MOX-1000MWth NEA-SFR Benchmark simulation by MCS at EOC

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1. Introduction

To improve the safety performance of nuclear reactors mostly the transient behaviour in an accident scenario, Nuclear Energy Agency (NEA) [1] has introduced different nuclear reactor designs for the Generation IV International Forum (GIF). Among these designs, the Sodium-cooled fast reactor (SFR) shares the most prominent and reasonable in terms of time scale for transient feedback and safety performance. To perform and achieve these goals for SFR, various nuclear reactor core designs have been considered such as large cores and medium cores with three different types of fuel (oxide, carbide, and metal). In this benchmark study of different fuels and core sizes, MOX-1000 MW (thermal) has been analyzed and documented here in this paper because of its peculiar discrepancies of neutronic parameters such as multiplication factor (k_{eff}), control rod worth ($\Delta\rho_{CR}$), sodium void worth ($\Delta\rho_{Na}$), and Doppler constant (K_D) at the end of the cycle (EOC). We use the in-house Monte-Carlo code (MCS) for all neutronic parameters simulation, developed at Ulsan National Institute of Science and Technology (UNIST).

2. Benchmark Description

2.1 Whole-Core Modelling

The MOX-1000 medium-size core comprised 118 drivers, 114 radial reflectors, 66 radial shields, and 19 control rod subassemblies (15 primary and 4 secondary assemblies). The active fuel region in the driver assembly is further divided into the inner core, middle core, and outer core. From the simulation's perspective, we choose the vacuum boundary condition in this modelling.

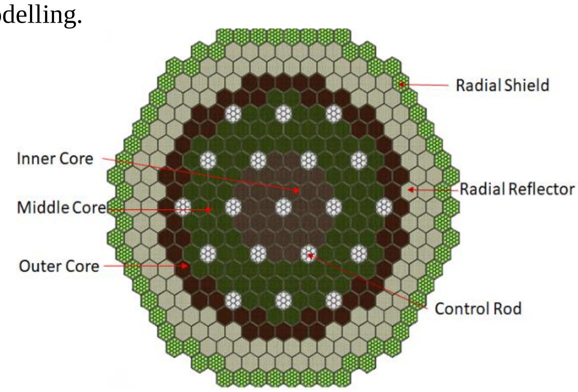

Fig. 1. Whole Core Layout of the MOX-1000 MW.

Table I: Whole-Core Characteristics

Fuel	(U, Pu) O_2
Thermal Power	1000 MW
Cladding Material	HT9
Number of control rod Primary control rod Secondary control rod	19 15 4
Operating temperature Fuel Structural temperature	 1300K 705.5K
Active core Region Inner core Middle core Outer core	180 30 60 90
Coolant	Na
Control Rod Absorber	B_4C

Fig. 1. Represents the whole core radial layout and the radial reflector surrounds the active core (inner, middle, and outer) followed by the radial shield. The whole-core characteristics are summarized in Table I. The nominal temperature of the fuel and structural material is 1300K and 705.5K.

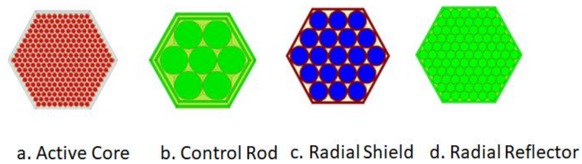

Fig. 2. Assembly layout (Active core fuel region, control rod, shield, and reflector) of the MOX-1000 MW.

Fig. 2. shows the assembly layout of the reflector, shield, control rod, and fuel core region [2].

2.2 Driver Subassembly Modelling

The schematics of the driver subassembly are represented in Fig. 3 [3]. The active fuel region of the driver subassembly is divided into five different zones. The plenum space is above the fuel, followed by the upper structure, below the fuel core is the lower reflector, and supported by the lower structure. The Table II. represents the driver subassembly structural parameters.

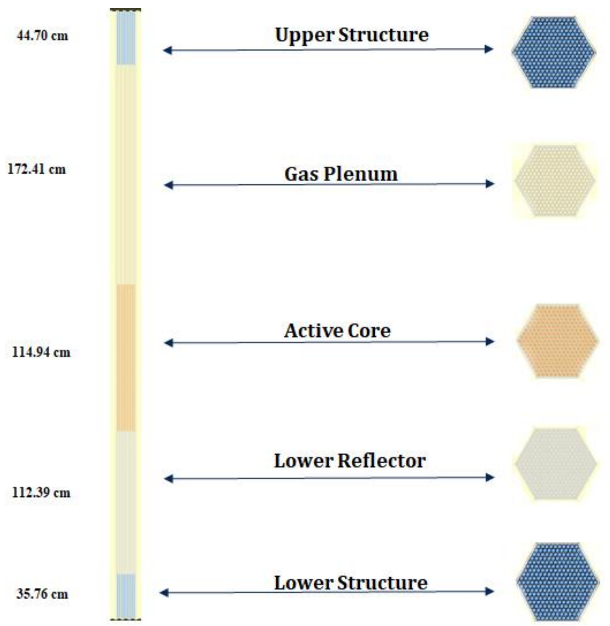

Fig. 3. Schematics of the driver subassembly of MOX-1000

The driver subassembly contains 271 fuel pins. The volume fraction of the upper structure, which is assumed to be identical to the lower reflector from a design point of view is 66.73% HT9 and 33.27% coolant (Na). The lower structure is a mixture of 70% coolant and 30% SS-316.

Table II: Structural Parameters (cm) of Driver Subassembly

Parameters For Driver Subassembly	Nominal Operating State (unit in cm)
Total Axial Height Lower-Structure Lower-Reflector Active Core Height Plenum Space Upper-Structure	480.20 35.76 112.39 114.94 172.41 44.70
Fuel Pellet Radius	0.3322
Clad Outer Radius Clad Inner Radius	0.3928 0.3322
Pellet Radius	0.3322
Assembly Pitch	16.2471
Wall Thickness	0.3966

3. Code and Simulation

3.1 Monte Carlo code MCS

MCS is a high-fidelity and high-performance Monte-Carlo code developed at UNIST. It is mainly implemented to solve highly complex whole-core problems. Multi-physics coupling with thermo-hydraulic feedback and fuel performance code with depletion capability are attributed in this code, which has been validated with international benchmarks such as Benchmark for Evaluation And Validation of Reactor Simulations, Virtual Environment for Reactor Applications, International Criticality Safety Benchmark Evaluation Project, etc [4].

3.2 MCS Simulation

The whole core of MOX-1000 MW th at EOC is simulated by using MCS code in ENDF-VII.1 nuclear data library with each criticality calculation running with 50,000 histories with 20 in-active cycles and 80 active cycles. The batch size is 100. The total criticality calculation for EOC takes 1457 core hours on a Linus cluster at the Computational Reactor Physics and Experiment Laboratory (CORE) lab, UNIST.

4. Results

4.1 Simulation Results

The end of the cycle (EOC) represents the reactor core state after one cycle of irradiation time. Here for MOX-1000 we simulate the operating power with 328.5 days, which is approximately 1 year cycle with 90% capacity. Table III. summarizes the MCS results of MOX-1000 at EOC with their standard deviation (pcm).

Table III: MCS results of MOX-1000 at EOC

Parameters	k_{eff}	Standard Deviation (in pcm)
Operating Temperature (1300K)	1.01528	2.82
Perturbed Temperature (1500K)	1.01429	2.87
Sodium Voided in Core	1.03483	3.04
Control Rod Inserted	0.83441	2.74

We also calculate the neutronic parameters such as multiplication factor, control rod worth, sodium void worth, and Doppler constant.

4.2 Doppler Constant

The Doppler constant (K_D) is the ratio of difference of reactivity (perturbed with nominal temperature) with respect to the logarithmic change of perturbed to nominal temperature. Equation 1 shows the Doppler constant, and ρ_{1500} and ρ_{1300} indicate the perturbed temperature of 1500K with the nominal operating temperature of 1300K.

$$K_D = \frac{\rho_{1500} - \rho_{1300}}{\ln\left(\frac{1500}{1300}\right)}, \tag{1}$$

4.3 Sodium Void Worth

Sodium void worth ($\Delta\rho_{Na}$) can be calculated by the reactivity difference of voiding completely the active fuel region such as inner, middle, and outer core with the normal state.

$$\Delta\rho_{Na} = \rho_{voided} - \rho_{normal}, \tag{2}$$

4.4 Control Rod Worth

Control rod worth $\Delta\rho_{ctrl}$ is defined as the reactivity difference of when all the control rods in with the normal condition during reactor operation.

$$\Delta\rho_{ctrl} = \rho_{insrt} - \rho_{normal}, \tag{3}$$

Equation 3 represents the control rod worth where ρ_{insrt} is the reactivity when all the control rods inserted and ρ_{normal} is the reactivity at normal operating conditions.

Table IV: Results at EOC of MOX-1000

Organization	Code	Library	k_{eff}	$\Delta\rho_{Na}$	$\Delta\rho_{crtl}$	K_D (-)
UNIST	MCS	ENDF/B VII.1	1.0152	1861	21350	671
CEN (1)	MCNPX	ENDF/B VII.1	1.0080	1849	20317	672
KIT	KANEXT	JEFF 3.1	1.0149	2243	22823	688
CEN (2)	MCNPX	JEFF 3.1.2	1.0160	1932	19983	631
CEA (10)	TRIPOLI-4	JEFF 3.1.1	1.0159	1745	19904	725
UIUC (3)	SERPENT	ENDF/B VII.0	1.0023	1681	20961	610
ANL (4)	ERANOS	ENDF/B VII.0	1.0139	2122	25212	868
Avg. SD. pcm			1.0136 ±820	1922 ±219	22226 ±2157	718 ±74

4.5 Results Analysis

The results at EOC of MOX-1000 whole core have been summarized in Table IV. For the benchmark, eleven research organizations and universities have participated like 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), etc. [1]. We have compared the neutronic results of CEA, ANL, KIT, CEN, and UIUC for the calculation of multiplication factor, sodium worth, control rod worth, and Doppler constant at the end of the cycle (EOC) with UNIST (MCS). Here one university or research organization has used various methodologies, nuclear data libraries, and different approximations just like CEN (1 and 2) or ANL (1, 2, 3, and 4). CEN-1 used ENDF/B VII.0 whereas CEN-2 used JEFF 3.1.2. Different deterministic and probabilistic numerical computer codes with various methodologies are implemented such as TRIPOLI-4, ERANOS, KANEXT, MCNPX, and SERPENT for comparison with MCS. MCS employs endf vii.1 nuclear data library for the calculations of all the neutronic parameters. From all the participant's results that have been summarized in Table IV, KIT and ANL (4) have Transport SP3 deterministic approach where as rest all UNIST, CEN (1 and 2), CEA (10), and UIUC (3), have stochastic Monte Carlo Approximation.

MCS results for K_{eff}, $\Delta\rho_{Na}$, $\Delta\rho_{ctrl}$, and K_D are 1.0152, 1861, 21350, and 671 respectively. The comparison of multiplication factor from KIT (KANEXT) with UNIST (MCS) exhibits a better agreement with a standard deviation of 30 pcm. MCS has a satisfactory agreement with TRIPOLI-4 for multiplication factor with 70 pcm standard deviation at EOC. TRIPOLI-4 (CEA-10) and KANEXT employ jeff 3.1.1 and jeff 3.1 nuclear data cross-section library. k_{eff} result from MCNPX (CEN-2, jeff 3.1.2) when compared with MCS, shows a good and adequate result with 80 pcm standard deviation. Other institutes have shown a poor agreement with MCS for multiplication factors. The average results of all eleven participants for MOX-1000 whole core at EOC of k_{eff}, $\Delta\rho_{Na}$, $\Delta\rho_{ctrl}$, and K_D are 1.0136, 1922, 22,226, and 718 with 820 pcm, 219 pcm, 2157 pcm, and 74 pcm in standard deviation respectively. The Doppler constant result from MCS is satisfactory better agreement with CEN-1, CEN-2, KIT, CEA-10, and UIUC-3 (SERPENT) of less than 65 pcm standard deviation. The sodium and control rod worth results from MCS showed moderately good agreement with all the research institutes except ANL.

5. Conclusion

This benchmark study demonstrated the whole-core neutronic analysis of medium-core MOX-1000 MWth by MCS. In conclusion, these discrepancies of all neutronic parameters from all eleven research institutes are because of mainly different data libraries for nuclear cross-section calculation and various numerical methodologies for the computational codes and with MCS too. MCS also uses different cross-section interpolation algorithms at 1500K, 1300K, and 705.5K of fuel as well as structural temperatures with other contributed participants for the benchmark. MCS exhibits overall better terms with CEN (1, 2), CEA-10, KIT, and UIUC-3 for multiplication factor, sodium and control rod worth, and Doppler constant calculation. It can be easily assessed our MCS results show relatively very good agreement with the average of all research participants. Further, the uncertainty and sensitivity analysis will be carried out in future work.

ACKNOWLEDGEMENT

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