

## Analysis of OECD/NEA SFR Benchmarks Using McCARD

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### 1. Introduction

As a part of international collaboration projects for evaluating performance of next generation nuclear energy systems, Working Party on Scientific Issues on Reactor System (WPRS) of OECD/NEA proposed four different types of SFR benchmark problems [1]. Two medium cores loading metallic fuel and MOX fuel respectively are designed for burner reactor, while other two large cores loading MOX fuel and carbide fuel respectively are designed to operate as a self-breeding reactor. To evaluate safety performance of each core, parametric studies on the properties of the fuel and reactivity feedback of the system have been conducted and compared among various reactor physics groups [2-3]. The comparison result shows a marked discrepancy among groups depending on geometric modelling, cross section libraries, calculation methods or code characteristics. The researches on the calculation method and condition for the best estimate of the four different SFR cores are ongoing. The purpose of this paper is to provide a whole core analysis of the SFR benchmark problems using McCARD, a Monte Carlo code for advanced reactor design and analysis developed in Seoul National University. Recently the Probability Table Method (PTM) generated by NJOY code [4] for treating cross section in unresolved resonance region is implemented in McCARD. With this PTM, McCARD equips with capability to analyze fast neutron system considering unresolved resonance region. The five neutronic parameters defined in benchmark problems such as effective multiplication factor, effective delayed neutron fraction, sodium void worth, control rod worth and Doppler constant are calculated both at the beginning of cycle and end of cycle with whole core depletion calculation. To confirm the effect of resonance treatment in unresolved resonance region, each calculation with PTM is compared with the case without PTM which utilizes the average smooth cross section. Additional analysis is done for diagnosis of fission source convergence in the fast neutron system using anterior stopping criteria implemented in McCARD [5].

### 2. Modelling of SFR Cores

#### 2.1 Medium Cores

Two medium size ABR core with metallic fuel and MOX fuel consist of total 379 hexagonal assemblies. The size of assembly pitch is 16.2471cm for both core. For metallic fuel core, the fuel region is divided into two regions of inner core and outer core while there is another sub-region of middle core for MOX fuel core. The core region is

surrounded by reflector and shield. There are two identical but independently operating control system for safety-grade reactivity control. The radial core layout of medium size cores are presented in Fig 1.

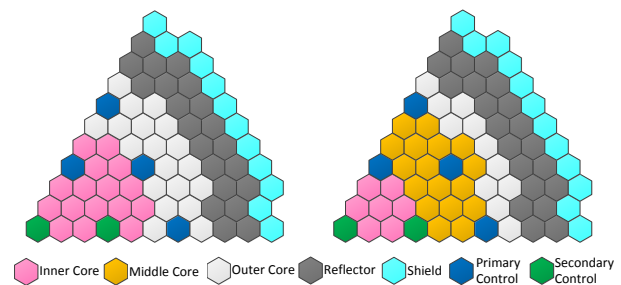


Fig. 1. Radial core layout of metallic fuel core (left) and MOX fuel core (right).

Each assembly has different number of clad pins arranged in triangular configuration inside the hexagonal outer duct. For core assembly, there are 271 pins containing 85.82cm and 114.94cm of active core zone. The active core zone is axially divided into 5 region and each region consists of same isotopes with different densities. Fig 2 shows cross sectional and axial view of core assembly. Replace sodium exists only in metallic fuel core to fill the gap between fuel slug and cladding due to high radiation-induced swelling. The axial regions from lower reflector to upper structure are pin-shaped, while lower structure has homogeneous hexagonal shape that is equal size with assembly pitch.

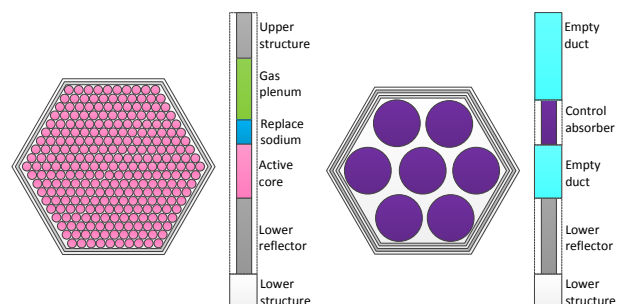


Fig. 2. Schematics of core assembly (left) and control assembly (right).

Control assembly has additional hexagonal inner duct in the control absorber region for free motion of control rods. Control absorber and lower reflector regions are pin-shaped and other parts are in hexagonal form.

## 2.2 Large Cores

Two large size self-breeding cores with MOX fuel and carbide fuel consist of total 817 assemblies. The size of assembly is larger than that of medium core to be 21.2205 cm and 20.9889 cm respectively. Both core consist of fuel region divided into inner core and outer core surrounded by reflector. There are also two independent control systems with different shapes. Fig 3 shows radial core layout of the large cores. It shows that large MOX fuel core has distinct symmetry line among other three cores.

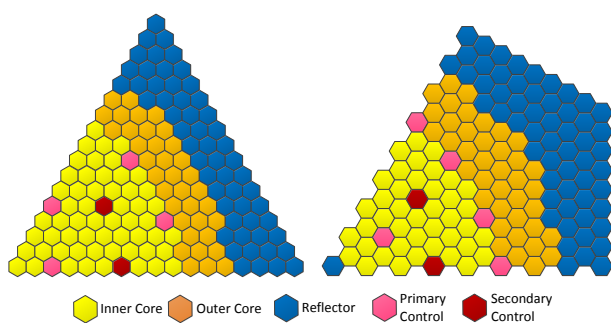


Fig. 3. Radial core layout of carbide fuel core (left) and MOX fuel core (right).

The core assembly has 469 and 271 clad pins inside the hexagonal duct for carbide fuel and MOX fuel respectively. Compared to the assembly of medium core which has homogeneous lower structure, large cores have pin-shaped geometry from bottom to top. Active core is axially divided into 5 zones and surrounded by two axial reflector and two gas plenum. All fuel pins have internal gas gap between cladding and inner material. As for MOX fuel, there is another gas hole in the center of the active core. Control assembly have additional inner duct for control absorber part and it has hexagonal shape for primary control and circular shape for secondary control. Reflector assembly is assumed to be filled with homogeneous material over the whole assembly volume. The core assembly and control assemblies are shown in the Fig 4.

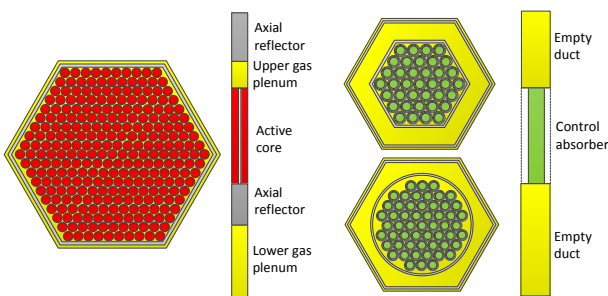


Fig. 4. Schematics of core assembly (left) and primary (up) and secondary control assembly (down).

## 2.3 Homogenous Model

Since there is large discrepancy among the calculation results of reactor physics groups, according to different cross section libraries, geometric model, and calculation method, validation is needed for fast neutron system with simple homogeneous model. Assembly-wise homogeneous model is made by calculating volume fraction of material for every axial divisions. Before analyzing heterogeneous SFR problem, neutronic parameters were calculated and compared with MCNP5 using the same homogeneous model.

## 3. Calculation Condition

### 3.1 Condition of Parameter Calculation

There are four conditions to be known to calculate five global neutronic parameters. The nominal state is when all control rods are located at the top of active core zone. Rod inserted state is when all rods are fully inserted down to the bottom of active core zone. Sodium voided state refers to voiding sodium out of the active core level inside the core assembly including gaps between core assemblies. The high temperature state is defined as doubling the fuel temperature in the unit of Kelvin. Using these four conditions, parameters can be calculated through following equations. The temperatures of structure and fuel for 4 cores in nominal state are followed by Table I.

$$\Delta\rho_{CR} = \rho_{inserted} - \rho_{nominal} \quad (1)$$

$$\Delta\rho_{Na} = \rho_{void} - \rho_{nominal} \quad (2)$$

$$K_D = \frac{\rho_{high} - \rho_{nominal}}{\ln 2} \quad (3)$$

Table I. Temperature of 4 Cores in Nominal State ( °C )

Core type	Structure Temp.	Fuel Temp.
Medium Metallic	432.5	534.0
Medium MOX	432.5	1027.0
Large MOX	470.0	1227.0
Large Carbide	470.0	987.0

### 3.2 Condition of Depletion Calculation

Depletion calculation is done with assembly-wise aggregation burnup model due to limitation of memory and computation time. Explicit fuel pins in a core assembly are aggregated into 5 axial active core cells. All calculations including parameter calculations and depletion calculation were conducted with 100,000 histories per cycle and the source was uniformly distributed over the fuel region. ENDF/B-VII.0 continuous energy neutron cross section library was used. The number of inactive cycles were predetermined by anterior stopping criteria implemented in McCARD and 100 active cycles were used for all calculations.

## 4. Results

### 4.1 Convergence of Fission Source Distribution

The number of inactive cycle is determined using the anterior stopping criteria. The whole source regions are divided into assembly-wisely aggregated cells without dividing axial direction. In Fig 5, the stopped cycle numbers are presented with  $k_{\text{eff}}$  of each cycle and cumulative  $k_{\text{eff}}$ . From the result of diagnosis and the trend of  $k_{\text{eff}}$ , the number of inactive cycle are determined to be 50, 50, 100, and 120 for each core. This is relatively small value compared to the result of source convergence in PWR core of BEAVRS benchmark [6]. It represents the characteristic of fast neutron system that the mean free path of neutron is 10 times longer than the thermal neutron system. The dominance ratio for each core are 0.91, 0.92, 0.98 and 0.98.

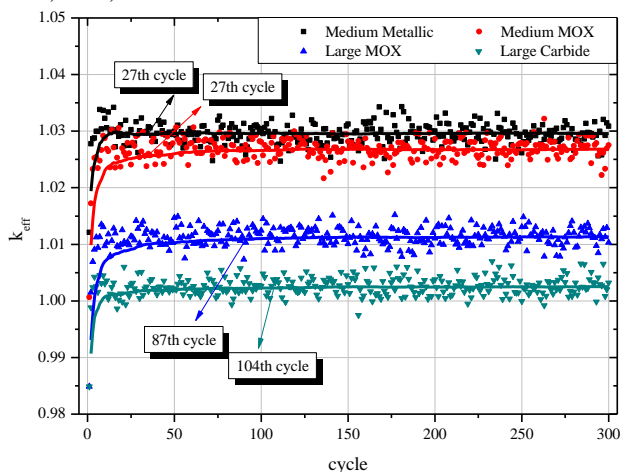


Fig. 5. Trend of  $k_{\text{eff}}$  along cycle and stopping criteria.

### 4.2 Parameter Calculation

The numerical results of parameter calculations are summarized in Table II and Table III. For homogeneous model, neutronic parameters are calculated and compared with the MCNP results. The parameters are calculated at the beginning of cycle including effective multiplication factor with and without PTM. The results in Table III

shows that all parameters are matched well within 95% confidence interval. Compared to the result of heterogeneous model, it shows that homogeneous model underestimate the effective multiplication factor by 500pcm to 600pcm.

Heterogeneous model calculations are conducted using McCARD with and without PTM options both at the BOC and EOC. As for the PTM, it appears that utilizing of PTM options have effect of higher estimation on  $k_{\text{eff}}$  from 15 to 80 pcm than not utilized case. This is the result of self-shielding effect on  $^{238}\text{U}$  capture cross section which is the most dominant reaction in SFR fuel rods. This is also presented in Fig 6 of depletion result that it shows higher  $k_{\text{eff}}$  value throughout burnup steps. Fig 6 also shows the trend of  $k_{\text{eff}}$  that it decreased over burnup steps for burner reactors, while it maintained or increased for self-breeding reactors.

In SFR system, voiding of sodium gives both positive and negative feedback on effective multiplication factor. The positive feedback is due to scattering and capture reaction in sodium [7]. There is no specific moderator in SFR system but voiding of sodium make the neutron spectrum hardened and neutrons to be less captured around the fuel rods. Negative feedback occurs when more neutrons go out of the system through voided medium but in this benchmarks, sodium is voided only around active core zone. This is why positive sodium void worth appears over all calculation results.

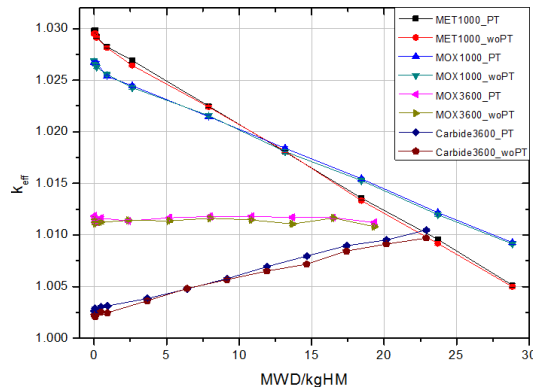


Fig. 6. Trend of  $k_{\text{eff}}$  along burnup steps

Table II. Numerical Results of Parameter Calculation with Homogeneous Model at the Beginning of Cycle

Core Type	McCARD						MCNP5					
	$k_{\text{eff, PT}}$	$k_{\text{eff, woPT}}$	$\beta_{\text{eff}}$	$\Delta\rho_{\text{Na}}$	$K_D$	$\Delta\rho_{\text{CR}}$	$k_{\text{eff, PT}}$	$k_{\text{eff, woPT}}$	$\beta_{\text{eff}}$	$\Delta\rho_{\text{Na}}$	$K_D$	$\Delta\rho_{\text{CR}}$
Medium Metallic	1.02426 (0.00014)	1.02415 (0.00014)	344 (2)	2,219 (31)	-364 (46)	-21,208 (27)	1.02415 (0.00014)	1.02392 (0.00015)	366 (21)	2,218 (29)	-270 (43)	-21,144 (27)
Medium MOX	1.02156 (0.00013)	1.02143 (0.00013)	335 (2)	2,006 (29)	-692 (37)	-23,041 (28)	1.02155 (0.00015)	1.02136 (0.00014)	321 (20)	2,048 (30)	-640 (42)	-23,012 (26)
Large MOX	1.00578 (0.00013)	1.00553 (0.00014)	367 (2)	2,051 (25)	-842 (39)	-6,652 (26)	1.00588 (0.00014)	1.00537 (0.00013)	369 (22)	2,082 (27)	-832 (38)	-6,626 (27)
Large Carbide	0.99739 (0.00013)	0.99691 (0.00013)	378 (2)	2,319 (27)	-909 (39)	-4,558 (27)	0.99709 (0.00013)	0.99689 (0.00014)	359 (21)	2,346 (26)	-897 (36)	-4,530 (26)

\* Except for  $k_{\text{eff}}$ , all values are in the unit of pcm.

Table III. Numerical Results of Parameter Calculation with Heterogeneous Model Using McCARD

Core Type	PTM	BOC					EOC				
		$k_{\text{eff}}$	$\beta_{\text{eff}}$	$\Delta\rho_{\text{Na}}$	$K_D$	$\Delta\rho_{\text{CR}}$	$k_{\text{eff}}$	$\beta_{\text{eff}}$	$\Delta\rho_{\text{Na}}$	$K_D$	$\Delta\rho_{\text{CR}}$
Medium Metallic	On	1.02980 (0.00015)	345 (2)	2,010 (31)	-344 (43)	-18,246 (27)	1.00513 (0.00016)	345 (2)	2,205 (31)	-325 (43)	-18,922 (30)
	Off	1.02950 (0.00016)	345 (2)	2,008 (32)	-327 (46)	-18,214 (31)	1.00498 (0.00016)	340 (2)	2,175 (32)	-322 (45)	-18,903 (29)
Medium MOX	On	1.02675 (0.00015)	337 (2)	1,796 (29)	-703 (40)	-19,731 (30)	1.00926 (0.00014)	336 (2)	1,919 (29)	-652 (39)	-20,244 (28)
	Off	1.02687 (0.00015)	339 (2)	1,769 (29)	-741 (42)	-19,791 (29)	1.00913 (0.00014)	334 (2)	1,905 (31)	-679 (40)	-20,222 (27)
Large MOX	On	1.01183 (0.00013)	369 (2)	1,790 (26)	-950 (36)	-5,885 (28)	1.01119 (0.00015)	360 (2)	1,953 (30)	-789 (42)	-6,111 (29)
	Off	1.01131 (0.00014)	370 (2)	1,802 (27)	-930 (40)	-5,851 (28)	1.01081 (0.00014)	362 (2)	1,945 (28)	-777 (39)	-6,120 (29)
Large Carbide	On	1.00263 (0.00014)	384 (2)	2,025 (30)	-940 (40)	-3,970 (28)	1.01049 (0.00014)	370 (2)	2,224 (27)	-866 (38)	-4,568 (26)
	Off	1.00223 (0.00015)	381 (2)	2,028 (30)	-973 (42)	-4,037 (27)	1.00969 (0.00013)	367 (2)	2,249 (27)	-794 (38)	-4,537 (27)

\* Except for  $k_{\text{eff}}$ , all values are in the unit of pcm

Doppler constant has negative value for all cores which is attributed to resonance cross section of  $^{238}\text{U}$ . As the resonances of  $^{238}\text{U}$  broadened, it reduces self-shielding effect and results in negative feedback on reactivity [7]. Table III also shows a tendency of increased sodium void worth and control rod worth from BOC to EOC. Fig 7 is a relative power distribution of carbide fuel core at the BOC and EOC. There is a significant power peak shift from outer cores to inner cores which makes the two parameters increased at the EOC. Other three cores also have the same tendency and this is a comparable result with the analysis of TRIPOLI-4 [8].

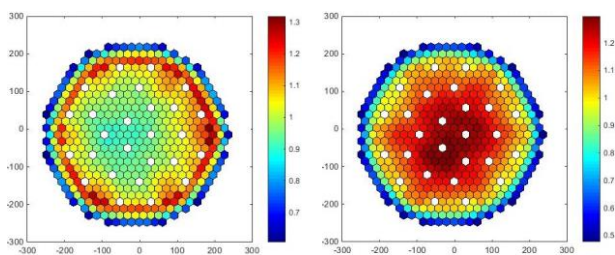


Fig.7. Relative power distribution of carbide fuel core at the BOC (left) and EOC (right).

## 5. Conclusions

OECD/NEA SFR benchmark problems were analyzed using McCARD with PTM. For the 4 cores of different size and fuel, five global neutronic parameters of effective multiplication factor, effective delayed neutron fraction, sodium void worth, control rod worth, and Doppler constant were estimated. Before the calculations, convergence of fission source distribution were estimated with Shim's anterior stopping criteria. The parameters were estimated for both at the BOC and EOC accompanied by whole core depletion calculation. All

calculations were done twice with and without PTM options. The parameters were compared with MCNP5 results for assembly-wise homogeneous model and the result matched well within stochastic error. Same calculation is done for heterogeneous model and the results were analyzed with the effect of PTM.

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