Whole-core Neutronic Analysis of MOX-1000 MW th in NEA-SFR Benchmark Using MCS Code

Saisundar Mohanty , Tuan Quoc Tran, Tung Dong Cao Nguyen, Deokjung Lee *
Department of Nuclear Engineering, Ulsan National Institute of Science and Technology, 50 UNIST-gil, Ulsan, 44919, Republic of Korea.
**Corresponding author: deokjung@unist.ac.kr*

1. Introduction

To estimate the neutronic core parameters for several Generation–IV Sodium-cooled Fast Reactor (SFR) concepts, a set of four numerical benchmarks of different cases are initially developed for different core size which was introduced by Nuclear Energy Agency (NEA) [1]. Among various core concepts, in this benchmark [2], medium-size oxide core MOX-1000 MW th is very concerned due to discrepancies between results from eleven participating research institutes. Hence in this study, the main neutronic parameters of the MOX-1000 including multiplication factor (k-effective), control rod worth($\Delta\rho_{CR}$), sodium void worth ($\Delta\rho_{Na}$), and Doppler constant (K_D) are being calculated by using Monte Carlo code-MCS which was developed at Ulsan National Institute of Science and Technology (UNIST).

2. Benchmark Description

2.1 Core Modelling

The medium oxide core MOX-1000 benchmark consisted of drivers, reflectors, shields, and control rods of 180, 114, 66, and 19 assemblies (15 primary and 4 secondary control rod assembly). The active core region on driver subassemblies are further divided into the inner (30), middle (90), and outer core (60) zone. In this MOX-1000 MW th core calculation, a vacuum boundary condition has been imposed. The radial layout of MOX-1000 from Figure.1 shows the active core (inner, middle, and outer core) surrounded by the radial reflector, and radial shield assemblies respectively.

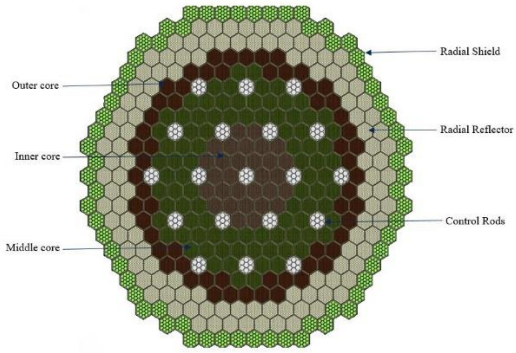

Fig. 1. Core Layout of the MOX-1000 MW th

Table I: MOX-1000 main core characteristics

Thermal Power	1000 MW
Fuel	(U, Pu) O_2
Cladding material	HT9
Assembly in Active core Outer core Middle core Inner core	180 60 90 30
Coolant	Sodium
Number of control rod a. Primary control rod b. Secondary control rod	19 15 4
Operating temperature Fuel Structural temperature	 1300K 705.5K

The average fuel and structural temperature of the medium oxide core are 1300K and 705.5K from Table I. Fig. 2. shows the schematics of the radial cross-sections of the driver, control rod, radial shield, and radial reflector assembly [2].

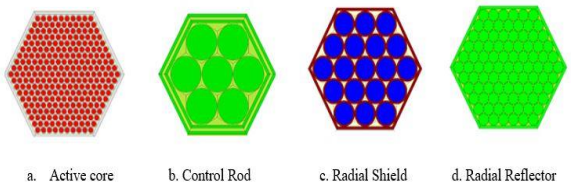

Fig. 2. Radial layout of the driver (active region), control rod, shield, and reflector assembly.

In the driver subassembly of 1000 MW th oxide core, the active region has divided into 5 zones and above with the gas plenum space that is axially followed by the upper structure. And below active fuel regions, it is followed by the radial reflector and lower structure respectively. Figure 3. Shows the driver assembly schematic axially. The driver subassembly of 1000 MW th oxide core has been summarized in Table II.

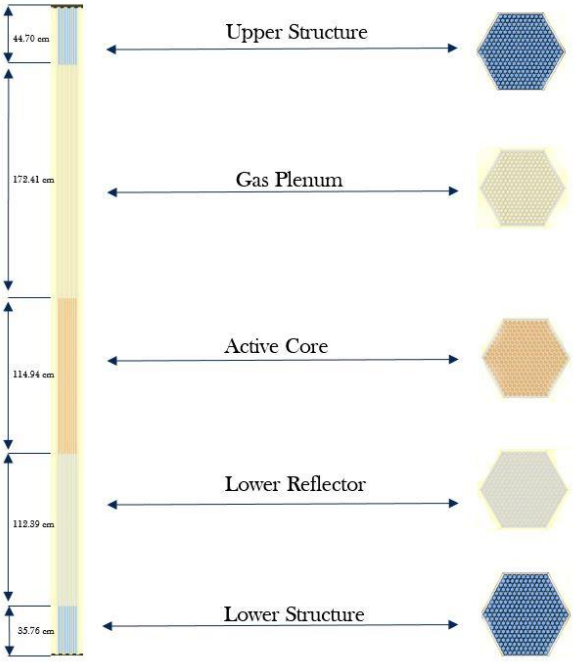

Fig. 3. Schematics of driver subassembly of MOX-1000 MW th oxide core

Table II: Driver sub-assembly of MOX-1000 oxide core structural parameters (in cm)

Fuel pellet radius	0.3322
Clad outer radius Clad inner radius	0.3928 0.3322
Number of fuel pins	271
Overall axial length Lower-structure Lower-reflector Active core Plenum Space Upper-structure	480.20 35.76 112.39 114.94 172.41 44.70
Pitch of Subassembly	16.2471
outer of duct flat-to-flat	15.8123
Duct wall thickness	0.3966

2.2 Code Description

MCS is a new Monte Carlo (MC) high fidelity neutron/photon transport code that has been developed at the Ulsan National Institute of Science and Technology (UNIST) by the COmputational Reactor physics and Experiment laboratory (CORE) group [3, 4]. It has aimed for performing multi-physics simulations for PWR and LWR, also in extend to fast reactors as well. MCS has been verified and validated with many benchmarks problem including Benchmark for Evaluation And Validation of Reactor Simulations (BEAVRS) [3], Virtual Environment for Reactor Applications (VERA) [4], International Criticality Safety Benchmark Evaluation Project (ICSBEP), etc.

2.3 Simulation and results

The MOX-1000 is modeled in MCS, using ENDF/B-VII.1 library and for each criticality simulation it runs with 20 numbers of in-active cycles and 80 active cycles with a batch size of 100 for 50,000 histories. The MCS simulation has been executed on a Linux cluster which takes about 375 core-hours for criticality calculations.

Table III: MCS results for MOX-1000 core at BOC

Parameters	k_{eff}	Standard Deviation (pcm)
Nominal Temperature	1.02974	2.31
High Temperature	1.02867	3
Sodium void worth	1.04848	3.03
Control rod worth	0.84707	2.76

The different calculations for neutronic parameters such as k-effective, $\Delta\rho_{CR}$, $\Delta\rho_{Na}$, and K_D have been obtained at the beginning of the cycle (BOC) and are well summarized in Table III.

The sodium void worth ($\Delta\rho_{Na}$) can be estimated by the reactivity change between the sodium voided and normal operating state. The subscripts indicate the voided sodium and normal operating conditions, respectively in Equation 1.

$$\Delta\rho_{Na} = \rho_{void} - \rho_{nominal}, \quad (1)$$

In this benchmark, $\Delta\rho_{Na}$ calculation has been achieved by creating void sodium state in the active core region axially as well as radially. The Doppler constant (K_D) has been defined by Equation 2, where ρ_{High} and $\rho_{nominal}$ indicates the core state with higher average and nominal fuel temperature [2].

$$K_D = \frac{\rho_{high} - \rho_{nominal}}{\ln\left(\frac{T_2}{T_1}\right)}, \quad (2)$$

In Equation 2, T_1 and T_2 are the nominal fuel temperature (1300K) and perturbed higher fuel temperature (1500K). The control rod worth ($\Delta\rho_{CR}$) can be estimated by the change of reactivity between two states, one where all the rods are inserted and withdrawn from the core during normal operating condition.

2.4 Results Analysis

The results of the simulation for MOX-1000 MW thc core benchmark from Commissariat à l'énergie atomique et aux énergies alternatives (CEA), Centre d'Etude de l'Energie Nucléaire (CEN), University of Illinois Urbana-Champaign (UIUC), Argonne National Laboratory (ANL), and Karlsruhe Institute of Technology (KIT) are used for comparison purpose and summarized in Table IV. The results for the k-effective exhibit apparently large discrepancies but the results for $\Delta\rho_{CR}$, $\Delta\rho_{Na}$, and K_D are appeared to be consistent.

Among the five research institution's results used for the comparison, ANL's results for multiplication factor calculation are observed very satisfactory agreement with MCS's. Both MCS and ANL employ JEFF-3.1 and ENDF/B-VII.1 cross-section library respectively which exhibits a profound result of 60 pcm difference for the k-effective calculation at BOC. There is a poor agreement for k-effective calculation from CEN-1, CEA-10, and UIUC-3 of 410 pcm, 560 pcm, and 970 pcm, which employ ENDF/B-VII.1, JEFF-3.1.1, and ENDF/B-VII.0 respectively with respect to MCS. There is a moderate agreement observed between KIT and MCS for k-effective results in 200 pcm difference at BOC which used same cross-section library. MCS's results for Doppler constant and sodium void worth are observed apparently in very good agreement with CEN-1,2 and KIT. The difference is less than 30 pcm in sodium void and 5 to 10 pcm in Doppler with MCS. The average results of all eleven participants for MOX-1000 for k-effective is 1.0287, $\Delta\rho_{Na}$ is 1831 pcm and $\Delta\rho_{CR}$ is 21,605 pcm with 620 pcm, 228 pcm, and 2021 pcm standard deviation respectively [2]. The numerous simulation methodologies are mainly responsible for variations in results from all the research participants. This is why several institutions have performed different calculations by adopting distinct methodologies to quantify some of the discrepancies that have been observed in this paper [2]. In general, at BOC, the k-effective values are larger in JEFF 3.1 as compared to ENDF/B VII.1 nuclear data library. The reason for the discrepancy in MCS with other research institutions is mainly for cross-section interpolation algorithms at different core temperatures such as at 1500K,1300K, and average structural temperature at 705.5K in ENDF/B VII.1 cross-section library [5].

As a partial conclusion in total, due to the cross-section of elements used at the different core and average structural temperature in MOX-1000 MW th benchmark by MCS, plays the most significant factor for the discrepancy with other institute's calculations with various nuclear data libraries. MCS exhibits good terms with ANL, KIT, CEN, CEA, and UIUC for k-effective, Doppler, control rod worth, and sodium void worth calculation respectively.

Table V: Summarized results for MOX-1000 MW th

Code	Library	k_{eff}	$\Delta\rho_{Na}$	K_D (-)	$\Delta\rho_{CR}$
MCS	ENDF/B VII.1	1.0297	1736	706	20942
CEN (1)	ENDF/B VII.1	1.0256	1760	709	19795
CEN (2)	JEFF 3.1.2	1.0348	1789	695	19505
ANL (3)	JEFF 3.1	1.0303	2130	N/A	23428
KIT	JEFF 3.1	1.0317	2121	709	22209
CEA (10)	JEFF 3.1.1	1.0353	1621	766	19431
UIUC (3)	ENDF/B VII.0	1.0200	1526	606	20115
Avg. SD. pcm		1.0287 ±620	1831 ±228	731 ±70	21605 ±2021

3. Conclusions

This study exhibits the deterministic whole-core neutronic analysis of MOX-1000 MW th medium core benchmark by MCS. All the estimated result is in good terms with KANEXT (KIT) for k-effective calculation. And for $\Delta\rho_{CR}$, $\Delta\rho_{Na}$, and K_D (which have been modelled and simulated by MCS) show good terms with MCNP (CEN and ANL), TRIPOLI-4 (CEA-10), and SERPENT (UIUC-3). We assumed, it is due to a difference in the algorithms used in the codes for interpolation of neutron cross-sections over different core as well as structural temperature. Our MCS results show relatively good agreement with the average of all the research institutes. It can be assessed that the performed whole-core simulation procedure and all neutronics parameters calculation were appropriate. Further, the uncertainty and sensitivity analysis will be carried out from as future work.

Acknowledgement

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