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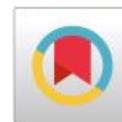## A knowledge Repository

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THE EFFECTIVENESS ANALYSIS OF FUEL BALL (KERNEL) DIMENSION SIZE AND URANIUM ENRICHMENT TO REACTOR REACTIVITY

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Abstract:

Reactor reactivity does not only depend on reactor diameter but also radius and enrichment of fuel ball (kernel) to operate reactor optimally. This research analyses effectiveness of kernel radius and enrichment to achieve critical reactor condition. The HTR in this research adopts HTR-10 China and HTR of pebble bed. The calculations are performed by using MCNPX code in each kernel radii of 320-350 μm and enrichments of 5-10% Uranium. Kernel is composed of Uranium Dioxide coated by four outer layers: Carbon, IpyC (Inner Pyrolytic Coating), SiC (Silicon Carbides) and OpyC (Outer Pyrolytic Coating). It is called TRISO and it is distributed in pebble-bed ball using Simple Cubic Lattice whereas pebble-bed and moderator balls are distributed in the core zone using a Body Centred Cubic (BCC) lattice by ratio of 57:43. The research results are obtained that the reactor will be effective to achieve critical condition in kernel radius of 325-330 μm at 9% Uranium enrichment and will be in supercritical condition if the reactor uses more than 330 μm of kernel radius and 9% enrichment of Uranium but the reactor will be subcritical if Uranium enrichment is 5-8%.

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1. INTRODUCTION

Many scientist attentions of reactor technology and nuclear energy in the world against the High Temperature Reactor (HTR) has increased in the past decade. The HTR utilizes graphite as the moderator at the same reflector and the fuel is a spherical particle (pebble-bed) with UO_2 composition as a neutron generator. This reactor uses helium as cooler of reactor. Due to the cooler has better hot transfer characteristic, the reactor has higher energy efficiency on

generation of electricity process. HTR also has other advantages like producing hot steam which can use to process Enhanced Oil Recovery, produce hydrogen and make liquid fuel form coal. In addition, HTR can save fossil fuel due to it can reduce CO_2 emission rate and pollution at atmosphere (Masdin, 2001) and one of the main factors that attract many people to study and develop HTR because it has capabilities to produce energy economically and inherent safety characteristics (Holbrook, 2008).

HTR is the types of gas-cooled high temperature reactor. HTR core design in this study is a blend HTR 10 in China with HTR pebble-bed. HTR design is a cylindrical with helium gas as a coolant and graphite as a moderator. In addition, the HTR uses pebble-bed fuel composed a large amount of particles of TRISO in graphite metrics. The concept of making that fuel is to obtain smaller fuels like coated particle which is able to not only save fissile product but also function as moderator because of graphite inside, so that temperature differences in fuel are small and the fuel cannot lead to a crack easily. TRISO particle is coated fuel particles by a radius of 175-300 μm and has 7-10% enrichment of UO_2 (Zuhair, 2012). It is coated by two until three pyrolytic carbide coats and added a silicon carbide coat (Rohanda, 2004). The shape of coat is showed in Fig.1 below. This TRISO will fill a pebble-bed using a lattice formation like shown in Fig.2 below.
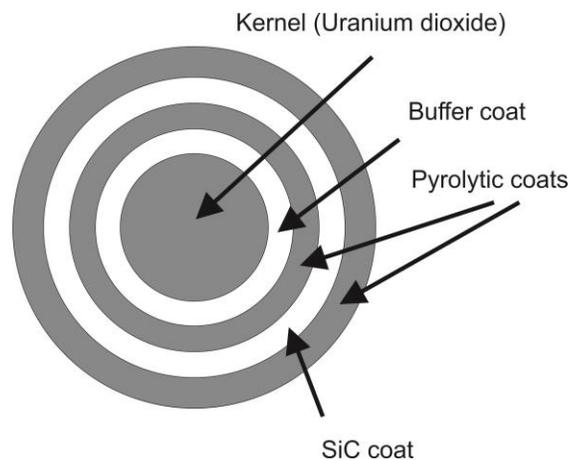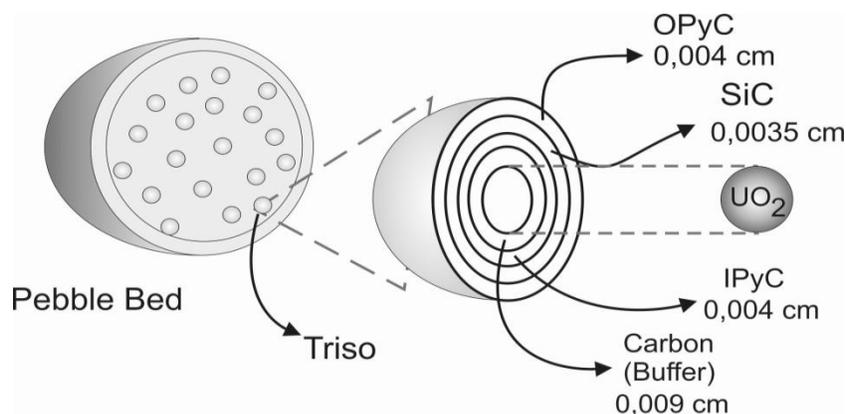

Figure 1: HTR fuel coated particles (TRISO)

Figure 2: Pebbele-bed and TRISO inside.

The kernel is a main fuel of uranium. The uranium will be enriched to increase fissile ratio in fuel. The enrichment is about increasing uranium-235 ratio from its natural ratio. The more enrichment of uranium is, the more uranium-235 in fuel is so that the fuel can be used for long times (Lewis, 2008). The enrichment process is done by gas diffusion. In the process, UF_6 is flowed through a coat which has small holes of 10^{-5} mm diameter. Uranium-235 has smaller diameter than the hole on coat, so that whole uranium-235 that through the holes are more than uranium-238. This process needs doing about 1500-1800 times to obtain the best enrichment of uranium (Akhadi, 1997).

A reactor in stable condition can be known from criticality value that is comparison of new whole neutron generations and old whole neutron generations. Critical condition can achieve if the criticality value of reactor is one. If the criticality value is more than one, it can make the reactor be supercritical and the reactor will be subcritical when the criticality value is less than one (Ridwan, 1978). This value is equal with reactivity value. The reactivity value shows that there is a change of whole neutron populations from generation to next generation. It also can consider knowing a reactor condition. If it is zero, the reactor will be in critical condition. The reactor will be in subcritical condition if the reactivity value is less than zero and if it is more than zero, the reactor will be in supercritical condition. When the reactor is in subcritical condition, the whole neutrons in reactor will decrease until the reactor shutdown. Besides, supercritical condition happens due to the whole neutrons in reactor increase uncontrollably. It can make the reactor temperature rise, so that control rod is used to control neutron increasing (Glasstone, 1967).

According to Hammam (2015) for HTR 10 MW that the larger radius is, the less enrichment of fuel needed to achieve critical condition. From other researches at same reactor, the reactor criticality is still in stable condition in each the rise of active core height from critical core height even though reactor reactivity increases 0.01 Δk/k and the minimum of pebble-bed and moderator needed to obtain critical condition is 11,805 pebbles and 8,906 moderators (Setiawati, 2015)

In HTR pebble-bed design, radius and enrichment of the fuel UO_2 (kernel) are a key parameter that can be chosen freely to determine the reactor reactivity. The value of reactor reactivity is a variable that describes the state of the reactor in order to operate optimally. Therefore, it is needed to simulate the reactor at different radius and enrichment of the kernel, so that is got the effective and enrichment to achieve critical condition in reactor.

2. MATERIALS AND METHODS

Materials used in this research were HTR10, HTR pebble-bed database and continuous energy nuclear data library ENDF/B-VII. Modelling of HTR uses the Monte Carlo code MCNPX. MCNP (Monte Carlo N-particle) is a general-purpose, continuous-energy, generalized-geometry, time-dependent, coupled neutron, photon and electron Monte Carlo transport code (Briesmeister, 1992). MCNP is also capable of calculating the multiplication factor (criticality) of fissile systems. This program has a good agreement both experimental and theoretical evaluations (Huda, 2008).

Criticality evaluations are done based on the principle of neutron balance. The number of neutrons in each generation is taken into account and comparison is made with the number of neutrons in the consequent generation. All possible mechanisms for the birth and loss of neutrons are accounted in bookkeeping. Thus, effective multiplication factor is evaluated for a given cycle. Each fission neutron is generated randomly out of possible locations containing fissile material. In order to generate statistical basis, simulations are repeated as many times as desired.

The initial step is to model the reactor core with diameter of 180 cm and height of 197 cm. Reactor core is surrounded by a graphite reflector, while the graphite reflector is surrounded by layer of boronated carbon bricks and core is filled by pebble bed and moderator balls. On the side reflectors near the active core there are ten boreholes with 130 mm diameter for the insertion of control rods and three boreholes of 130 mm diameter for irradiation. On the side of the reflector there are twenty flow channels in the form borehole with 80 mm diameter for helium inlet. Pebble-bed is distributed in the reactor core which is composed of many TRISO particles. TRISO is a fuel that is composed of Uranium Dioxide coated by four outer layers: Carbon, IpyC (Inner Pyrolytic Coating), SiC (Silicon Carbides) and OpyC (Outer Pyrolytic Coating). Both of PyC have density differences. The first layer next to kernel (UO_2) has lower density than others that is functioning to intercept gas of fissile product. SiC layer serves as a barrier to the production of fissile active movement like Cs, Sr and Ag. SiC is also a mechanical and chemical barrier at high temperatures (IAEA, 2003). The basic characteristics of the fuel elements are shown in Table 1.

Pebble-bed and moderator balls is distributed in the core zone of the HTR using a body-centred cubic (BCC) lattice by packing fraction and the percentages of the pebble and moderator balls of 0.61 and 57:43. BBC lattice modelling in MCNP uses lattice option at any active core height variation. MCNP model for BBC lattice, pebble-bed and TRISO is shown in Fig.3 and 4. Fig. 5 is full reactor geometry.

Table 1: Fuel element characteristics

| Fuel kernel		Coatings	
Diameter of ball (cm)	6.0	Coating layer materials (starting from kernel)	C/IPyC/SiC/OPyC
Diameter of fuelled region (cm)	5.0		
Density of graphite in matrix and outer shell (g/cm^3)	1.73	Coating layer thickness (mm)	0.09/0.04/0.035/0.04
Enrichment of 235U (w%)	16	Coating layer density (g/cm^3)	1.1/1.9/3.18/1.9
Equivalent natural boron content of impurities in uranium (ppm)	4.0		
Equivalent natural boron content of impurities in graphite (ppm)	1.3		
Radius of the kernel (μm)	225		
UO_2 density (g/cm^3)	10.4		
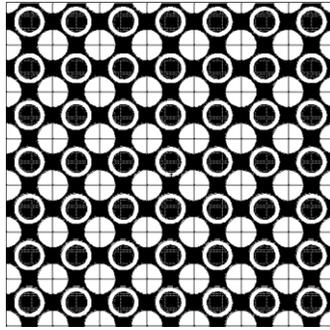
Figure 3: Pebble-bed and Moderator ball is in BCC lattice in reactor core.

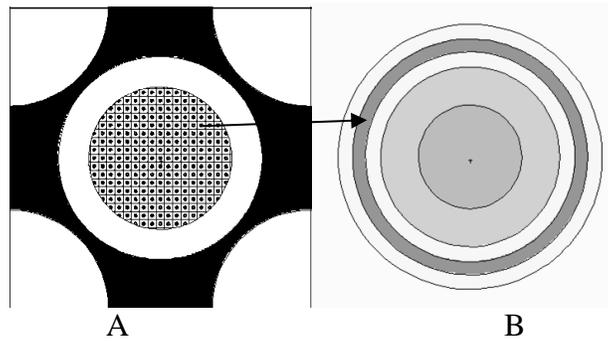A   B

Figure 4: Pebble-bed with Moderator ball in every corner (A) and TRISO coated by UO_2, Carbon, IPyC, SiC and OPyC (B).
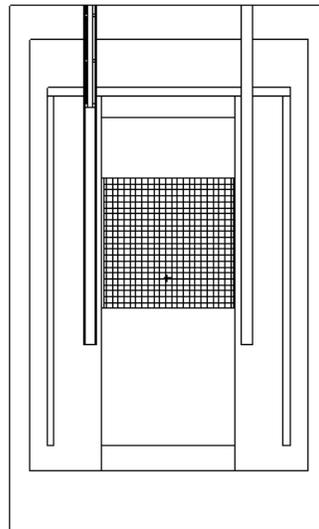

Figure 5: MCNP model of HTR geometry at XZ coordinate.

After reactor core has been modelled, the next process is calculation of reactor criticality done in each radii of kernel 320, 325 and 350 μm and enrichments of 5-10% Uranium with the number of neutrons simulated in KCODE card and neutron source in SDEF card which are specified by reactor core design. 5000 neutrons in each cycle are simulated by estimation criticality value (K_{eff}) of 1.0 selected in order that the final accumulation results are expected nearly equal to the critical condition. Having got criticality from calculation MCNP, the next process is to do interpolation method to obtain criticality from other radii between 320-325 μm and 325-350 μm.

3. RESULTS AND DISCUSSIONS

In the calculation of HTR pebble-bed using MCNPX, pebble-bed core model was approximated by utilizing a BCC lattice and TRISO was distributed in pebble-bed ball by Simple Cubic lattice. Repeating structure of MCNP led to the emergence of partial pebble around the core which could have added extra fuel into the core. Excess fuel contributed by this partial pebble was eliminated by reducing the volume of the core where a pebble packing fraction was maintained unchanged. This approach relied on an exclusion zone which compensated contribution of partial pebble.

The calculations in all of kernel radii and enrichments used continuous energy nuclear data library ENDF/BVII with a temperature of 27^oC. From the calculations, we obtained that the criticality of reactor achieved one for all radii at about 9-10% enrichments of Uranium but the larger the radius of kernel was, the more criticality increased in the same enrichment. The results of criticality of reactor were shown in Fig. 6. The large enrichment which is used led to increasing of criticality value due to thermal and fast neutron utilities became higher than before, and the reactor loaded many uranium-235.
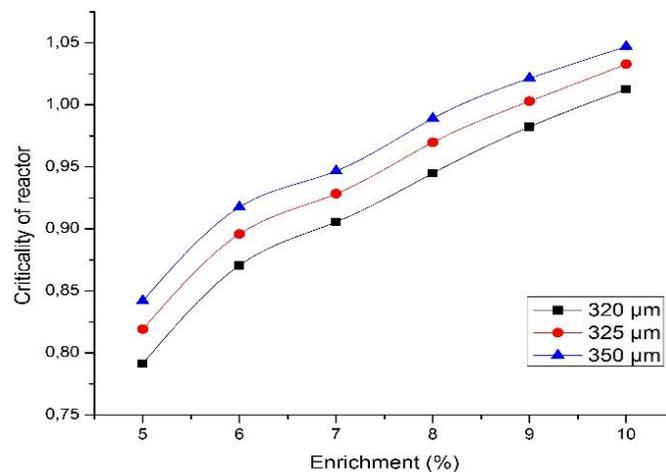

Figure 6: The MCNP result of reactor criticality.

The large criticality was, the more the reactivity of reactor increased. From graph of reactivity in Fig. 7, the reactor would have been in critical condition at 9% enrichment of Uranium in radius kernel of 325 μm with the value reactivity of 0.00294 whereas the reactivity of 320 μm and 350 μm radius kernel were more than zero in 9-10% enrichment of Uranium.
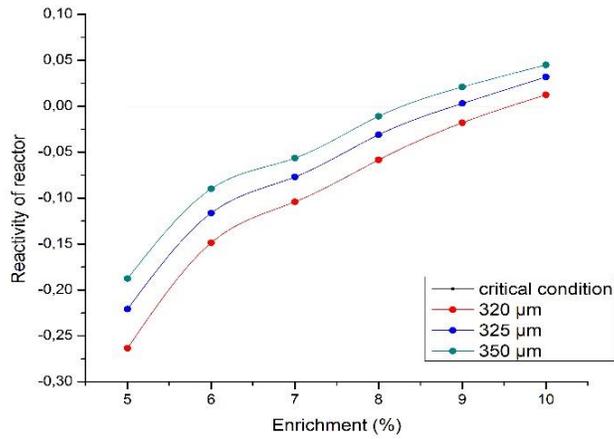
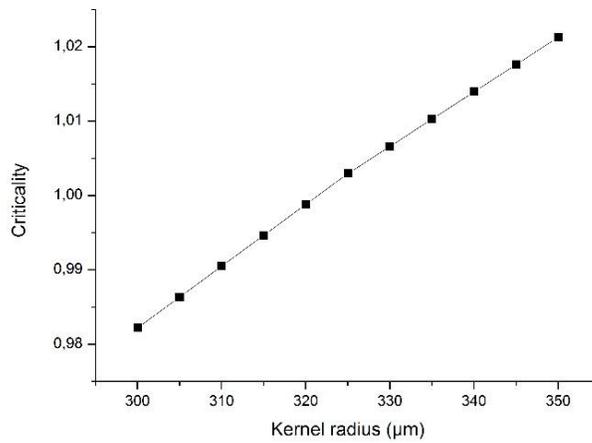Figure 7: The MCNP result of reactor reactivity.

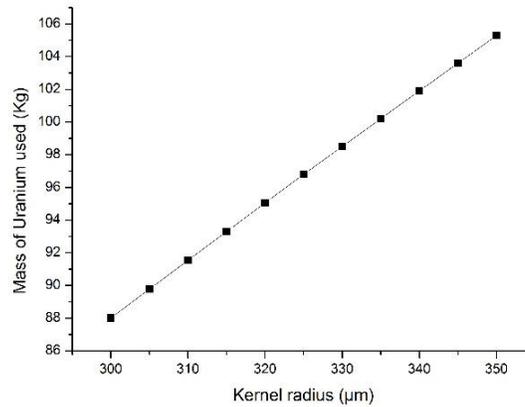Figure 8: The Interpolation result of reactor criticality at 9% enrichment.

Figure 9: The Mass of Uranium used each radius at 9% enrichment.

From graph in Fig. 8 we could have looked that criticality reactor at 325-330 μm was still able to be considered to use due to the criticality was nearby critical condition and we could have considered it from graph in Fig. 9 that the use of Uranium mass was still 96-98 Kg. That was still lower than the use of uranium at 335-350 μm. it saved 2-4 % from the use of uranium above 330 μm.

The larger radius kernel made, the more increasing of reactor reactivity was. This happened due to the neutron cross-section reaction increased comparable with the increasing of reactivity so that there were many fission reactions. It would have been made reactor in supercritical condition if the reactor used more than 330 μm of radius kernel and 9% enrichment of Uranium.

4. CONCLUSIONS & RECOMMENDATIONS

From the results explained above could have been concluded that from the results of MCNPX calculations the use of large kernel radius made reactor to be supercritical where the number of neutrons increased and it also happened for increasing of Uranium enrichment. This occurred due to there were many fission reactions in reactor so that reactivity reactor increased. However, the use of kernel radius of 325-330 μm at 9% Uranium enrichment was the most effective of 320 μm and 350 μm kernel radii at all Uranium enrichments, but it must do other aspects like the use of Uranium density, power reactor and so on to consider the optimum reactor operation.

5. ACKNOWLEDGEMENTS

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