International Journal of Engineering Research and Science & Technology

ISSN : 2319-5991
Vol. 5, No. 3
August 2016

www.ijerst.com

Email: editorijerst@gmail.com or editor@ijerst.com

International Journal of Engineering Research and Science & Technology

ISSN 2319-5991 www.ijerst.com
Vol. 5, No. 3, August 2016

Research Paper

BURNUP AND CRITICALITY ANALYSIS OF CARBON COATED PARTICLE FUEL IN HTR-10 REACTOR

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The enhanced safety features of the High Temperature Gas cooled Reactors (HTGR) fuel are based on its coated fuel particle design (TRISO). It consists of minute uranium particles coated with layers of carbon and silicon carbide. The coated particles permit high fuel burnup, confirm fuel resistance to extreme temperatures under accident conditions and can withstand high internal gas pressure without the release of fission products to the environment. HTR-10 is a high temperature gas cooled reactor, with a thermal power of 10 Mw. The reactor has a unique capability to provide coolant temperature to 950 °C. It uses spherical fuel elements that are coated with carbon. In the present work, MCNPX2.7 code is used to model and analyze the burnup of the carbon coated spherical fuel ball of HTR-10. Two models are simulated for the fuel ball, homogenous and heterogeneous models. The relationship between the multiplication factor ($K_{infinity}$) and the burnup of the ball is determined. Burnup of U-235 and Build up of Pu isotopes are calculated. Moreover, the thermal flux and power distribution inside the homogenized fuel ball are determined. The results obtained for $K_{infinity}$ at zero burnup showed good agreement with those of the benchmark related to Initial Testing of HTR-10 Reactor. It is also shown that the homogeneous model is able to accurately represent an HTR-10 fuel ball that burns at high burnup values.

Keywords: HTR-10, HTGR, TRISO fuel, MCNPX

INTRODUCTION

HTR-10 is China's modular high temperature gas cooled reactor. The reactor represents the design features of the modular HTGR which is primarily characterized by inherent safety features and a unique capability to provide coolant with high temperature (950 °C) for a variety of industrial heat applications and for efficient electrical power generation. The safety design philosophy deviates from the traditional approach that relies on highly reliable redundant and diversified active components and systems as well as their power supply. Fuel elements used are the spherical type fuel element with carbon coated fuel particles

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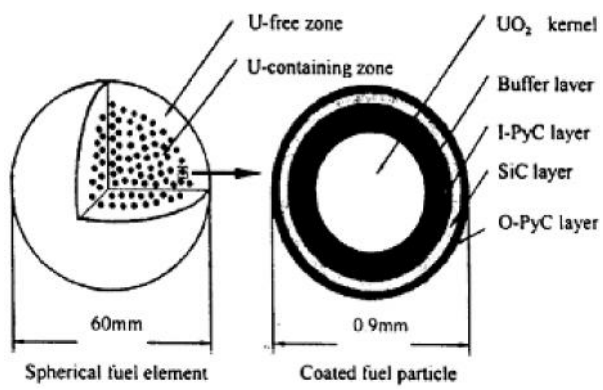
(TRISO). The reactor equilibrium core contains about 27,000 spherical fuel elements forming a pebble bed core that is 180 cm in diameter and 197 cm in average height. The core is surrounded by graphite reflectors and Helium is used as a primary coolant. The spherical fuel elements move through the reactor core in a multipass pattern. Each fuel element contains a large number of fuel particles; each is coated with different layers of SiC and PyC. The enrichment of U-235 is of 17% with a design mean burnup of 80,000 MWd/t (IAEA TECDOC 1382, 2003).

In order to analyze the burnup and criticality of the spherical fuel ball, two models are designed, homogeneous and heterogeneous models. The two models are assumed to be burned up to a very high burnup level reaching 120,000 MWd/t. The results obtained for multiplication factor ($K_{infinity}$) at zero burnup for the two models are compared with each other and with those of the benchmark related to Initial Testing of HTR-10 Reactor to validate the simulated models. MCNPX2.7 (Pelowitz, 2011) code is used to simulate the burnup processes in conditions similar to reactor operation. The cross-section data are derived from the evaluated nuclear data library ENDF/B-VII.1 (Chadwick *et al.*, 2011).

DESCRIPTION OF THE SPHERICAL FUEL ELEMENT OF HTR-10

Fuel elements used in HTR-10 reactor are the German type spherical fuel elements with carbon coated fuel particles. They move through the reactor core in a multi-pass pattern. As shown in Figure 1, the fuel element is 6 cm in diameter, including a fuel zone with 5 cm in diameter and a graphite reflector surrounding the fuel zone. In the fuel zone, there exist about 8400 coated fuel particles. Each fuel particle consists of a UO2 kernel, which is coated with four layers. These are; low-density pyrolytical carbon, inner high-density pyrolytical carbon, silicon carbide and outer high-density pyrolytical carbon layer. The uranium content per fuel element will be 5 gm with U-235 enrichment of 17% (Sen *et al.*, 2001; IAEA TECDOC 1382, 2003; Hu *et al.*, 2004; and Tiawo *et al.*, 2005).

Figure 1: A Systematic View of the Spherical Fuel Element of HTR-10



For the initial core loading, dummy balls (graphite balls without nuclear fuel) will be placed into the discharge tube and the bottom region of the reactor core. Then, a mixture of fuel balls and dummy balls will be loaded gradually to approach first criticality. The percentages of fuel balls and dummy balls are envisaged to be 57% and 43% respectively. After the first criticality is reached, mixed balls of the same ratio will be further loaded to full core in order to make the reactor capable of being operated at full power (IAEA TECDOC 1382, 2003). The basic characteristics of both the fuel elements and the fuel particles are presented in Table 1.

MCNPX MODEL

Two models are designed using the MCNPX2.7 code (Pelowitz, 2011) to simulate the spherical

Table 1: The Fuel Element Characteristics

Diameter of ball	6.0 cm
Diameter of fuel zone	5.0 cm
Density of graphite in matrix and outer shell	1.73 g/cm^3
Heavy metal (uranium) loading (weight) per ball	5.0 g
Enrichment of U-235 (weight)	17%
Equivalent natural boron content of impurities in uranium	4 ppm
Equivalent natural boron content of impurities in graphite	1.3 ppm
Volumetric filling fraction of balls in the core	0.61
Fuel kernel	
Radius of the kernel	0.25 mm
UO2 density	10.4 g/cm^3
Coatings starting from kernel	
Coating layer materials	PyC/PyC/SiC/PyC
Coating layer thickness	0.09/0.04/0.035/0.04 mm
Coating layer density	1.1/1.9/3.18/1.9 g/cm^3

fuel ball that is burned up to a very high burnup level reaching 120,000 MWd/t:

Model A: Homogeneous Fuel Ball

Model B: Heterogeneous Fuel Ball

In Model A, the fuel zone is homogenized including the coated fuel particles together with the graphite reflector surrounding the fuel zone. In this model the fuel zone (with diameter 5 cm) is divided into 12 equal volume layers to calculate the radial flux and power distribution. Figure 2 represents a typical model of the homogenous fuel ball.

Model B is the heterogeneous model of the spherical fuel ball. In this model the internal fuel zone is represented with 8400 TRISO fuel particles dispersed in a graphite matrix and every TRISO particle is composed of 5 layers. The sphere in the heterogeneous model is converted into a rectangular form with volume and mass conservation for all materials. Model B is shown in Figure 3.

Figure 2: The Homogeneous Model of the Fuel Ball

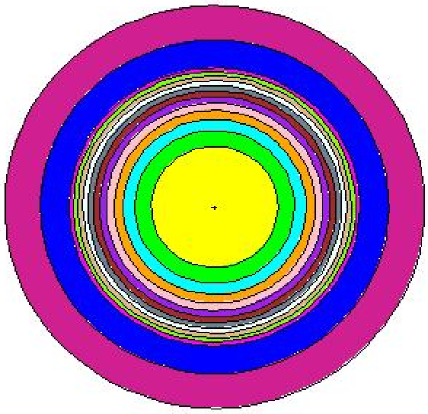
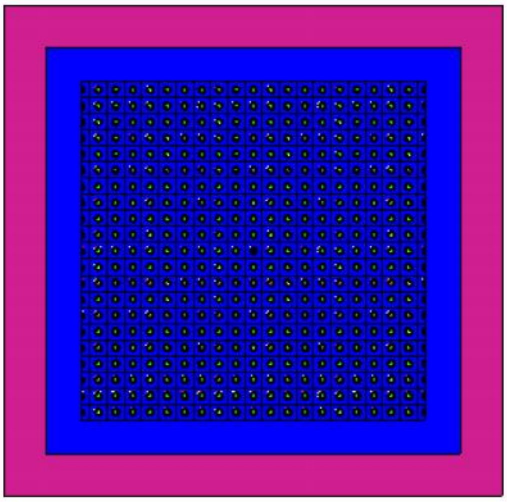


Figure 3: The Heterogeneous Model of the Fuel Ball



RESULTS AND DISCUSSION

Phase 1: Comparison Between Homogeneous and Heterogeneous Models

Table 2 illustrates a comparison between the

Table 2: The Multiplication Factors for Fuel Ball at 0.0 GWd/t

	$K_{infinity}$
France-APOLLO2	1.71926
France-TRIPOLI4	1.76155
Germany-VSOP	1.7475
Model A	1.66793
Model B	1.71793

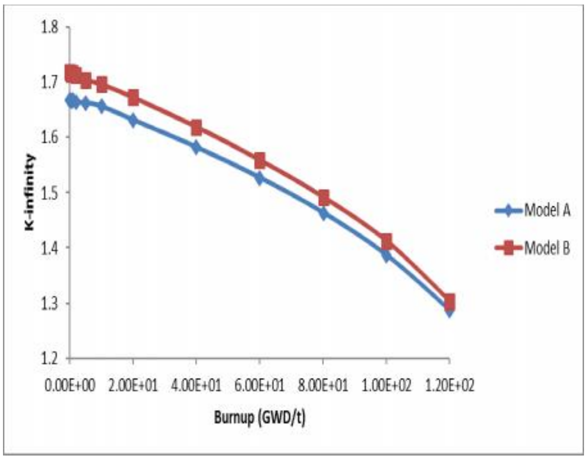
multiplication factor ($K_{infinity}$) of the fuel ball at burnup = 0.0 GWd/t as calculated with both the homogenous and heterogeneous models of MCNPX2.7 and those mentioned in reference (1). There are three values mentioned in the reference, the first two values are obtained by France using APOLLO2 and TRIPOLI4 codes. The third value is obtained by Germany using VSOP code.

As shown in the table, the results of the two models are close to those of reference (1). This indicates that the two models can accurately represent the spherical fuel ball of HTR-10.

Figure 4 illustrates the multiplication factor ($K_{infinity}$) as a function of burnup (GWd/t) for Models A and B. It can be recognized that the variation of $K_{infinity}$ with burnup is the same for both models, it decreases with burn up. It is also shown that the specified models for HTR-10 fuel ball can sustain very long burnup cycles up to 120 GWd/t.

From the analysis of the burnup results obtained above for the two models, it is shown that the results obtained using the homogeneous model, are close to those of the heterogeneous model. This means that the homogeneous model is able to accurately simulate an HTR-10 fuel ball that burns at high burnup values. This will save in time and effort in core calculations of HTR-10 to

Figure 4: The Multiplication Factor ($K_{infinity}$) as a Function of Burnup (GWd/t) for HTR-10 Fuel Ball



a great extent, where it is difficult to heterogeneously model 27,000 spherical fuel balls forming a pebble bed core with 8400 coated fuel particles in each.

Phase 2: Results Obtained for Model A

Figure 5 illustrates the change in U-235 concentration (atom/barn.cm) with burnup (GWd/t). Figure 6 illustrates the buildup concentration of Pu isotopes (atom/barn.cm) with burnup (GWd/t).

Figure 5: The Change in U-235 Concentration with Burnup for Model A

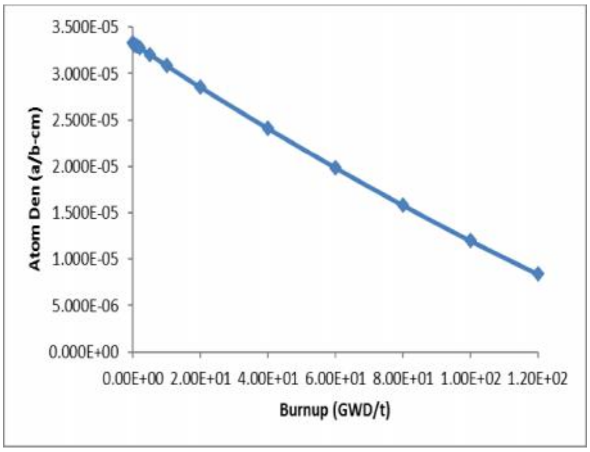


Figure 6: The Buildup Concentration of Pu Isotopes with Burnup for Model A

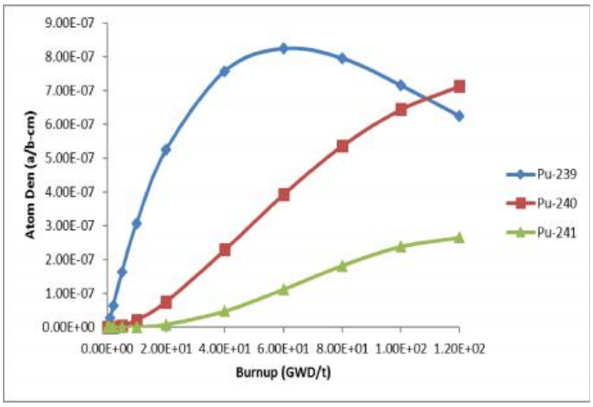


Figure 7: Thermal Neutron Flux Distribution with the Radial Distance for Model A

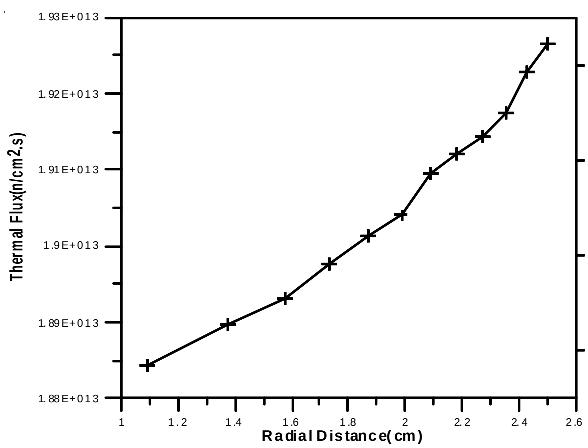
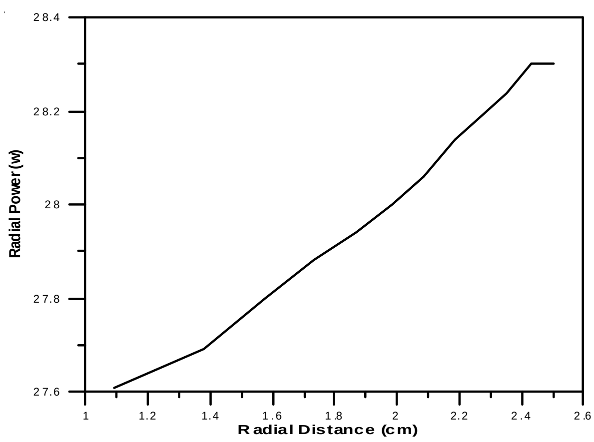


Figure 8: Power Distribution with the Radial Distance or Model A



As shown in Figure 6, Pu-239 reaches its maximum value at 60 GWd/t with concentration 8.24E-7 (atom/barn.cm), and then Pu-239 reaches to its asymptotic (saturation) concentration and decreases slightly with burn up. The concentrations of the Pu-240 and Pu-241 isotopes are also determined and they are always increasing with burnup.

Figures 7 and 8 present the thermal flux distribution and the total power distribution through the radial distance (cm) respectively for Model A at burnup 0.0 GWD/t. The results indicate that both the thermal flux and the power increase with distance. The maximum thermal flux occurs at a zone adjacent to the moderator with value 3.22E+13 n/cm^2.s. The ratio between the flux at the outer zone to that at the inner zone is 1.0223. While the ratio between the power at the outer zone to that at the inner zone (sphere center) is 1.0293.

CONCLUSION

MCNPX2.7 code is used to model and analyze the burnup of the carbon coated spherical fuel ball of HTR-10. Two models are simulated for the fuel ball, homogenous and heterogeneous models. The relationship between the multiplication factor and the burnup of the ball is determined for both models. Burnup of U-235 and Build up of Pu isotopes are calculated. Moreover, the thermal flux and power distribution inside the homogenized fuel ball are determined.

The present paper showed that the results of the multiplication factors at burnup 0.0 GWD/t for the two models are close to those of the benchmark related to Initial Testing of HTR-10 Reactor, which indicates that the two models are able to accurately represent the spherical fuel ball of HTR-10. The results obtained for the variation of multiplication factor with burnup for both models showed that the homogeneous model is able to accurately model an HTR-10 fuel ball that burns at high burnup values. This will save in time and effort in core calculations of HTR-10 to a great extent.

For the homogeneous model, the concentrations of the Pu-239, Pu-240 and Pu-241 isotopes are determined. Finally, at burnup 0.0 GWD/t the results indicated that both the radial thermal flux and power for the homogeneous model increase with distance.

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International Journal of Engineering Research and Science & Technology
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ISSN 2319-5991