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Fuel Performance Analysis of BEAVRS Benchmark Cycle 1 Depletion using MCS

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1. Introduction

With the increase of computational capability and the requirement of Monte Carlo neutron transport, the CORE group at UNIST has been developing Monte Carlo neutron transport code – MCS [1], which will be applied in whole analysis with high fidelity especially for large scale LWRs, instead of only one reference tools for benchmark testing. Correspondingly, the CTF [2] and FRAPCON [3] have been fully coupled within it to construct the MCS based multi-physic coupling code system [4,5].

The thermal/hydraulic analysis for the BEAVRS cycle 1 whole core depletion has been performed with UNIST in-house Monte Carlo code MCS with internal T/H feedback [6]. However, this paper will focus on the fuel performance of this coupling system in the application of 3-D whole core analysis. Section 2 introduces the key features and methodologies of MCS code; Section 3 describes the BEAVRS cycle 1 depletion benchmark and its computational condition; the followed Section 4 depicts the numerical results from the MCS simulation and the discussions to the phenomenon of interest. Finally Section 5 summaries this work, draws conclusion based on the simulation results from sections 3 and outlines our future work.

2. Methodologies

2.1 One-Dimensional Enthalpy Rise Model

The one-dimensional closed-channel enthalpy rise model from FRAPCON solver has been used in MCS code. This model can provide T/H feedbacks such as single channel based coolant temperature, coolant density when it receives axial power distribution from Monte Carlo neutron transport procedure.

2.2 Steady-state Fuel Behavior Prediction Model

The steady-state fuel behaviour prediction code FRAPCON has been coupled into MCS code to provide the detailed fuel performance information by the 2-way coupling interface. The fuel thermal conductivity is varied with the increase of burnup from zero to more than 60GWd/tU and the temperature ranging from zero to more than 3000 in Kelvin degree. The thermal conductance of the gap between fuel pellet outer surface and the cladding inner surface is determined by the thermal-mechanics interaction using the Finite Difference Method (FDM) method.

2.3 Predictor-Corrector Depletion Model

The full and semi-predictor-corrector model has been implemented in MCS to accomplish the whole core pin-wise depletion capability, which has a detailed burnup chain of 1,374 isotopes including actinides, fission products and fission products. To solve this massive depletion caused large scale Bateman linear equations, the Chebyshev Rational Approximation Method (CRAM) has been applied in MCS.

2.4 On-The-Fly Cross Sections Treatment

The T/H feedback origins from coolant temperature, coolant density and fuel temperature，where coolant density will affect the moderate ability of coolant in PWRs, coolant temperature will have impact on neutron absorption ability of coolant in case of the change of soluble boron in the coolant. Fuel temperature should significantly influence criticality system by mean of Doppler broadening effect of ^{238}U absorption reaction cross sections. Recently, MIT has developed Windowed Multi-pole representations method to express resonance point-wise cross sections, which allows the application of Doppler broadening analytically based on resonance parameters along with the Faddeeva function. This method has been also implemented in MCS code to realize the On-The-Fly treatment for the resolved resonance cross sections with temperature dependent. Moreover, the windowed multi-poles library should be converted from the resolved resonance parameters in R-Matrix format (for instance, SLBW, MLBW, Reich-Moore) for more than 300 isotopes with resonance parameters stored in ENDF/B-VII.1 neutron sub-library.

2.5 burnup-dependent thermal conductivity

The fuel thermal conductivity is considered in FRAPCON as a function of temperature, density and burnup, due to thermal expansion, irradiation swelling, and densification effects. Therefore, the fuel thermal conductivity model in FRAPCON code bases on the following expression developed by Nuclear Fuels Industrial model (NFI) with modifications.

3. Benchmark Description

3.1 Benchmark description

The BEAVRS benchmark (Benchmark for Evaluation And Validation of Reactor Simulations) presents a typical 4-loop Westinghouse PWR with as much detailed operation information as possible, which has been released by CPRG group at MIT in 2015. The current release is version 2.0.1, which provides the core loadings and detector signals from the realistic nuclear power plant for the first two cycles of operation [7]. Fig. 1 illustrates the top view and left view of these quarter core modeling layouts. For more details (fabricated fuel assembly loadings, burnable absorber pin layouts, operational histories and control rod positions, and boron concentration), please refer to the manual of this benchmark. The detailed power history of BEAVRS cycle 1 model is shown in Fig. 2. Table I lists the T/H boundary condition of fuel performance feedback through the whole depletion simulation.

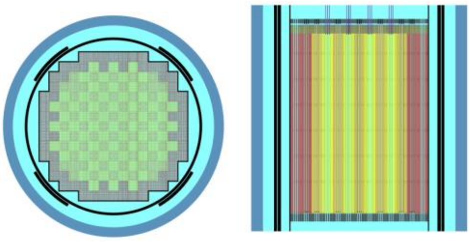


Fig. 1. Top view and front view of BEAVRS full core layout.

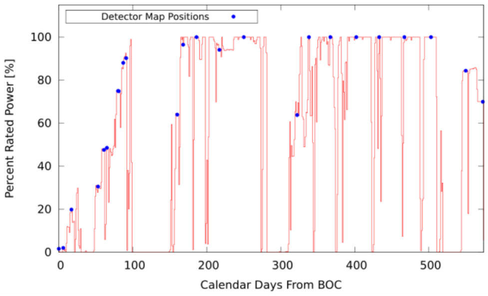


Fig. 2. Power history of BEAVRS cycle 1

Table I: T/H Boundary Condition

Power (%)	100%
Outlet Pressure (MPa)	15.513
Inlet mass flow rate (kg/s)	17083.33
Inlet Temperature (℃)	292.70
Gap conductance (W/m-K)	10000

3.2 Computational Condition

Multi-cycle technique is used in MCS Monte Caro neutron transport to ensure that the fissions source distribution reaches converged as quickly as possible. In this simulation, 20 inactive and 40 active multi-cycles are simulated, each multi-cycle having 300 single cycles, each single cycle including 10,000 histories. Finally RMS of pin-wise flux tallied from neutron transport is less than 5 % for the quarter core model. In FRAPCON solver, the criteria used to determine the convergence of gas release in pellet-cladding gap is 1 % in general. FRAPCON feedback are performed every 10 multi-cycle of Mont Carlo neutron transport, which can be guaranteed that the variance of tallied power density for the quarter core between two successive T/H conductions is globally converged.

4. Results and Discussions

The results of cycle 1 depletion with fuel performance feedbacks has been collected and analysed in this section.

4.1 CBC Results

Firstly, the critical boron concentration of BEAVRS quarter core model changes with the increase the burnup in this depletion simulation. Meanwhile, the results from MCS code without any fuel performance feedback (actually only TH1D feedback) are also presented as the reference.

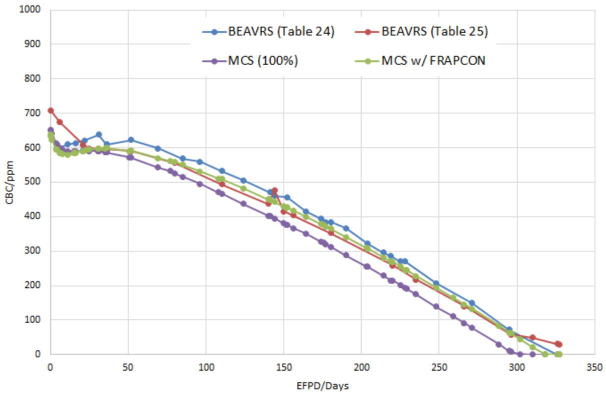


Fig. 3. CBC letdown with EFPD.

As shown in Figure 3, the CBC letdown swings with the increase of the EFPD (Effective Full Power Days), which is the unit of this fuel cycle. As it is, the result from MCS with FRAPCON coupling lies between the Table 24 and Table 25 except at the very beginning of cycle (within 20 EFPD), which agree with them very well. However, the results of MCS code without

FRAPCON coupling are underestimated among the whole fuel cycle.

4.2 Neutronic Results

The power distributions at the beginning, mediate and end of 1st cycle for BEAVRS full core model are displayed in the Figure 4. It can be seen that the power distribution shape become more flat with the increase of burnup.

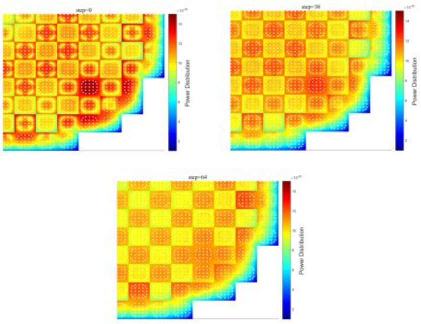


Fig. 4. Power distribution at BOC, MOC and EOC.

4.3 T/H Results

The distributions for some thermal/hydraulic quantities, for instance, coolant temperature and coolant density are presented in the following Figure 5 and Figure 6. It can be seen that either coolant temperature or density do not change a lot. Only the values in the area with the highest power level changed visually. Surely, the increase of temperature means the decrease of density.

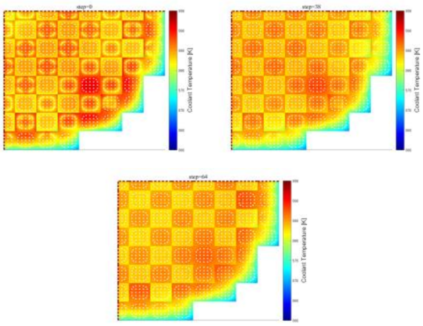
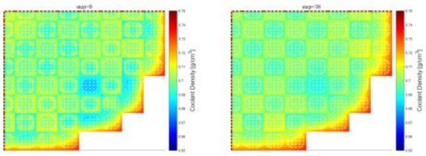


Fig.5. Coolant temperature distribution at BOC, MOC and EOC.



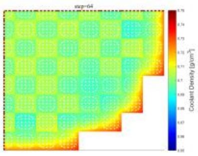


Fig.6. Coolant density distribution at BOC, MOC and EOC.

4.4 Fuel Performance Results

The fuel performance results can be obtained only by this depletion simulation with fuel behaviour feedbacks. For example, Figure 7 through 10 respectively show the distribution for fuel temperature, gap conductance, hoop stresses and the oxide layer thickness. Figure 11 shows the swelling effect of the fuel pin with the peak power.

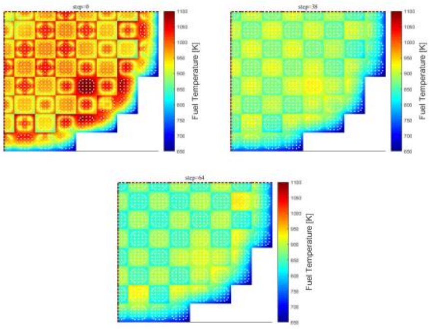


Fig.7. Fuel temperature distribution at BOC, MOC and EOC.

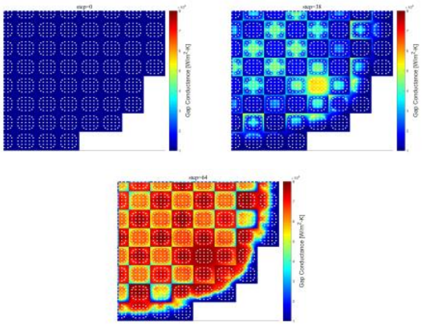
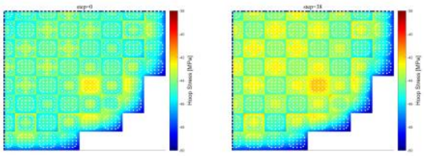


Fig.8. Fuel-Cladding gap conductance distribution at BOC, MOC and EOC.



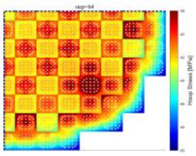


Fig.9. Hoop stresses distribution at BOC, MOC and EOC.

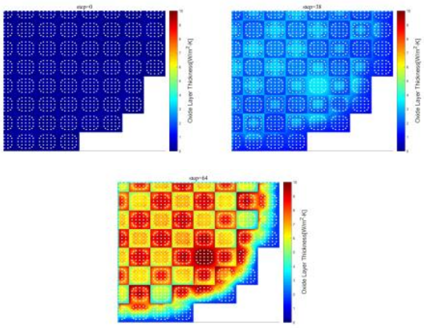


Fig.10. Oxide layer thickness distribution at BOC, MOC and EOC.

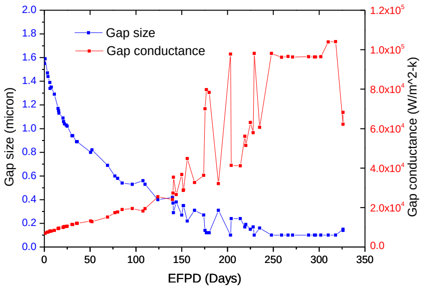


Fig. 11. Swelling effect of fuel pin with peak power.

Looking through these distributions, it can be found that with the increase of burnup, the overall level of the fuel temperature decreases in this simulation, which is caused by the complex thermal conductivity relation with the temperature and burnup. However, the fuel-cladding gap thermal conductance rises a lot due to the decrease of gap size, even the hard contact of the inner cladding surface and the outer fuel pellet surface. Similarly, the hoop stress existed in the cladding and the oxide layer thickness deposited in cladding outer surface accumulates from BOC to MOC and EOC.

5. Conclusions

The BEAVRS Benchmark cycle 1 depletion with fuel performance feedback has been performed using MCS code coupled with steady-state fuel behavior prediction code - FRAPCON. Firstly, the CBC letdown was compared with the measured values shown in Table 24 and 25 of the manual, which show a very good agreement between MCS results and measurement. Afterwards, the detailed distributions, such as power density, fuel temperature, coolant temperature and coolant density has been presented in this paper. Furthermore, some unique quantities which can be only simulated by fuel behavior prediction code are illustrated to performance the multi-physics coupling capability of MCS code.

5. Acknowledgement

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