

Analysis of High Temperature Reactor Control Rod Worth for the Initial and Full Core

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Abstract. Control rod is one important component in a nuclear reactor. In nuclear reactor operations the control rod functions to shut down the reactor. This research analyses ten control rods worth of HTR (High Temperature Reactor) at initial and full core. The HTR in this research adopts HTR-10 China and HTR- of pebble bed. Core calculations are performed by using MCNPX code after modelling the entire parts of core in condition of ten control rods fully withdrawn, all control rods in with 20 cm ranges of depth and the use of one control rod. 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 use of one control rod will decrease the reactor criticality of 2.04 ± 0.12 % $\Delta k/k$ at initial core and 1.57 ± 0.10 % $\Delta k/k$ at full core. The deeper control rods are in, the lesser criticality of reactor is with reactivity of ten control rods of 16.41 ± 0.11 % $\Delta k/k$ at initial core and 15.43 ± 0.11 % $\Delta k/k$ at full core. The results show that the use of ten control rods at full core will keep achieving subcritical condition even though the reactivity is smaller than reactivity at initial core.

1. Introduction

Attention scientist of reactor technology and nuclear energy in the world against the High Temperature Reactor (HTR) has increased in the past decade. Inherent safety characteristics and capabilities to produce energy economically are the main factors that attract many people to study and develop HTR. The HTR utilizes graphite as the moderator at the same reflector and the fuel is a spherical particle (pebble-bed) with UO₂ composition as a neutron generator [1].

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. Thermal reactor power is 10 MW with inlet and outlet helium temperatures of 250°C and 700°C. 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 TRISO particle is coated fuel particles by a radius of 175-300 μm . According to Hammam, kernel radius of 225 μm with enrichment of 16% can use in HTR due to reactor has been critical [2-5].

The criticality of reactor is a variable that describes the state of the reactor in order to operate optimally. The reactivity of reactor can be controlled by control rod. Therefore, it is needed to determine the control rods worth so that reactor is in critical or subcritical condition at initial and full core [6].



Calculation of the reactor criticality at any control rods depth variations is done with modelling techniques of MCNPX which is a software that can simulate the interaction of particles in a reactor with a Monte Carlo approach. The modelling is done by making the geometry of reactor, control rod and pebble-bed which is distributed by using body-centred cubic lattice in the reactor core.

2. Experimental Method

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. MCNP is also capable of calculating the multiplication factor (criticality) of fissile systems. A system is defined by generating cells bounded by surfaces in three dimensions. Any kind of geometry can be defined as a cell and this cell can be rotated and moved to anywhere in the space. MCNP can simulate particle transport. Monte Carlo simulates individual particles and recording some aspects (tallies) of their average behaviour [7].

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 calculate atom density from reactor and fuel, then 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 [8]. The basic characteristics of the fuel elements are shown in Table 1.

Table 1. Fuel element characteristics

Fuel kernel	
Diameter of ball (cm)	6.0
Diameter of fuelled region (cm)	5.0
Density of graphite in matrix and outer shell (g/cm^3)	1.73
Enrichment of ^{235}U (w%)	16
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

Coatings	
Coating layer materials (starting from kernel)	C/IPyC/SiC/OPyC
	0.09/0.04/0.035/0.
Coating layer thickness (mm)	04
Coating layer density (g/cm ³)	1.1/1.9/3.18/1.9

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 Figure 1 and 2, while MCNP reactor model is shown in Figure 3.

There are ten control rods placed in the side reflector of reactor. Boron Carbide (B₄C) is used as the neutron absorber. Each control rod contains five B₄C ring segments which are housed in the area between an inner and an outer sleeve of stainless steel. The inner and outer diameter of the B₄C ring is 60 mm and 105 mm respectively, while the length of each ring segment is 487 mm. the inner/outer diameters of the inner and outer stainless steel sleeves are 55 mm/59 mm and 106 mm/110 mm, respectively. The length of each joint is 36 mm. the lengths of the lower and upper metallic end are 45 mm and 23 mm. The basic characteristics of the control rod are shown in Table 2. Figure 4 shown control rod of reactor.

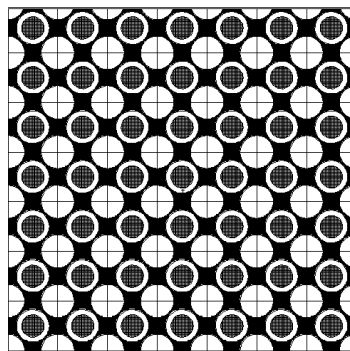


Figure 1. Pebble-bed and Moderator ball is in BCC lattice in reactor core

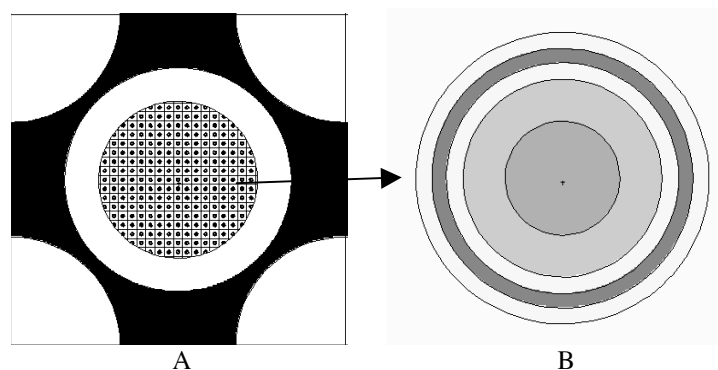


Figure 2. Pebble-bed with Moderator ball in every corner (A) and Triso coated by UO₂, Carbon, IPyC, SiC and OPyC (B).

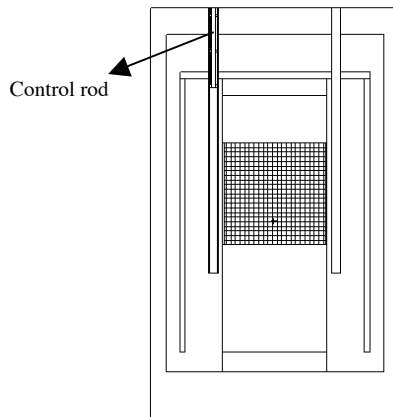


Figure 3. MCNP model of HTR geometry at XZ coordinate



Figure 4. MCNP model of control rod at XZ coordinate

Table 2. Control rod characteristics

Elemen	
B4C (g/cm ³)	7.9
Cr (%)	18
Fe (%)	68.1
Ni (%)	10
Si (%)	1
Mn (%)	2
C (%)	0.1
Ti (%)	0.8
Description	
Control rod channel radius (cm)	6.5
Radial position of channel center (cm)	102.1
Length of B4C segment (cm)	48.7
Length of bottom metallic end (cm)	4.5
Length of metallic joins (cm)	3.6
Length of top metallic end (cm)	2.3
Inside radius of inner stainless-steel sleeve (cm)	2.75
Thickness of stainless-steel sleeve (cm)	0.2
Thickness of gap between sleeve and B4C (cm)	0.05
Thickness of B4C annulus (cm)	2.25
Density of B4C (cm)	264.7
Length of control rod (cm)	1.7

After reactor core has been modelled, the next process is calculation of reactor criticality done in initial and full core in each control rod condition: fully withdrawn, one control road fully in and all

control rods in with 20 cm ranges of depth 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. Using skipping 10 cycles is done before data accumulation of criticality value from a total of 210 cycles to prevent convergence of the source and that the fission sources can be stable before criticality values are used to average its final estimation. SDEF card is utilized to specify fission source distributions in reactor core and $S(\alpha, \beta)$ graph. 01t of thermal neutron scattering data is applied in all materials containing graphite to consider binding effect at thermal neutron and graphite moderator under energy of 4 ev.

3. Results and Discussion

In MCNP In the calculation of HTR pebble-bed, pebble-bed core model is approximated by utilizing a BCC lattice. Repeating structure of MCNP leads to the emergence of partial pebble around the core which can add extra fuel into the core. Excess fuel contributed by this partial pebble is eliminated by reducing the volume of the core where a pebble packing fraction is maintained unchanged. This approach relies on an exclusion zone which compensates contribution of partial pebble. The size of the exclusion zone is given by the pebble radius determined by the ratio of the number of fuel pebble with the number of pebble in unit cells, thus obtained exclusion zone thick is 1.71 cm around the core with fuel pebble and moderator ratio is 57:43.

All of MCNP5 calculations utilize the continuous energy nuclear data library ENDF/B-VII with a temperature of 27°C. From the MCNPX calculations, the results are obtained that the use of one control rod will decrease the reactor criticality of 2.04 ± 0.12 % $\Delta k/k$ at initial core and 1.57 ± 0.10 % $\Delta k/k$ at full core. The results of HTR criticality calculation with ten control rods in of 20 cm ranges are plotted in graph and are shown in Figure 5 and the control rods worth are shown in Figure 6.

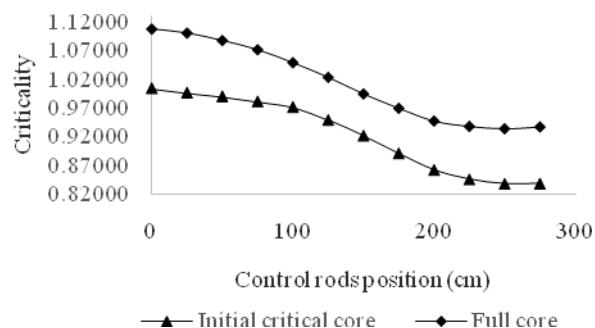


Figure 5. The results of criticality reactor (K_{eff}) in each control rods position

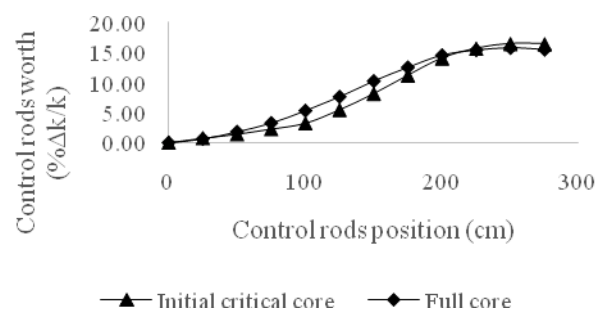


Figure 6. The control rods worth in each control rods position

From the results shown in Figure 5 and 6 seem that the deeper control rods are in, the lesser criticality of reactor is with reactivity of $16.41 \pm 0.11 \text{ } \Delta k/k$ at initial core and $15.43 \pm 0.11 \text{ } \Delta k/k$ at full core. That occur as the use of B_4C in control rod where B_4C has a function as the neutron absorber. The Boron material is a effective material to absorb neutron. When many B_4C are in core, many neutrons will be absorbed. That result shown that control rod can make subcritical condition either in initial core or in full core.

4. Conclusion

From the results explained above can be concluded that from the results of MCNPX calculations the use of control rods can make reactor to be subcritical where the number of neutrons decrease. The deeper control rods are in, the lesser criticality of reactor is. This is occurred due to there are many Boron in B_4C used in control rods so activity of fission in reactor decreases. However, the use of ten control rods at full core still achieves subcritical condition even though reactivity smaller than reactivity at initial core.

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