dioxide with TRIZO

The fissile material for UO2 fuel is U-235 and the fertile material is U-238. From the data of material, the amount of U-238 material is more than U-235. This greater amount of U-238 allows for the formation of new fissile material, Pu-239. The k-inf graph increases because of high neutron cross section value on Pu-239 which increase the number of neutrons. The infinite multiplication factor (K-inf) for thorium dioxide with ZrC coating layer have been calculated as shown in figure 2.

Figure 2. Infinite multiplication factor (k-inf) thorium dioxide with TRIZO

The fissile material on Th (UO2) is U-233 and the fertile material is Th-232. From the data of material, the number of Th-232 material is more than U-233. This greater amount of Th-232 allows for the formation of new U-233 fissile material caused by neutron catches by Th-232. Because the fissile material formed is the same as enriched fissile material (U-233), there is no increase in k-inf value at the beginning of the time interval.

The multiplication factor (K-eff) for uranium dioxide and thorium dioxide with ZrC and SiC coating layer have been calculated as shown in figure 3 and 4 respectively.
Both figures represent the multiplication factor of reactor using standard TRISO coated particles (SiC coating layer) and TRIZO coated particles (ZrC coating layer). The k-eff values of both uranium dioxide and thorium dioxide fuels, show the same behaviour. The fuels with ZrC coating layer have lower number of multiplication factor (k-eff) than the fuels with SiC coating layer. This is related to a neutronic point of view, however, Zr has higher capture cross-section (n, γ) as compared to Si [1]. The neutron is captured by ZrC more than SiC and as the result, the k-eff will be lower.

The comparison of multiplication factor (k-eff) for uranium dioxide and thorium dioxide with TRIZO coated particle have been calculated as shown in figure 5.
Figure 5. Comparison of Multiplication Factor (k-eff) TRIZO Uranium Dioxide dan Thorium Dioxide Fuel

It is known that in thorium dioxide fuel, fissile material used is U-233, while in uranium dioxide fuel fissile material used is U-235. From the cross-section data table, it can be seen that the value of the U-235 cross section capture is twice that of the U-233, while the cross-section fission value of both fuels is not much different. This causes at the beginning of the time interval, the probability of a neutron capture on U-235 is greater than U-233 so that the zero-day k-inf value of UO₂ is smaller than (Th, U) O₂.

Next after burning, fertile material will capture neutrons to turn into fissile material. Based on the cross-section data between Th-232 and U-238, the Th-232 capture cross section is much larger than U-238. This causes Th 232 to tend to capture neutrons and change to U-233 so that the k-eff value decreases. Besides that, the fissile material produced is the same as enriched fissile material, so the behaviour of k-inf graph tends to decrease. Unlike U-238 which turns into a new fissile material, Pu-239 with a cross section of fission greater than U-233, the probability of a fission reaction will be greater. Because of that reason the k-eff graph trend on UO₂ fuels tends to increase.

4. Conclusion

In summary, we have calculated and analyzed the neutronic aspect with the advanced coating layer using zirconium carbide (ZrC). ZrC has a superior characteristic compared to SiC, which is the ability to endure higher temperatures. Besides, ZrC has excellent properties, specifically good thermodynamic stability, and high melting point. The melting point of ZrC is around 3450 °C but can decrease to 2850 °C when interacting with carbon (PyC) which is a TRISO coating, while SiC decomposes at temperatures below 2000 °C. The calculation shows from the neutronic aspect, with the same parameter, the TRIZO coated fuel particle has lower k-eff than TRISO coated fuel particle. It is related to the properties of material used. However, the thermal-hydraulic and safety calculations are needed as a total evaluation of a good reactor design.

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