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Verify Super Double-Heterogeneous Spherical Lattice Model for Equilibrium Fuel Cycle Analysis AND HTR Spherical Super Lattice Model for Equilibrium Fuel Cycle Analysis

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Verify Super Double-Heterogeneous Spherical Lattice Model for Equilibrium Fuel Cycle Analysis

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Introduction

Advanced High Temperature gas-cooled Reactors (HTR) currently being developed (GFR, VHTR - Very High Temperature gas-cooled Reactor, PBMR, and GT-MHR) are able to achieve a simplification of safety through reliance on innovative features and passive systems. One of the innovative features in these HTRs is reliance on ceramic-coated fuel particles to retain the fission products even under extreme accident conditions. The effect of the random fuel kernel distribution in the HTR is addressed through the use of the Dancoff correction factor in the resonance treatment. In addition, the Dancoff correction factor is a function of burnup and fuel kernel packing factor, which requires that the Dancoff correction factor be updated during Equilibrium Fuel Cycle (EqFC) analysis.

The double-heterogeneous MCNP model recently developed at the Idaho National Engineering and Environmental Laboratory (INEEL) contains tens of thousands of cubic fuel kernel cells, which makes it very difficult to deplete the fuel, kernel by kernel (KbK), for the EqFC analysis. In addition, it is not possible to preserve the cubic size and packing factor in a spherical fuel pebble. To avoid these difficulties, a newly developed and validated HTR pebble-bed Kernel-by-Kernel spherical (KbK-sph) model, has been developed and verified in this study. The verified double-heterogeneous KbK-sph MCNP[1] model will be used for a genetic HTR EqFC analysis and important safety parameters validation.

HLM Lattice Model and Results

The Next Generation Nuclear Plant (NGNP)[2] pebble unit lattice was chosen as a reference case in this study. NGNP pebble unit lattice consisted of a graphite reflected, 8.0 wt% enriched, uranium pebble-bed system. NPNG fuel zone contains 13,271 discrete TRISO fuel kernels[4] (UO_2, OD = 0.05 cm, density = 10.7 g/cc). The pebble fuel zone has an OD = 5.0 cm (fuel C-matrix zone volume = 65.45 cm^3), graphite shell OD = 6.0 cm, and a pebble packing factor = 0.64. The kernel density = 13,271 / 65.45 = 202.8 kernels / cm^3.

The homogeneous lattice model (HLM) consists of fuel kernels in a graphite matrix zone, graphite and Si-C outer zone, and He filled void zone (void volume ratio = 1 - 0.64). First, the homogenized pebble fuel zone x-y angle ($0° < \theta$ 360°) was divided into 30 shells as shown in Fig. 1. Then, the x-z cone angle ($\Delta\varphi$=4.15°) was selected to cut the one of 1/30 sliced sphere to 1/13.824 (13271 / 30 / 32 = 13.824) divided volume, such that each divided slice will contain 32 fuel kernels, which is the number of kernels in each divided slice of the Super KbK-sph lattice model. Note that 13.824 is not an integer-multiple of 2. Then, these three zones are bounded by two pairs of reflecting (θ, ϕ) boundaries, and an outer He gas filled white boundary as shown in the Fig. 1.

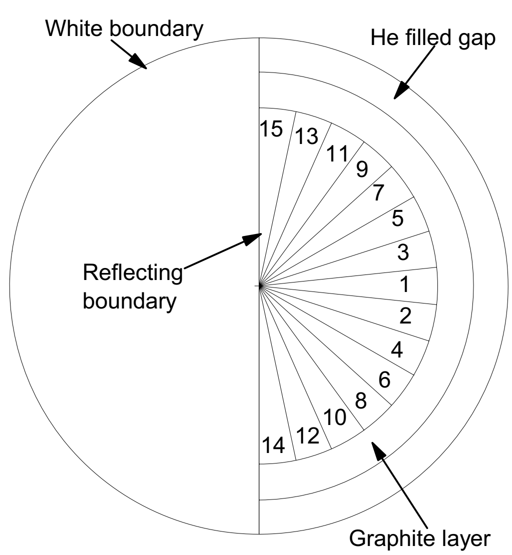

Figure 1. X-Y cross-section view of a double-heterogeneous triangular fuel unit lattice model with fuel kernels.

There are 9 homogeneous fuel zone cases:
(1) One whole pebble,
(2) One slice of x-y angle (0° < φ < 360°),
(3) Three slices of x-y angle (0° < φ < 360°),
(4) Five slices of x-y angle (0° < φ < 360°),
(5) Seven slices of x-y angle (0° < φ < 360°), (6) Nine slices of x-y angle (0° < φ < 360°),
(7) 11 slices of x-y angle (0° < φ < 360°),
(8) 13 slices of x-y angle (0° < φ < 360°), and
(9) 15 slices of x-y angle (0° < φ < 360°).

The MCNP-calculated K_∞ of the single-heterogeneity of the HLM, i.e. without fuel kernel self-shielding by smearing the fuel kernels in the fuel zone, of these nine cases are 1.401675±0.0006, 1.400787±0.0006, 1.399847±0.0007, 1.399738±0.0007, 1.402251±0.0007, 1.400266±0.0007, 1.400951±0.0007, 1.399698±0.0006, 14.00162±0.0006, respectively.

For each case, the MCNP KCODE mode (with PVM = 4 tasks, 80 cycles with 5000 source neutrons) calculation run requires 60 minutes of DELL-650 XEON-2-CPU 3.06 GHz workstation computer time to achieve a one standard deviation (1σ) less than 0.06%.Theses results indicate that a whole pebble lattice can be represented by any number of slices of pebble in the HLM. As a result, the KbK-sph model, which contains only 32 fuel kernels in each slice with reflecting boundaries, can adequately represent the randomly distributed 13,271 fuel kernels.

Super KbK-sph Lattice Model and Result

To build a super double-heterogeneous MCNP Kernel-by-Kernel particle Fuel with a spherical lattice (KbK-sph) model from HLM with 10 fuel pebble slices, first, each fuel zone slice volume is 65.45/30.0 /13.824 = 0.1578 cm^3, which will contain exactly 32 fuel kernels. Then, the fuel C-matrix is spherically divided into 32 equal-volume shells, such that, each sub-shell contains one fuel kernel to maintain a constant kernel density, as shown in the Fig. 2. To make 32 kernels distribute more random-yet-orderly, the fuel kernel was allocated by the cone-shaped spiral curve around the slice median-axis in each of 32 subdivided radial shells.

The MCNP-calculated K_∞ of the single-heterogeneity of the HLM, i.e. without fuel kernel self-shielding by smearing the fuel kernels and pebble and the double-heterogeneity KbK-sph model are 1.4007±0.0006 and 1.5008±0.0005, respectively, which represents a ΔK = 0.1001. The verification and validation (V&V) of the HTR one slice lattice KbK-sph model was presented in Ref. 3 and 4.

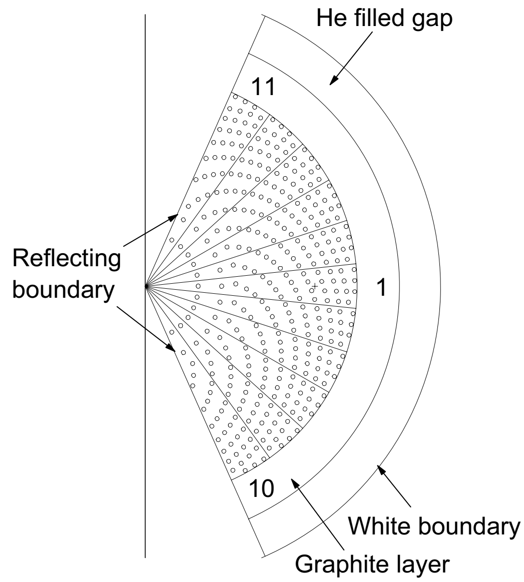

Figure 2. X-Y cross-section view of a super double-heterogeneous KbK lattice model with random orderly fuel kernel distribution

The NGNP (600 MWt) design can achieve a continuous on power refueling cycle with pebble total residence time of about 660 days. Let us assume the number of passes per pebble is 11 (this number can be varied to a specific design need) and 60 days per one fuel shuffling interval. The EqFC can be achieved by the following shuffling scheme. At the beginning of the 2nd 60 effective full power days (EFPD), slice one will be reset to fresh fuel kernels, while the rest of fuel slices are kept the same for the new 60 EFPD cycle. At the beginning of 3rd 60 EFPD cycle, the 2nd fuel slice will be reset to fresh fuel kernels. The beginning of EqFC state can be achieved at the beginning of 11th shuffling cycle by resetting the 10th fuel slice to fresh fuel kernels. Then, at the end of 11th shuffling cycle, the 11th slice will achieve the discharge burnup with 660 EFPD.

Conclusions

In this study, we show that HLM and KbK-sph models with any number of slices of pebble can adequately represent the whole pebble lattice characteristics. The double-heterogeneous KbK-sph model with fuel pebble used in this study can handle the complex spectral transitions at the boundaries between the kernels in a straightforward fashion and treat the entire lattice at once.

A new verified depletion tool MCWO[5], (MCNP coupled With ORIGEN-2[6]) will be used to analyze the KbK-sph and HLM EqFC burnup characteristics. The MCWO-calculated results, such as, K_∞ , Xe-worth, and important burnup characteristics versus EFPD are compared and discussed in the further study.

The KbK-sph and HLM and MCWO can be used to perform the neutronics analysis for particle fuel testing in the Advanced Test Reactor (ATR). The KbK-sph and HLM can also be used in a wide variety of other applications, including advanced HTR (both fast and thermal neutron flux Gen-IV reactors) fuel cycle performance analysis, long life minor actinide transmutation, strong absorber depletion analysis, and HTR fuel and reactor materials test assembly design.

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HTR Spherical Super Lattice Model for Equilibrium Fuel Cycle Analysis

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ABSTRACT

The currently being developed advanced High Temperature gas-cooled Reactors (HTR) is able to achieve a simplification of safety through reliance on innovative features and passive systems. One of the innovative features in these HTRs is reliance on ceramic-coated fuel particles to retain the fission products even under extreme accident conditions. Traditionally, the effect of the random fuel kernel distribution in the fuel pebble / block is addressed through the use of the Dancoff correction factor in the resonance treatment. However, the Dancoff correction factor is a function of burnup and fuel kernel packing factor, which requires that the Dancoff correction factor be updated during Equilibrium Fuel Cycle (EqFC) analysis.

An advanced KbK-sph model and whole pebble super lattice model (PSLM), which can address and update the burnup dependent Dancoff effect during the EqFC analysis. The pebble homogeneous lattice model (HLM) is verified by the burnup characteristics with the double-heterogeneous KbK-sph lattice model results. This study summarizes and compares the KbK-sph lattice model and HLM burnup analyzed results. Finally, we discuss the Monte-Carlo coupling with a fuel depletion and buildup code - ORIGEN-2 as a fuel burnup analysis tool and its PSLM calculated results for the HTR EqFC burnup analysis.

KEYWORD: Monte-Carlo, ORIGEN-2, MCWO, HTR, Equilibrium Fuel Cycle (EqFC) analysis.

1. INTRODUCTION

Advanced High Temperature gas-cooled Reactors (HTR) currently being developed (GFR, VHTR - Very High Temperature gas-cooled Reactor, PBMR, and GT-MHR) are able to achieve a simplification of safety through reliance on innovative features and passive systems. One of the innovative features in these HTRs is reliance on ceramic-coated fuel particles to retain the fission products even under extreme accident conditions. The effect of the random fuel kernel distribution in the fuel pebble / block is addressed through the use of the Dancoff correction factor in the resonance treatment. The Dancoff correction factor is a function of burnup and fuel kernel packing factor, which requires that the Dancoff correction factor be updated during Equilibrium Fuel Cycle (EqFC) analysis.

Although HTR fuel is rather homogeneously dispersed in the fuel graphite matrix, the heterogeneity effects in between fuel kernels and pebbles cannot be ignored. The double-heterogeneous lattice model recently developed at the Idaho National Laboratory (INL) contains tens of thousands of cubic fuel kernel cells, which makes it very difficult to deplete the fuel, kernel by kernel (KbK), for the fuel burnup analysis. In addition, it is not possible to preserve the cubic size and packing factor in a spherical fuel pebble. To avoid these difficulties, a newly developed and validated HTR pebble-bed Kernel-by-Kernel spherical (KbK-sph) model, has been developed and verified in this study.

The objective of this research is to introduce the KbK-sph model and whole pebble super lattice model (PSLM), which is used for EqFC analysis. The pebble homogeneous lattice model (HLM) is verified by the burnup characteristics with the double-heterogeneous KbK-sph lattice model results. This study summarizes and compares the KbK-sph lattice model and HLM burnup analyzed results. Finally, we discuss the Monte-Carlo coupling with a fuel depletion and buildup code - ORIGEN-2 as a fuel burnup analysis tool and its PSLM calculated results for the HTR EqFC burnup analysis.

2. HTR PEBBLE HOMOGENIZED LATTICE MODEL

The Next Generation Nuclear Plant (NGNP)[1] pebble unit lattice was chosen as a reference case in this study. Next Generation Nuclear Plant (NGNP) pebble unit lattice consists of a graphite reflected, 8.0 wt% enriched, uranium pebble-bed system. NPNG fuel zone contains 13,271 discrete TRISO fuel kernels (UO2, OD = 0.051 cm, density = 10.7 g/cc). The pebble fuel zone has an OD = 5.0 cm (fuel C-matrix zone volume = 65.45 cm^3), graphite shell OD = 6.0 cm, and a pebble packing factor = 0.64. The kernel density = 13,271 / 65.45 = 202.8 kernels / cm^3.

The pebble HLM consists of homogenized fuel kernels in a graphite matrix zone, graphite and Si-C outer zone, and He filled gap zone (He-coolant volume ratio = 1 - 0.64). First, the homogenized pebble fuel zone x-y angle ($0° < \theta \;\; 360°$) was divided into 30 shells as shown in Fig. 1. Using the one intersected volume formula,

$$V = \int_0^{360/30} d\theta \int_0^{7.96} d\varphi \int_0^{2.5} r^2 \sin\varphi dr,$$

the x-z cone angle ($\Delta\varphi$=7.96°) was selected to cut the 1/30 sliced sphere to a 1/13.824 (13271 / 30 / 32 = 13.824) divided volume, such that each divided slice will contain 32 fuel kernels, which is the number of kernels in each divided slice of the KbK-sph Super lattice model. Note that 13.824 is not an integer-multiple of 2. Then, these three zones are bounded by two pairs of reflecting (θ, ϕ) boundaries, and an outer He gas filled white boundary as shown in the Fig. 1.

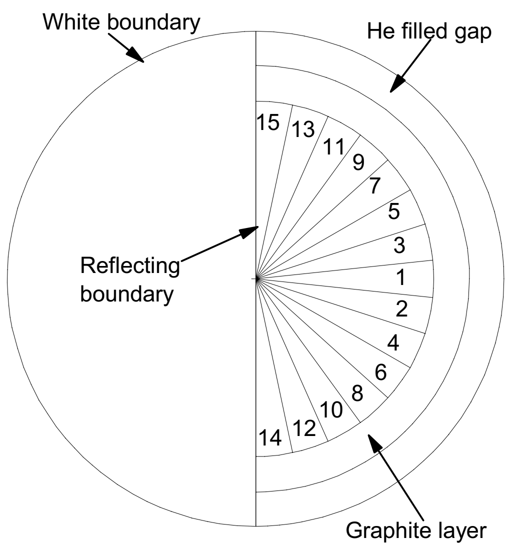

Figure 1. X-Y cross-section view of the multiple single-heterogeneous triangular fuel unit lattice models.

From Fig. 1, we setup 9 HLM cases:
(1) One whole pebble,
(2) One slice of x-y angle ($0° < \theta \; < 360°$),
(3) Three slices of x-y angle ($0° < \theta \; < 360°$),
(4) Five slices of x-y angle ($0° < \theta \; < 360°$),
(5) Seven slices of x-y angle ($0° < \theta \; < 360°$),
(6) Nine slices f x-y angle ($0° < \theta \; < 360°$),

(7) 11 slices of x-y angle (0° < θ < 360°),
(8) 13 slices of x-y angle (0° < θ < 360°), and
(9) 15 slices of x-y angle (0° < θ < 360°).

The MCNP-calculated K_∞ of the single-heterogeneity of the HLM, i.e. without fuel kernel self-shielding by smearing the fuel kernels in the fuel zone, of these nine cases are 1.401675±0.0006, 1.400787±0.0006, 1.399847±0.0007, 1.399738±0.0007, 1.402251±0.0007, 1.400266±0.0007, 1.400951±0.0007, 1.399698±0.0006, 1.400162±0.0006, respectively.

For each case, the MCNP KCODE mode (with PVM = 4 tasks, 80 cycles with 5000 source neutrons) calculation run requires 60 minutes of DELL-650 XEON-2-CPU 3.06 GHz workstation computer time to achieve a one standard deviation (1σ) less than 0.06%. These results indicate that a whole pebble lattice can be represented by any number of slices of pebble in the HLM. As a result, the KbK-sph model, which contains only 32 fuel kernels in a single slice with reflecting boundaries, can adequately represent the randomly distributed 13,271 fuel kernels. The detailed verification of the HTR one slice lattice KbK-sph model was presented in Ref. 2 and 3.

3. KbK-sph LATTICE MODEL

To build a double-heterogeneous MCNP Kernel-by-Kernel particle fuel with a spherical (KbK-sph) lattice model from HLM with one fuel pebble slice, first, each fuel zone slice volume is 65.45/30.0 /13.824 = 0.1578 cm^3, which will contain exactly 32 fuel kernels. Then, the fuel C-matrix is spherically divided into 32 equal-volume shells, such that, each sub-shell contains one fuel kernel to maintain a constant kernel density, as shown in the Fig. 2. To make 32 kernels distribute more random-yet-orderly, the fuel kernel was allocated by the cone-shaped spiral curve around the slice median-axis in each of 32 subdivided radial shells.

The MCNP-calculated K_∞ of the HLM and the double-heterogeneity KbK-sph lattice model are 1.4045±0.0006 and 1.5216±0.0005, respectively, which represents a ΔK = 0.167.

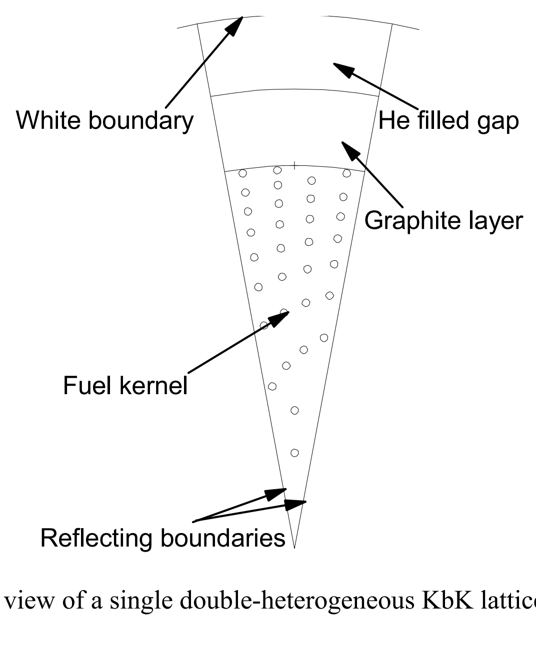

Figure 2. X-Y cross-section view of a single double-heterogeneous KbK lattice model with random orderly fuel kernel distribution.

4. HOMOGENIZED PEBBLE SUPER LATTICE MODEL

The NGNP (600 MWt) design with average pebble power density of 850 W/Pebble can achieve a continuous on power refueling cycle with pebble total residence time of about 660 days. A whole PSLM was setup as shown in Fig. 3 for the EqFC analysis.

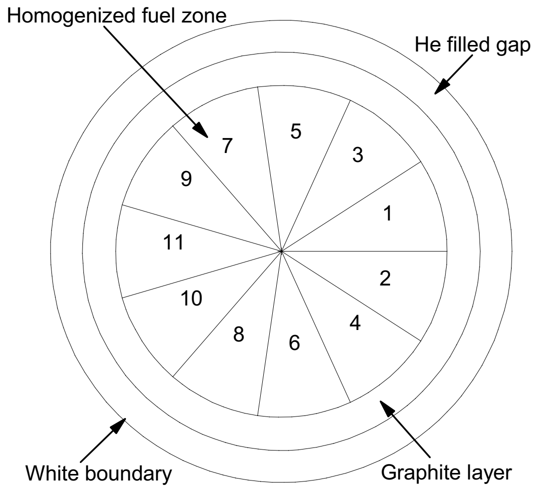

Figure 3. X-Y cross-section view of a whole Pebble super lattice model (PSLM) with 11 sliced homogeneous fuel zone.

The NGNP (600 MWt) design can achieve a continuous on power refueling cycle with pebble total residence time of about 660 days. The EqFC can be achieved by the following shuffling scheme. Let us assume the number of passes per pebble is 11 (this number can be varied to a specific design need) and 60 days per one fuel shuffling interval. The EqFC can be achieved by the following shuffling scheme. At the beginning of the 2nd 60 effective full power days (EFPD), slice one will be reset to fresh fuel kernels, while the rest of the fuel slices are kept the same for the new 60 EFPD cycle. At the beginning of 3rd 60 EFPD cycle, the 2nd fuel slice will be reset to fresh fuel kernels. The beginning of EqFC state can be achieved at the beginning of the 11th cycle by resetting the 10th fuel slice to fresh fuel kernels. Then, at the end of the 11th cycle, the 11th slice will achieve the discharge burnup with 660 EFPD.The corresponding whole PSLM with 11 sliced homogeneous fuel zones is shown in Fig. 3. EqFC burnup analysis of a PSLM is performed and its results will be discussed in the following sections.

5. MCWO METHOD

The major source of uncertainty in the fuel burnup calculation comes from burnup-dependent cross-section (XS), resonance treatment of neutron spectrum vs. fuel enrichment, and minor long-life actinide XS. A new verified depletion tool MCWO[4], (<u>MC</u>NP[5] coupled <u>W</u>ith <u>ORIGEN</u>-2[6]) was used to analyze the KbK-sph and HLM fuel cycle burnup characteristics. MCWO, which can update the actinide XS at the beginning of each time step, is a UNIX shell script that couples the MCNP and ORIGEN2 computer codes automatically from Beginning of Life (BOL) to End of Life (EOL) without the need for any manual interface. The flow chart of the MCWO calculation is shown in Fig. 4.

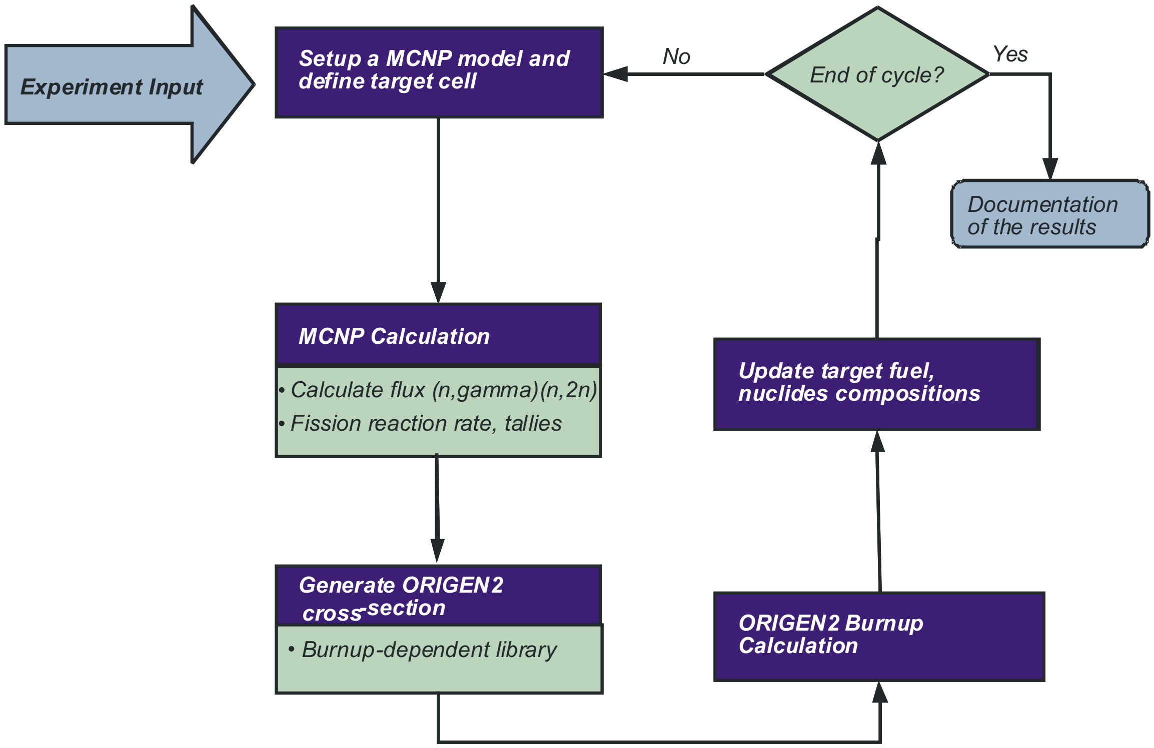

Figure 4. Schematic flow chart of MCNP Coupling with ORIGEN2 codes.

The validated MCWO and lattice models can provide accurate neutronics characteristics of the particle fuel burnup performance. The KbK-sph model takes the double-heterogeneity of the HTR fuel unit cell into account, i.e. self-shielding of the fuel kernels, which can handle the complex spectral transitions at the boundaries between the fuel kernel and graphite matrix and treat the entire lattice at once. Particularly, the KbK-sph model can analyze the mix of fissile and fertile kernels in the fuel compact burnup performance and neutronics characteristics in a Kernel-by-Kernel fashion.

6. RESULTS AND DISCUSSION

MCWO was used in this study to analyze HTR KbK-sph lattice model with a double-heterogeneity for the detailed Kernel-by-Kernel burnup characteristic analysis. The average effective full power of a pebble is assumed to be 850 W/cm^3. The MCWO-calculated (with each depletion time interval set to 20 effective full power days - EFPD) results, such as, K_∞, Xe-worth, and relative slice's fission power density versus EFPD are presented and discussed.

6.1. Comparison of KbK-sph Lattice Model and HLM versus EFPD

MCWO was used to analyze the KbK-sph lattice model and PLM burnup chracteristics, such as, K_∞ and Xe-worth versus the burnup. The MCWO and KbK-sph-; HLM-calculated K_∞ versus EFPD is shown in Fig. 4. As discussed in the previous section, the MCNP-calculated K_∞ of KbK-sph and PLM at BOL has a $\Delta K = 0.1029$. The ΔK of MCWO-calculated K_∞ of KbK-sph lattice model and HLM keeps almost constant versus burnup. The same small ΔK variation between the Kernel-by-Kernel and the homogenized lattice model in a VHTR hexagonal fuel block system was observed and discussed in Ref. 7. The results in Fig. 4 suggest that we can use a simpler homogenized super PLM, as shown in Fig. 2, to perform the HTR EqFC analysis in the next section.

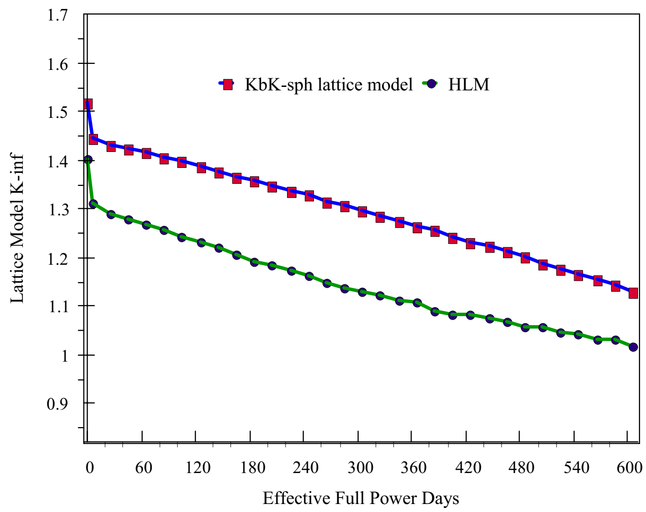

Figure 4. K_∞ comparison of KbK-sph and HLM lattice models versus EFPD.

Using the formula Xe-reactivity worth ($) = ℓn ($K_{xe}/K_{xe=0}$) / delayed neutron fraction (0.0072), the MCWO-calculated the MCWO-calculated Xe-reactivity worth ($\Delta\rho_{Xe}$) of the KbK-sph lattice model and HLM versus EFPD is shown in Fig. 5. The averaged $\Delta\rho_{Xe}$ of the KbK-sph lattice model and HLM are -$7.91 and -$6.99, respectively, which represents a Δk = $0.92. Fig. 5 indicates that the important safety parameter $\Delta\rho_{Xe}$ provided by the HLM needs to be validated by the KbK-sph lattice model.

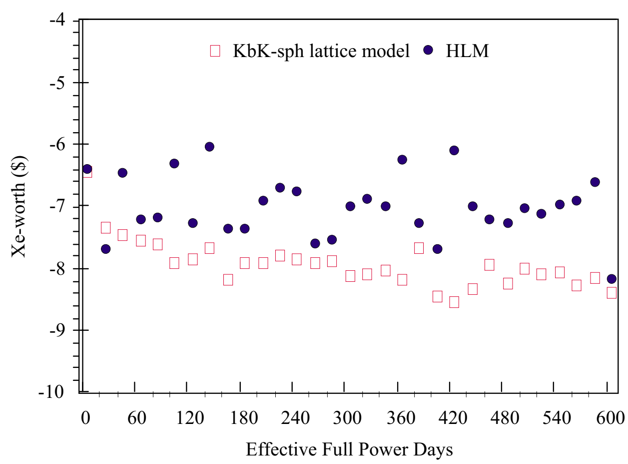

Figure 5: Xe-worth comparison of KbK-sph and PLM lattice models versus burnup

6.2. EqFC Burnup Characteristics versus Refueling Cycles

The MCWO-calculated K_∞ of a super PSLM versus assumed refueling cycles (60 EFPD) during EqFC analysis is shown in Fig. 6. At the beginning of each refueling cycle, the corresponding fuel slice in PLM is reset to the fresh fuel, which cause a K_∞ jump as shown in Fig. 6. The Fissions per Initial heavy Metal Atom (FIMA) at discharged burnup (660 EFPD) is 8.05%. The K_∞ of PSLM at the middle of 11^{th} EqFC state is 1.11 plus an offset ΔK = 0.1029, which can provide an adequate excess reactivity for the neutron leakage compensation and HTR power load control.

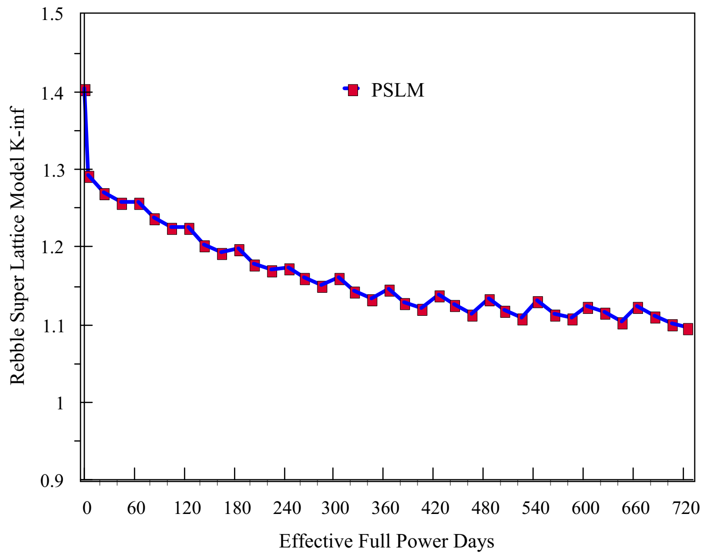

Figure 6. K_∞ of PSLM super lattice model versus refueling cycles

MCWO-calculated relative slice's fission power density versus EFPD during the refueling cycles are plotted in Fig. 7, which reveals that the refreshed slice will bump the local power density to average ratio (L2AR) as we expected.

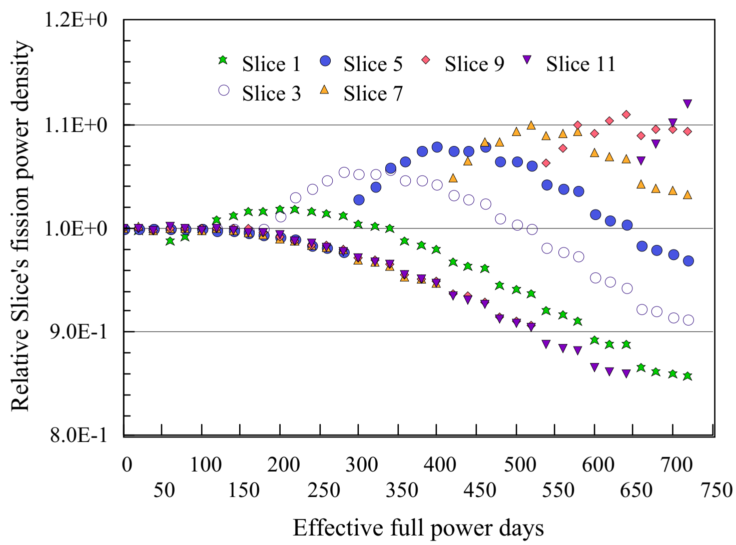

Fig. 7. Relative slice's fission power density versus refueling cycles.

When PSLM reached 11th refueling cycle, the L2AR of the 11th fuel slice is 1.11, which indicates that the refueled fresh pebble needs to contain a certain amount of burnable poison to reduce the peak power density.

7. CONCLUSIONS

In this study, we show that HLM and KbK-sph lattice models with any number of slices of a pebble can adequately represent whole pebble lattice neutronics burnup characteristics. The double-heterogeneous KbK-sph model with fuel pebble used in this study can handle the complex spectral transitions at the boundaries between the kernels in a straightforward fashion and treat the entire lattice at once. The

MCWO-calculated results in this study indicate that there is an rather constant ΔK_∞ between KbK-sph lattice model and HLM versus burnup. It shows that the PSLM can be used in the HTR EqFC analysis. However, the difference of ΔXe-worth between KbK-sph lattice model and HLM is about $0.92. It suggests that a further study is needed to establish an extended correlation between KbK-sph and HLM lattice models over the important safety parameters, such as, Doppler, temperature and void coefficients, etc. In the PSLM EqFC analysis also shows that L2AR of 11^{th} fuel slice, during the 11^{th} refueling cycle, increases to about 1.11. How to reduce this L2AR during refueling needs further study.

The developed MCWO and KbK-sph model can provide accurate neutronics characteristics of the particle fuel burnup performance. The KbK-sph model can simulate the double-heterogeneity of the HTR fuel unit lattice without the Dancoff correction factor preparation. The method developed in this work can be used in the HTR safety related confirmatory analysis. The KbK-sph model can also be used in a wide variety of other applications, including advanced HTR (both fast and thermal neutron flux Gen-IV reactors) fuel cycle performance analysis. The KbK-sph model and MCWO can also be used to perform the neutronics analysis for particle fuel testing in the Advanced Test Reactor (ATR).

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