Core Physics Analysis of An Assembly of HTTR Reactor using Homogeneous and heterogeneous model

Moustafa Aziz

Nuclear and Radiation safety Center, Atomic Energy Authority, 3 Ahmed Alzomer Str. Nasr City, Cairo, Egypt

ARTICLE INFO

ABSTRACT

MCNPX computer code based on Monte Carlo method is used to design a computer model for an assembly of high temperature testing reactor (HTTR). Two models are used in the analysis, namely homogeneous and heterogeneous models. The reactor uses TRISO fuel, Graphite moderator and helium coolant. The multiplication factor of the assembly is determined as a function of fuel burnup and operation time. Axial power mapping distributions are evaluated. Time evolution of actinides (U^{235} and Pu^{239}) is calculated as a result of fuel burnup. Fuel and moderator temperature coefficient of reactivity are determined as a function of operating temperature. The effect of Helium coolant losses on reactor criticality is evaluated (by assuming reduction of helium density to one percent of its nominal density). Calculations indicated that homogenous model results are in good agreement with heterogeneous models with an average difference of approximately 5 %. This enable homogeneous model to be used in full reactor core simulations. This is much easier and saves modeling and computational time.

I- INTRODUCTION

The HTTR is a 30-MWth high temperature testing reactor, helium-cooled, graphite-moderated. The reactor located at the Oarai Research and Development Center in Japan and currently operated by the Japan Atomic Energy Agency's (JAEA). This facility was constructed with the objective to establish and upgrade the technological basis for advanced high temperature gas-cooled reactors (HTGRs) as well as to conduct various irradiation tests for innovative high-temperature research. The core has a high excess reactivity which is necessary for compensation of temperature, xenon, and burnup effects during power operations [1,2].

The reactor uses TRISO particles as fuel. The fuel zone contains 182,000 TRISO per fuel rod, and every block contains 33 fuel rods with 5 blocks per fuel column (or assembly). This corresponds to approximately thirty million TRISO particles in every fuel assembly [3,4,5]. Representing this large number of TRISO particles is a heavy computational load. One of the widely used and common method is to homogenize the fuel zone which contains TRISO particles. This homogenization is carried out with the conservation of both volume and mass in the fuel zone.

MCNPX code is used to design a computational model to an assembly of High Temperature Testing Reactor (HTTR). Two models; namely homogeneous and heterogeneous; are used in the analysis. The models are used to analyze the design parameters and simulate the fuel burn up inside the nuclear reactor. Reactor multiplication factor is calculated as a function of operational time. Axial and radial power distributions, isotopic transformation ^{235}U burnup and Pu buildup, fuel and moderator temperature coefficient of reactivity, Kinetic parameters such as delayed neutron fraction and prompt neutron lifetime are calculated. The effect of coolant losses on reactor criticality is evaluated. The homogeneous model results are compared with heterogeneous model to test the efficiency and accuracy of homogeneous results to be used in a further core model.

In the following, Section II contains reactor descriptions and data, Section III includes the MCNPX model, section IV contains results and discussions, conclusions and the references are given at the end of the paper.

II-REACTOR DATA AND DESCRIPTION

The reactor column or assembly consists of 9 axial blocks with a length of 58 cm each. From the top, the first two blocks are reflector blocks followed by 5 Fuel blocks and then two reflector and moderator at the bottom. The active core has a height of 290 cm (5x58 cm) hexagonal graphite columns are 58 cm high and 36 cm across flats (. The active core contains 30 fuel assemblies. Each fuel block has 31 or 33 coolant channels, into which fuel rods are inserted. Fuel rods consist of a graphite sleeve containing 14 fuel compacts. Each fuel compact contains about 13,000 coated fuel particles (CFPs) randomly embedded in a graphite matrix (each fuel rod contains 182000 TRISO particles) [1,6].

The core has different uranium enrichments between 3.4 and 5.9 wt% to optimize and increases the outlet temperature of the helium gas. Fuel blocks of highly enriched uranium are placed in the upper- and outer-core regions. Burnable poisons (BPs), made of boron carbide and carbon, are inserted into two of three holes. Sixteen pairs of CRs are used for reactivity control [7,8,9].

Table 1 illustrates the major design specifications of HTTR fuel column and reactor core   Figure 1 also illustrates the fuel coated TRISO fuel particles, fuel compact, fuel rod, fuel Block, and fuel column (assembly). As indicated in the figure, TRISO fuel particle contains fuel kernel followed by four layers; namely, low density PyC (i.e., pyrolytic carbon), High density PyC, Silicon Carbide (SiC) and high density PyC. Figure 2 illustrates the dimensions of a complete fuel block of length 58 cm and 36 cm flats. Table 2 contains axial fuel enrichment distributions through fuel blocks. Block No. 1 contains maximum fuel enrichment to maximize output fuel temperature [950 °C to 1000 °C]

Table (1): Major design Specification for HTTR [1,2]

Thermal Power	30 MWth
Inlet temperature	395 °C
Outlet temperature	950 °C
Primary Helium pressure	4 MPa
Average power density	2.5 W/cm^3
Fuel	UO$_2$
Type of fuel	bin in block
Fuel compact outer diameter	2.6 cm
Fuel compact inner diameter	1.0 cm
Packing fraction of Triso fuel	30 % by volume
Fuel kernel diameter	600 µm
Triso Coated particle diameter	920 µm
Coating materials	PyC/PyC/SiC/PyC
Coolant material	Helium gas
Flow direction in core	downward
Top Reflector thickness	116 cm
Side Reflector thickness	0.99 cm
Bottom Reflector	116 cm
NO. of fuel blocks	150
No. of fuel Columns in the core	30
No. of Control rods In core	7
No. of Control rods In reflector	9

Table (2) Axial Enrichment Distribution Through Fuel Blocks [1,2]

Block No.	Block 1	Block 2	Block 3	Block 4	Block 5
Enrichment %	6.7	5.2	4.3	3.4	3.4
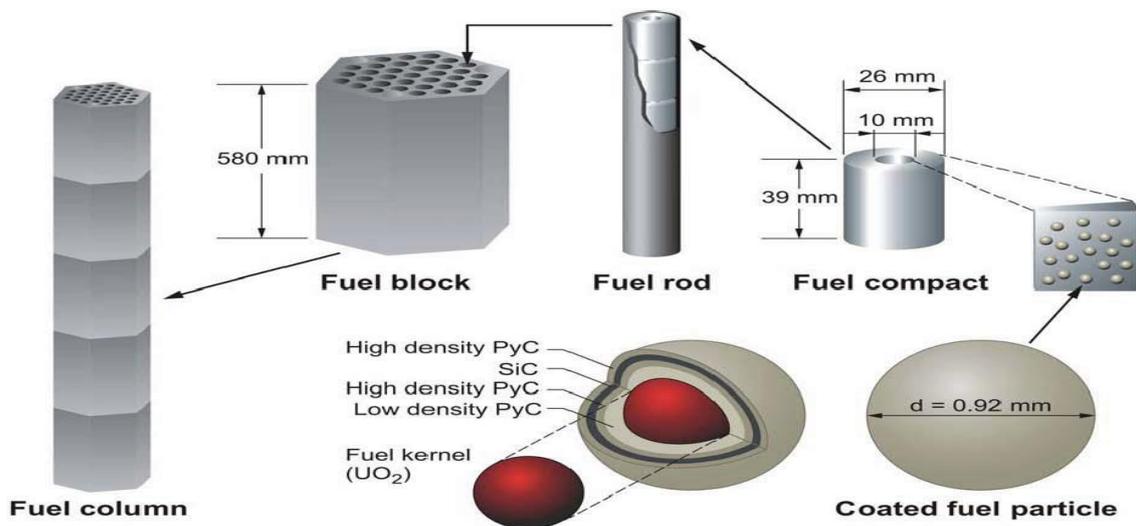
Fig. (1): HTTR fuel kernel to fuel column schematic [1]
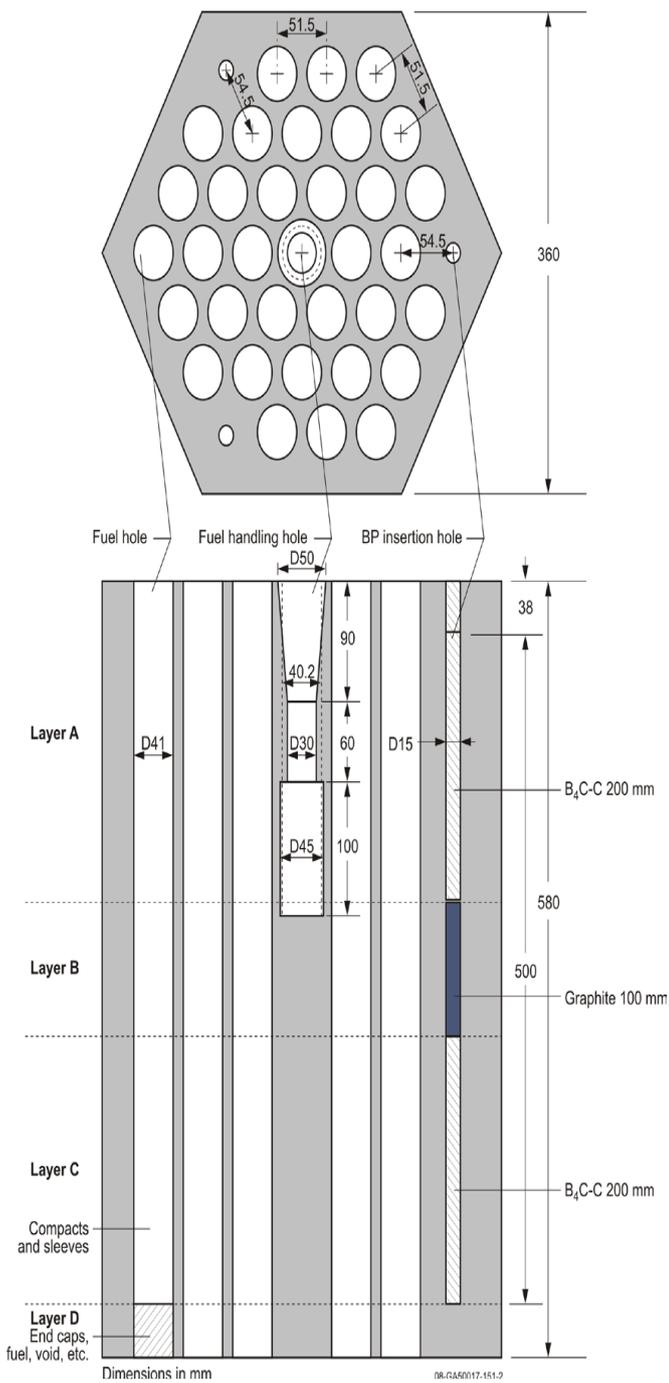
Fig. (2): Fuel block for 33-pin fuel assembly (dimensions are in mm)

III - MCNPX MATHEMATICAL MODEL

MCNPX code [10] is used to develop two models for the HTTR assembly to simulate fuel burnup and operation of the assembly inside the reactor core namely: Models A and B as explained below. Figure 3 illustrates the Horizontal and vertical layout of the fuel column.

Model A (Heterogeneous): Three dimensional and exact dimensions and compositions are considered in which each fuel block is divide into 14 fuel compacts and each fuel compacts contains 13000 TRISO fuel kernel. Each spherical kernel consists of 5 layers fuel kernel namely UO_2, low density PyC, high density PyC, SiC and High density PyC, as indicated in Figure 4.a illustrates arrangement of TRISO particles in fuel zone. Figure 4.b indicates the composition of coated TRISO particle with 5 zones.

Model B (Homogeneous): The composition of each fuel zone is homogenized based on volume and mass preservation in each zone. And a homogenized material is prepared for each fuel compact zone. As indicated in Figure 5.

1.2E+6 neutron histories are used to scan the assembly and accumulate the problem Tallies (Output). These neutrons are divided into 60 cycles with 20,000 neutrons per cycle. The fuel is burned up to 1470 days which corresponds to 50,000 MWd/T, the time domain was divided into 17 time-steps with Δt (days) range between 30 and 120 days. Five axial fuel zone are allowed to burn during the time dependent mode of the model. The power per assembly is 1 MW. Outer surfaces are reflected to consider interaction (to take into consideration) the assembly with the neighboring assembly inside the reactor.
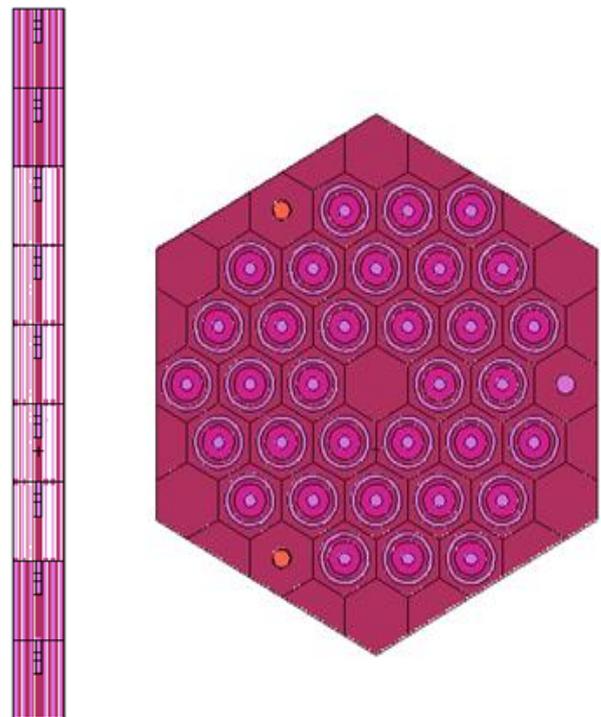
Fig. (3) MCNPX model for 33-pin fuel column (assembly).
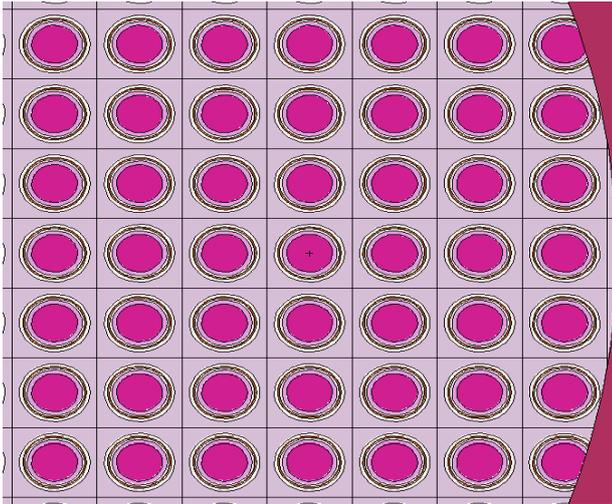
Fig. (4.a) TRISO fuel Model A for Heterogeneous Fuel Zone
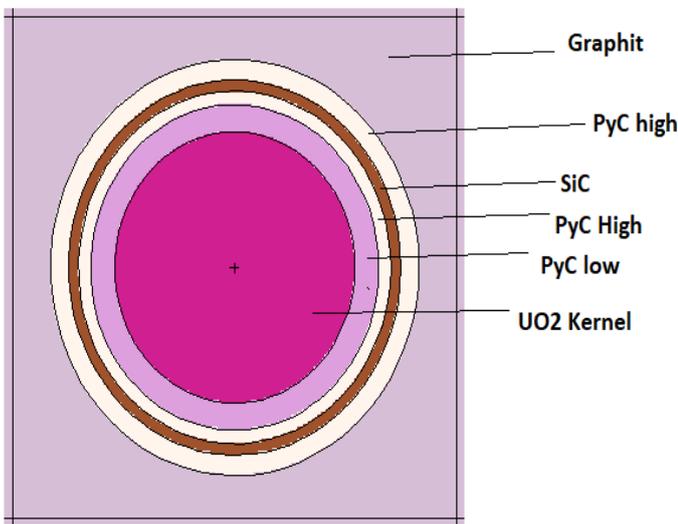
Fig. (4.b) TRISO fuel Model A for Heterogeneous Fuel Zone
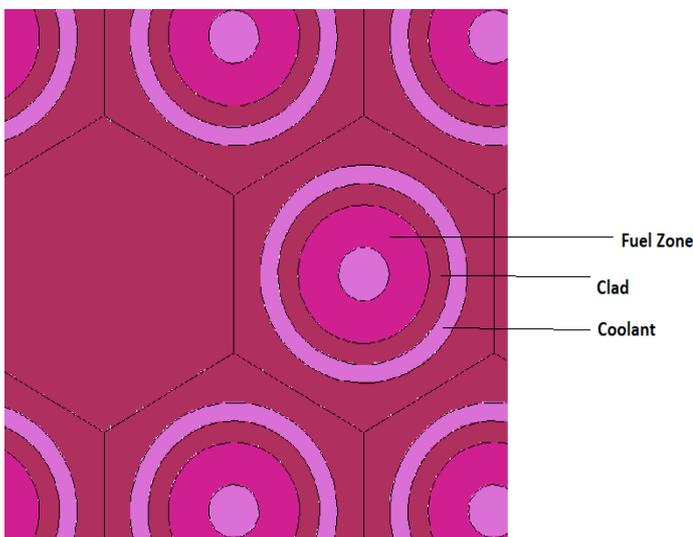
Fig. (5): TRISO fuel Model B for Homogeneous Fuel zone

IV- RESULTS AND DISCUSSIONS

Figure 6 illustrates the multiplication factor for the assembly versus operation times (in days). The figures compare between homogeneous and heterogeneous models. At time = 0.0 K_{inf} =1.21624 and 1.20777 for heterogeneous and homogeneous models respectively. The difference at time (t = 0.0) for fresh fuel between the two results $\Delta K \% = \frac{K_{hetro.} - K_{homo.}}{K_{hetro.}} x100$ = 0.69641 %. At time 630 days, K_{inf}=1.01427 and 1.00482 for heterogeneous and homogeneous models respectively.

Figure 7 illustrates Masses U^{235} and Pu^{239} versus operation time (in days) for block No. 1 from the top of the reactor. The figure shows comparison between Heterogeneous and Homogeneous model. The initial mass of U^{235} for the two models is 396.4 gm per block. The difference between the two models for U^{235} in the range of 0.5 to 5 % during the entire operation time and approaches 10 % if burnup continues to 1470 days. The results indicate that 84 % of U^{235} are burned after 1470 days. For Pu^{239} buildup after 1470 days, 53.4 g buildt up in heterogeneous model.

Figure 8 illustrates Masses U^{235} and Pu^{239} versus irradiation time for block No. 2 from the top of fuel. The figure shows comparison between Heterogeneous and Homogeneous models. The initial U^{235} mass is 307.7 gm per block and decreases to 42.9 gm at the end of 1470 days with Pu^{239} build up at the same time to 53.1 gm per block. The results indicate that 86 % of U^{235} are burned after 1470 days.

Figure 9 illustrates Masses U^{235} and Pu^{239} versus irradiation time for block No. 5 the last fuel block, initial mass of U^{235} is 201.2 gm per block and decreases to 54.85 gm after 1470 days. While Pu^{239} build up to 53.1 gm per block after 1470 days, The results show comparison between Heterogeneous and Homogeneous model. The results indicate that 72.7 % of U^{235} are burned after 1470 days.

Figure 10   Axial power distributions (Kw) for Heterogeneous and homogeneous model.

versus axial distance (cm) for first block (Number 1) The results indicate good agreement between Heterogeneous and Homogeneous. The fuel Enrichment in first block is 6.7 % (see Table 2)

Figure 11 Axial power distributions (Kw) for Heterogeneous and homogeneous model versus axial distance (cm) for Second block (Number 2). The results

indicate also good agreement between Heterogeneous and Homogeneous. The fuel Enrichment in first block is 5.2 % (see Table 2)

Figure 12 Axial power distributions (Kw) for Heterogeneous and homogeneous model versus axial distance (cm) for Fifth block (Number 5) The results indicate also good agreement between Heterogeneous and Homogeneous. The fuel Enrichment in first block is 3.4 % (see Table 2)

Figure 13 shows Temperature coefficient of reactivity for the fuel (pcm / °K) as function of temperature $\alpha_T(\frac{\Delta k}{T})$ calculated from the relation $\frac{\Delta \rho}{\Delta T} = \frac{\Delta k}{K_1 K_2 \ \Delta T}$ the results indicate that α_T has negative value.

Figure 14 shows moderator coefficient of reactivity for the Graphite moderator as function of temperature $\alpha_{T_m}(\frac{\Delta k}{T_m})$ calculated from the relation $\frac{\Delta \rho}{\Delta T_m} = \frac{\Delta k}{K_1 K_2 \ \Delta T_m}$ the results indicate that α_T has also negative value. As the moderator temperature increase the graphite density decrease, It is noted that the relation between temperature and density of graphite is taken from reference [11]. The results indicate that moderator temperature coefficient of reactivity is negative.

The effect of Helium losses (coolant)

It assumed that the density of Helium is reduced to 0.01 of its operational density to calculate the effect of loss of Helium from the core. It is found that ΔK due to Helium loss is -6.49E-3 or -649 pcm. Negative coefficient is expected because Helium contributes to neutron slowing down. Homogeneous model is used in the calculations of fuel, moderator temperature coefficient of reactivity and the effect of helium loss.

V- CONCLUSIONS

MCNPX computer code is used to design two models, heterogeneous and homogeneous models for an assembly of High Temperature Testing Reactor (HTTR). The purpose of the models is to test the efficiency of homogeneous model in the calculation of physical parameters of the HTTR. The model is used to calculate assembly multiplication factor, power distribution and fissile isotopes transmutation. Comparisons of heterogeneous and homogeneous models show that differences between them are in the range of 0.5 to 5 % for burnup time of 1000 days and reaches to 10 % for 1470 days. Run time for homogeneous and heterogeneous models are 1450 and 3249 minutes respectively but it depends on the number of neutrons used to scan the system and details of axial distributions.
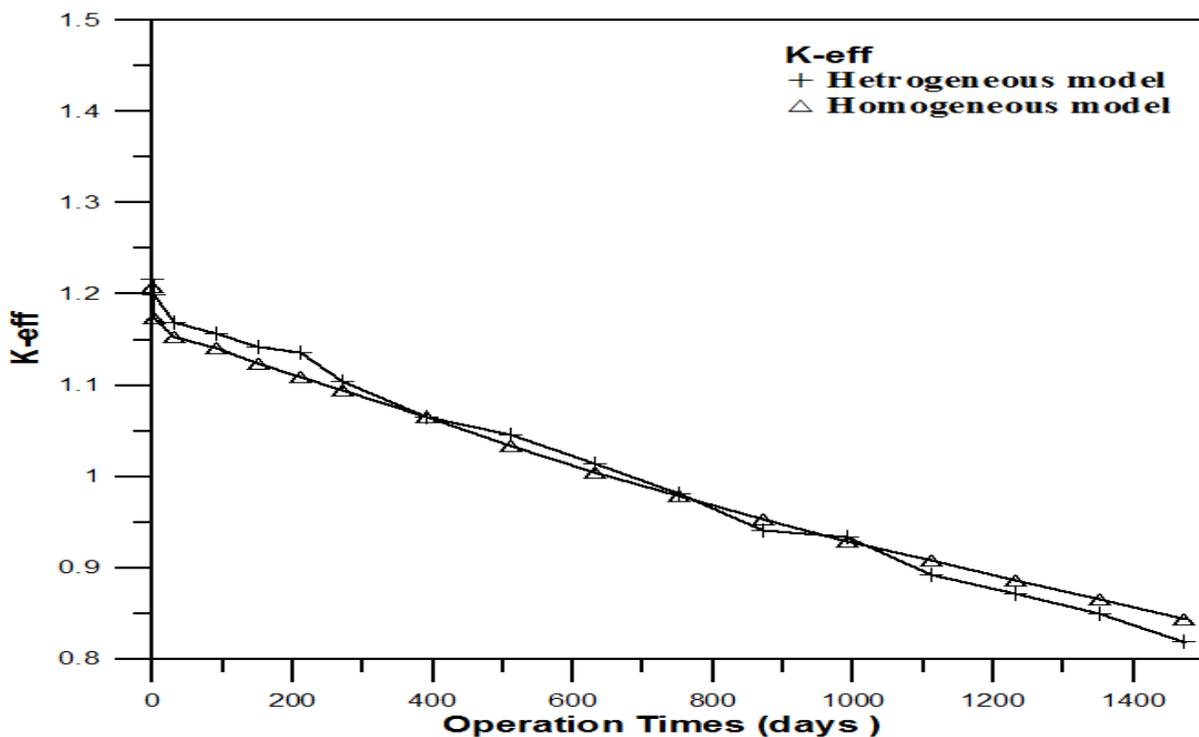
Fig. (6): Multiplication factor for the fuel assembly versus operation times (in days)
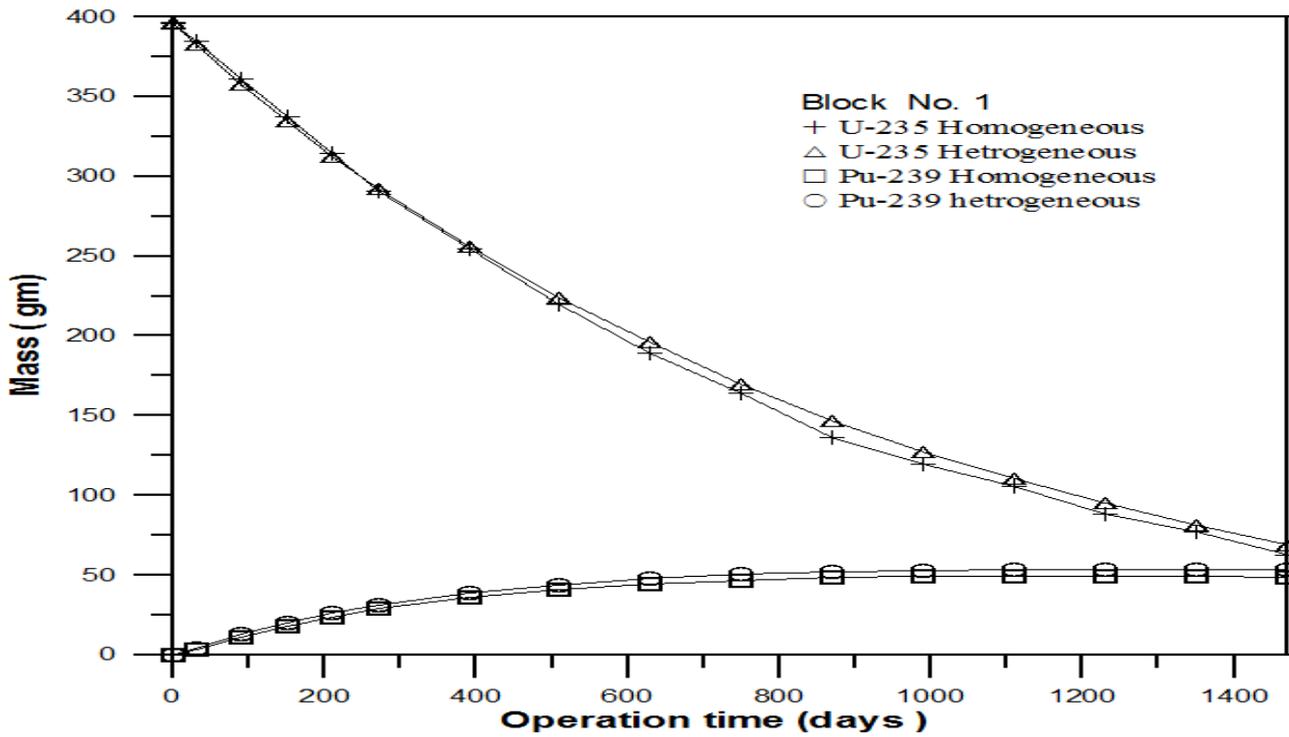
Fig. (7): Comparison between Masses of U^{235} and Pu^{239} versus irradiation time for block 1 for Heterogeneous and Homogeneous models
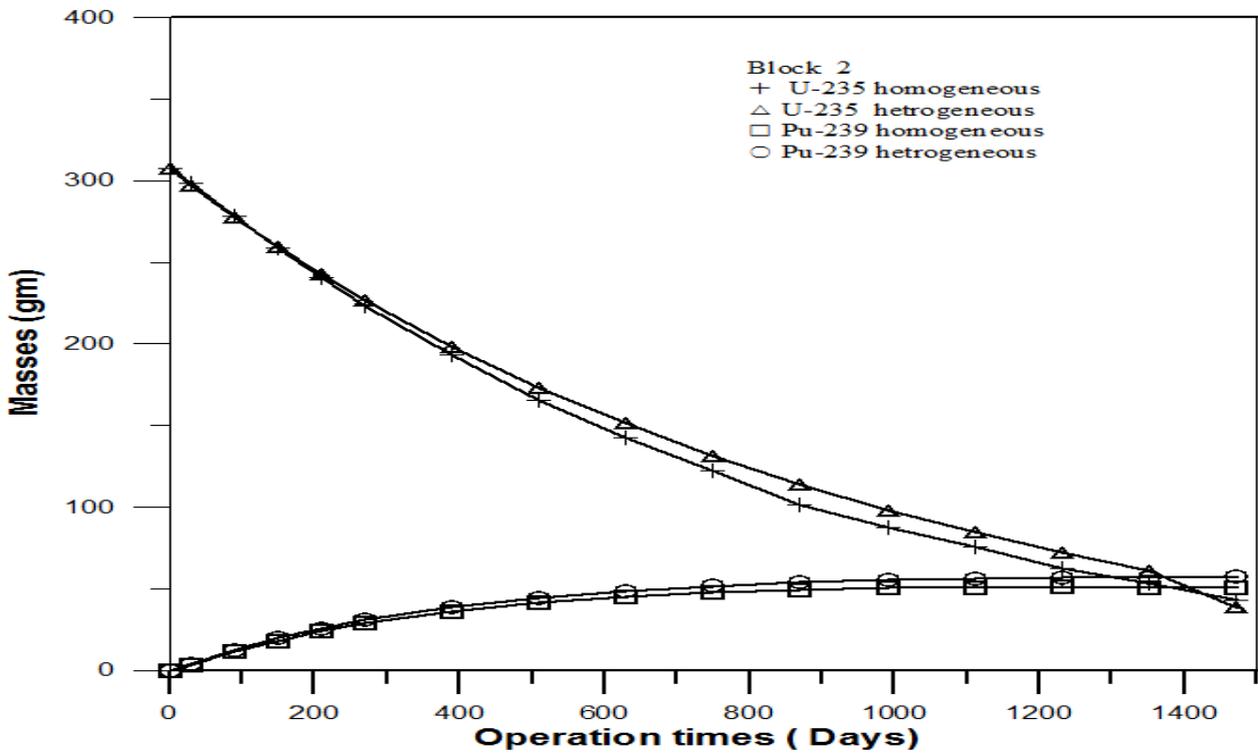
Fig. (8): Comparison between Masses of U^{235} and Pu^{239} versus irradiation time for block 2 for Heterogeneous and Homogeneous models
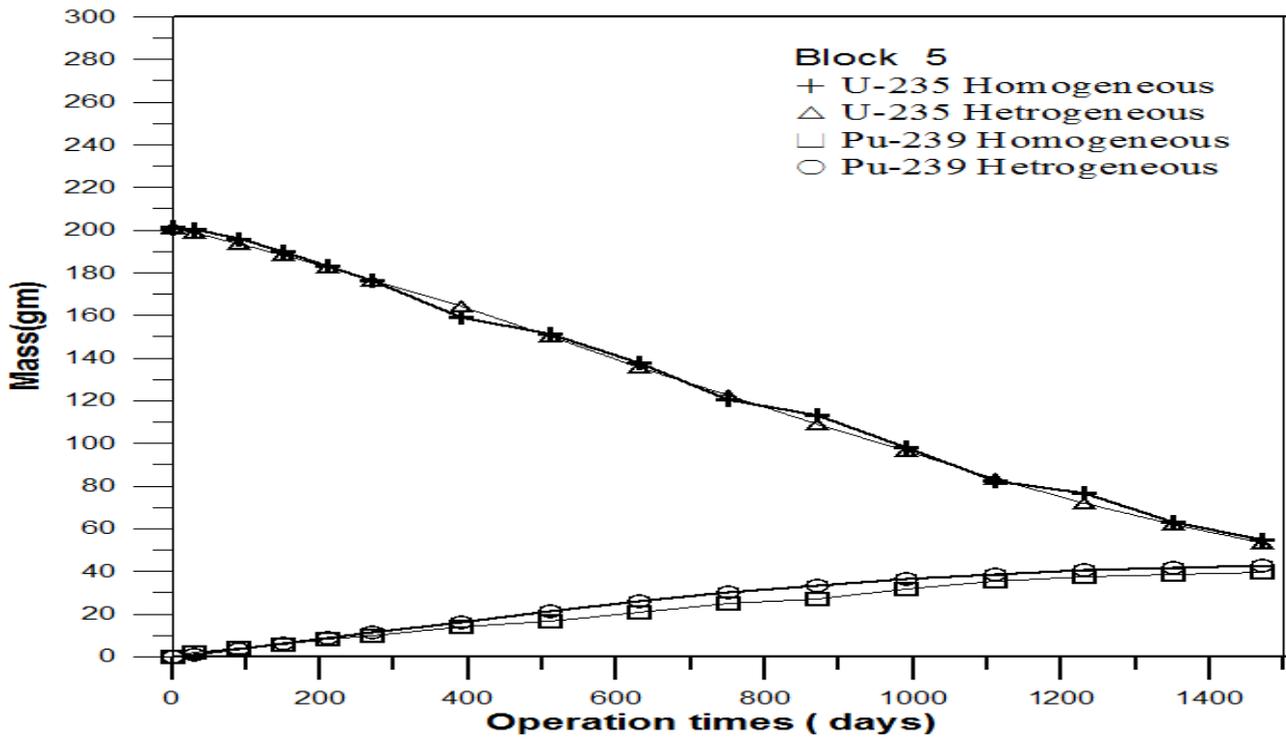
Fig. (9): Comparison between Masses of U^{235} and Pu^{239} versus irradiation time for block 5 for Heterogeneous and Homogeneous models
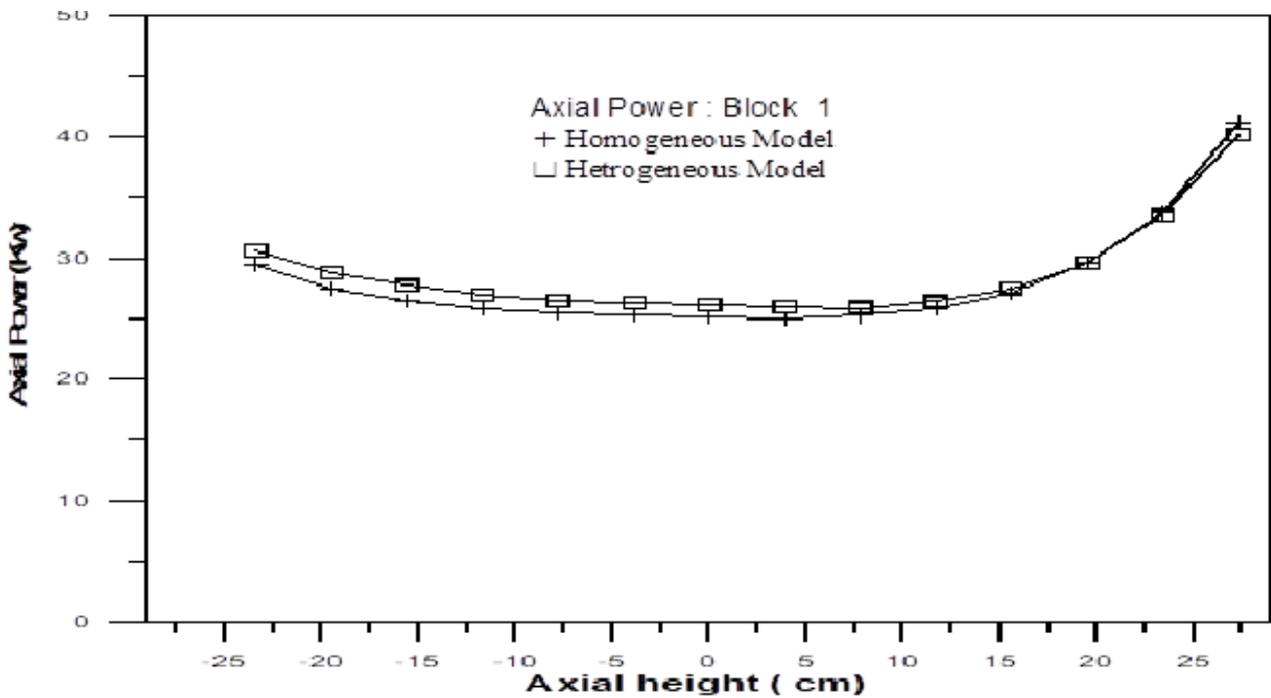
Fig. (10): Axial power distributions (KW) versus axial height for Blok No. 1 for both heterogeneous and homogeneous models
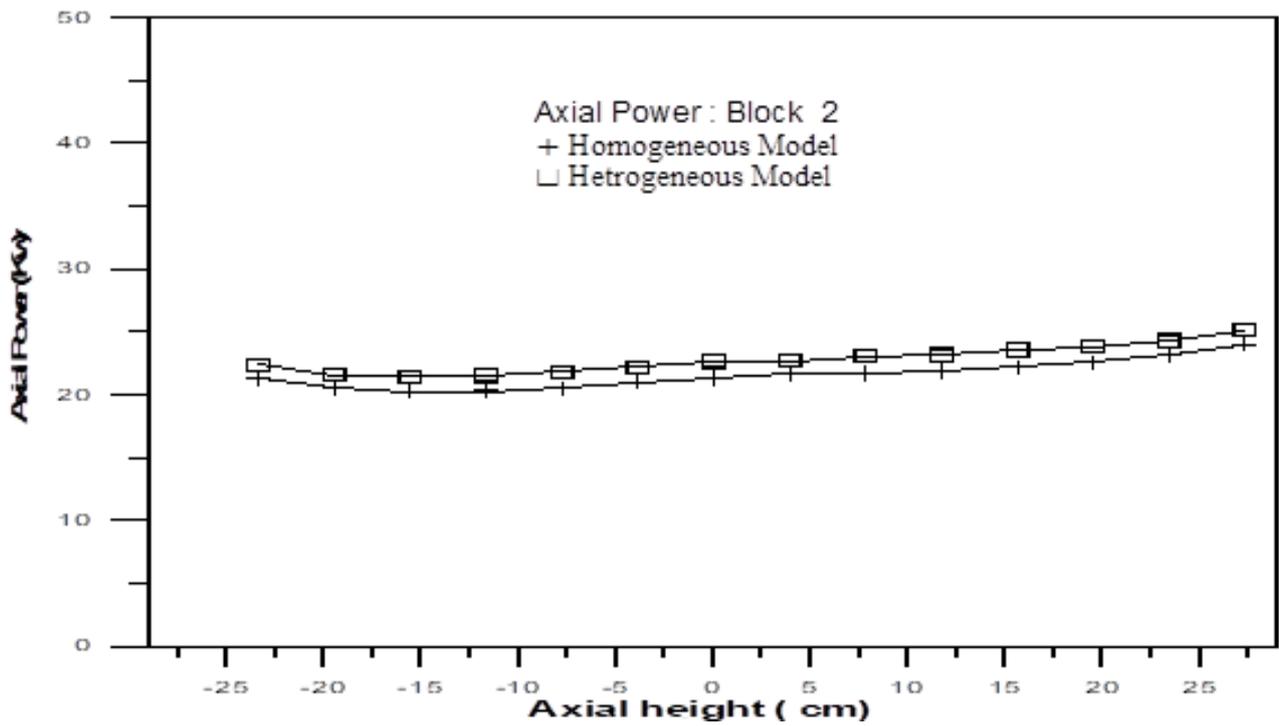
Fig. (11): Axial power distributions (KW) versus axial height for Blok No. 2 for both heterogeneous and homogeneous models
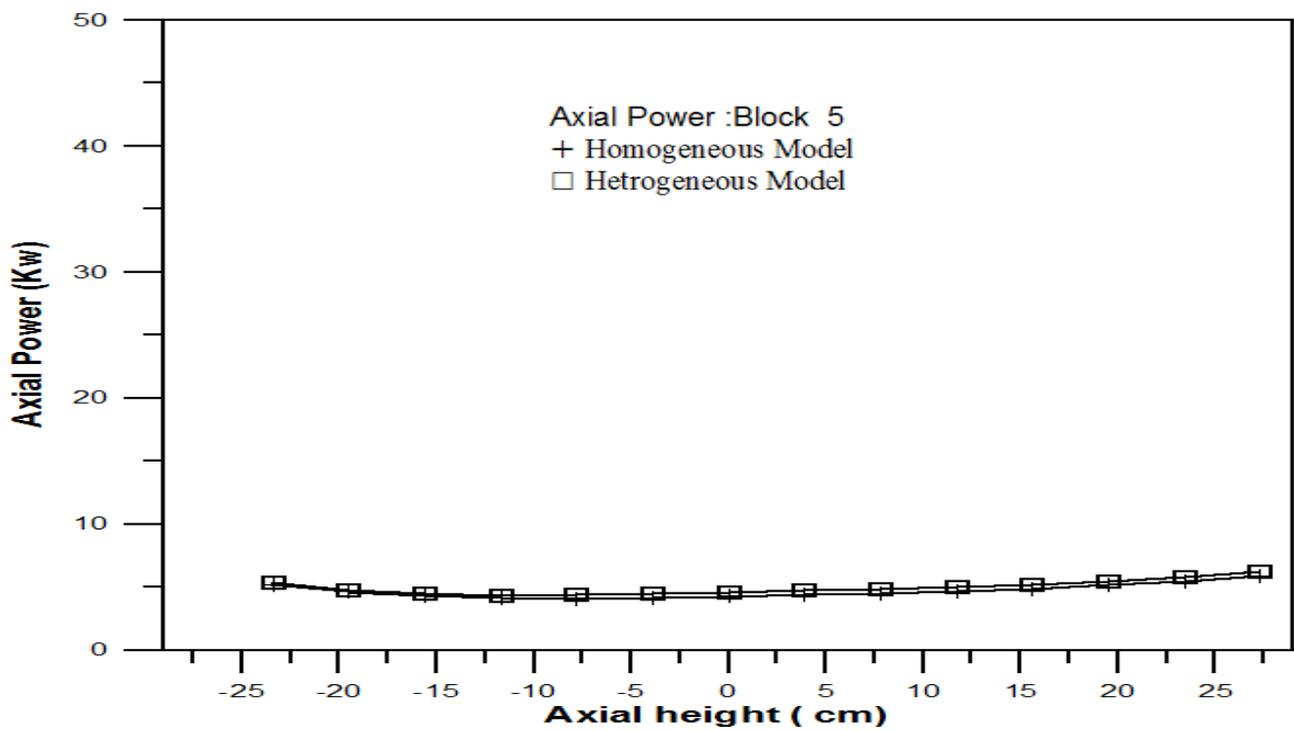
Fig. (12): Axial power distributions (KW) versus axial height for Blok No. 2 for both heterogeneous and homogeneous models
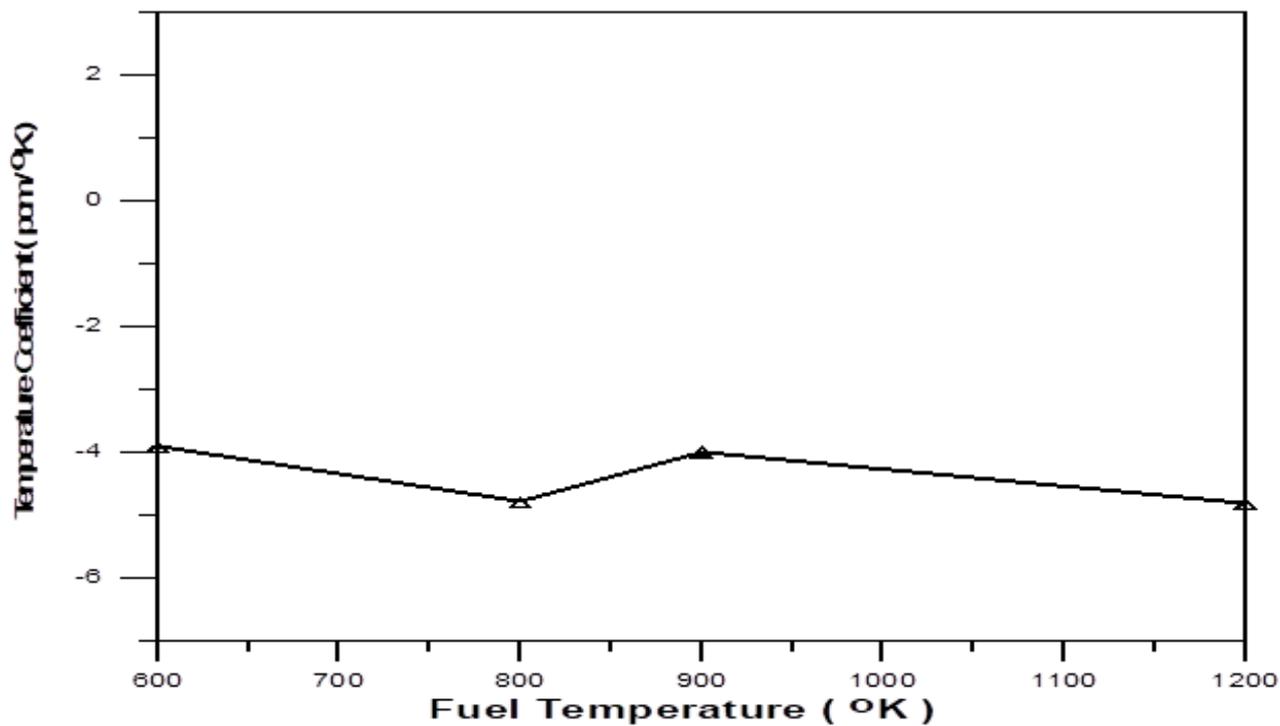
Fig. (13): Temperature coefficient of reactivity (pcm/ K) versus Fuel temperature (ᵒK)
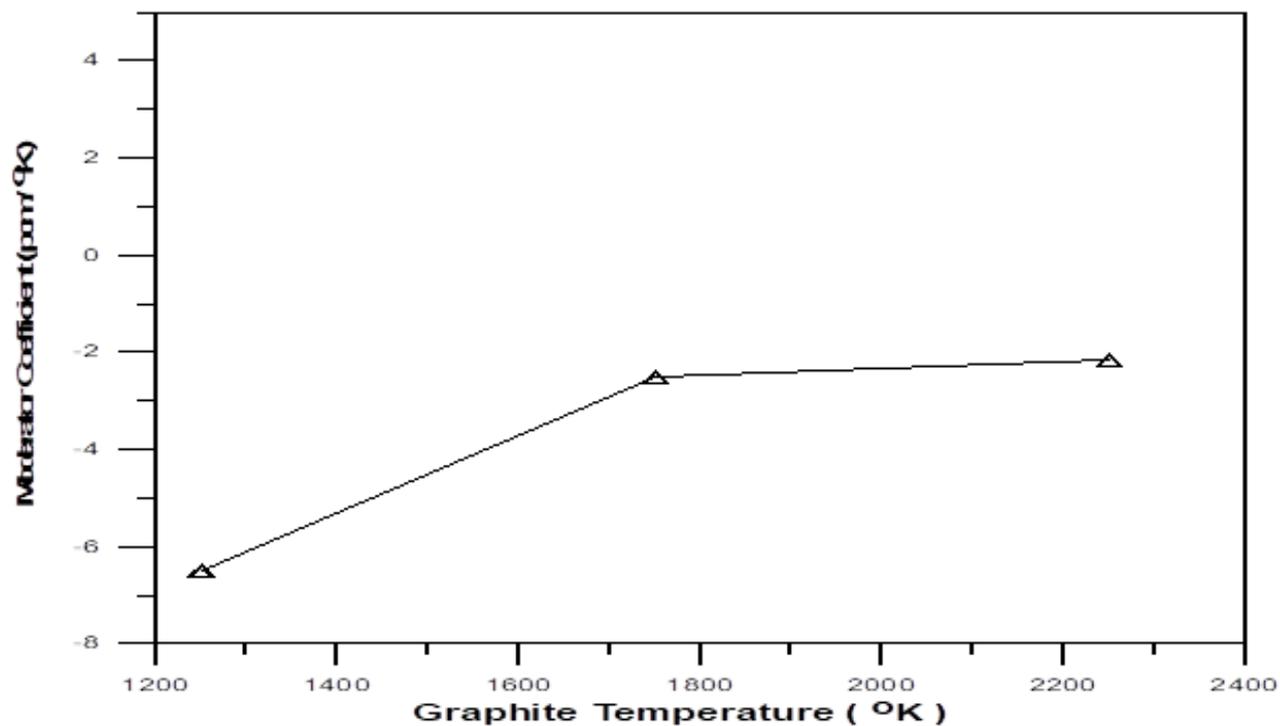
Fig. (14): Moderator coefficient of reactivity (pcm/K) versus Graphite temperature (ᵒK)

VI- REFERENCES

[1] IAEA-TECDOC-1382 Evaluation of high temperature gas cooled reactor performance: Benchmark analysis related to initial testing of the HTTR and HTR-10 November 2003 IAEA , Vienna

[2] J. Ortensi , et. al., Deterministic Modeling of the High Temperature Test Reactor. Idaho National Lab. Next Generation Nuclear Plant Project, Idaho Falls, Idaho 83415 (U S A)

[3] J. D. Bess, N. Fujimoto, J. W. Sterbentz,L. Snoj, and A. Zukeran Evaluation of the StartUp Core Physics Tests at Japan's High Temperature Engineering Test Reactor (Annular Core Loadings). Idaho National Lab. Idaho Falls, Idaho 83415, (U S A) March 2010

[4] J. M. Beck and L. F. Pincock High Temperature Gas-cooled Reactors Lessons Learned Applicable to the Next Generation Nuclear Plant, Idaho National Laboratory, Next Generation Nuclear Plant Project, Idaho Falls, Idaho 83415. April 2011

[5] Goto, N. Nojiri & S. Shimakawa Neutronics Calculations of HTTR with Several Nuclear Data Libraries J. of Nuclear Science and Technology, Vol. 43, No. 10, p. 1237–1244 (2006)

[6] James W. Sterbentz, Bren Phillips, Robert L. Sant, Gray S. Chang, and Paul D. Bayless. Reactor Physics Parametric and Depletion Studies in Support of TRISO Particle Fuel Specification for the Next Generation Nuclear Plant Idaho National Engineering and Environmental Laboratory Bechtel BWXT Idaho, LLC (2004).

[7] J. D. Bess and N. Fujimoto Benchmark Evaluation of Start-Up and Zero-Power Measurements at the High-Temperature Engineering Test Reactor.

[8] D.Chapin,S. Kiffer and J. Nestell The Very High Temperature Reactor: A Technical Summary, MPR Associates, Inc 320 King Street Alexandria, VA 22314

[9] W. S. Yang and H. S. Khalil, Whole-core depletion studies in support of fuel specification for the next generation nuclear plant (NGNP) core Nuclear Engineering Division, 9700 South Cass Avenue,Argonne National Laboratory Argonne, IL 60439 (2004)

[10] Hendricks J. S. et.,al. MCNPX2.6D Computer Code package. Los Alamos National Lab. (2007) LA-UR 074137

[11] V N Senchenko and R S BelikovExperimental investigation of linear thermal expansion of pyrolytic graphite at high temperatures. IOP conf. Series: Journal of physics: Conf. Series 891 (2017) 012338