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Sensitivity Analysis of MOX-1000 MW_{th} in NEA-SFR Benchmark Using MCS Code

Saisundar Mohanty, Tuan Quoc Tran, Siarhei Dzianisau, 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

Sodium-cooled fast reactors (SFRs) stand out as promising innovations in the Generation IV class, bringing distinct advantages compared to traditional light-water reactors. These benefits encompass heightened nuclear safety features and operational perks like lower primary loop pressure, utilization of an intermediate coolant system, efficient heat conduction with sodium, substantial thermal inertia, and a generous safety margin before encountering coolant boiling conditions. Despite these advantages, SFRs grapple with certain technical challenges, particularly concerning elevated operating temperatures, the reactivity of sodium, and the management of the positive sodium void effect, especially in larger reactor cores. To evaluate neutronic core parameters for various Generation IV Sodium-cooled Fast Reactor (SFR) concepts, a series of four numerical benchmarks were established with different core sizes, as introduced by the Nuclear Energy Agency (NEA) [1]. Within this benchmark, particular attention is given to the medium-sized oxide core MOX-1000 MW_{th} due to observed discrepancies in results from eleven participating research institutes [2]. For this reason, sensitivity analysis serves as a valuable tool for nuclear engineers in reactor analysis and design calculations for the evaluation of safety parameters. It allows engineers to explore how changes in input parameters affect the system response, offering insights into crucial processes and providing a means to evaluate the repercussions of parameter variations. To identify the main discrepancies in designing parameters the sensitivity analysis was performed by using Monte Carlo code-MCS which was developed at Ulsan National Institute of Science and Technology (UNIST) [3].

2. Benchmark Description

2.1 Core Modelling

The MOX-1000 benchmark, featuring a medium oxide core, is composed of 180 driver assemblies, 114 reflector assemblies, 66 shield assemblies, and 19 control rod assemblies (including 15 primary and 4 secondary control rod assemblies). The active core region within the driver subassemblies is further subdivided into three zones: inner (30 assemblies), middle (90 assemblies), and outer core (60 assemblies) [1].

In this MOX-1000 MW thermal core calculation, a vacuum boundary condition has been applied. The radial arrangement of MOX-1000, as illustrated in Figure 1, depicts the active core (including inner, middle, and outer core) surrounded by radial reflector and radial shield assemblies.

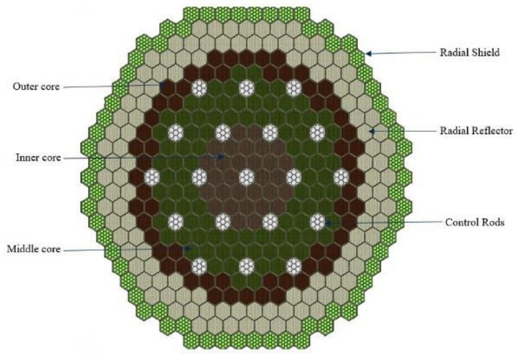

Fig. 1. Core Layout of the MOX-1000 MW th

The medium oxide core's average fuel and structural temperatures are recorded as 1300K and 705.5K, respectively, as per Table I.

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

In the oxide core's driver subassembly, the active region is segmented into five zones and more, with the gas plenum space positioned above. This arrangement is followed axially by the upper structure. Beneath the active fuel regions, there is a sequence comprising the radial reflector and lower structure. Refer to Figure 3 for an axial schematic representation. A detailed summary of the driver subassembly specifics for the 1000 MW thermal oxide core can be found in Table II.

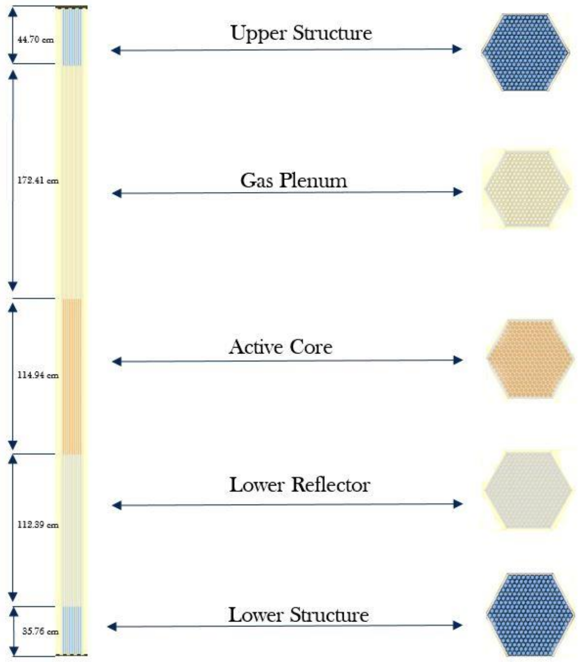

Fig. 3. Schematics of driver subassembly of MOX-1000 MW th oxide core

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
Subassembly outer of duct flat-to-flat	15.8123
Duct wall thickness	0.3966

2.2 Code Description

The MCS (Monte Carlo Simulation) code is an advanced neutron/photon transport code developed by the COmputational Reactor physics and Experiment laboratory (CORE) group at the Ulsan National Institute of Science and Technology (UNIST) [3, 4]. Designed for high-fidelity simulations, MCS is versatile, catering to multi-physics scenarios for both Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR), and extending its capabilities to fast reactors. Its reliability has been thoroughly demonstrated through verification and validation processes involving benchmark problems such as the Benchmark for Evaluation And Validation of Reactor Simulations (BEAVRS), Virtual Environment for Reactor Applications (VERA), and the International Criticality Safety Benchmark Evaluation Project (ICSBEP).

3. Sensitivity Analysis and Results

3.1 Sensitivity Analysis

Sensitivity analysis examines how changes in a model's output, whether numerical or otherwise, can be distributed among various sources of variation, either qualitatively or quantitatively. This analysis examines the model's reliance on the provided information. Typically, sensitivity analysis is conducted for verification, identifying singular points, determining the primary factors influencing a specific response, and identifying correlations among input variables [5]. To facilitate the uncertainty analysis, a preliminary step involves a sensitivity analysis to identify key input parameters. This analysis entails perturbing each input parameter and assessing its impact on the Figure of Merit (FOM). For instance, by introducing a percentage of perturbation “p” (like 1%), the sensitivity analysis helps characterize the influence of each parameter on the FOM.

$$\acute{\eta} = \eta\,(1+p) \tag{1}$$

Where:
$\acute{\eta}$ is the perturbed input parameter value
η is the nominal input parameter value
p is the perturbation value

Table III: Input Parameters Sensitivity Analysis

Input Parameters	Nominal value	Small Sensitivity	Large Sensitivity
Subassembly duct outer flat-to-flat (cm)	15.8123	15.9704 (+1%)	16.2076 (+2.5%)
		15.6541 (-1%)	15.4169 (-2.5%)
Cladding outer radius (cm)	0.3928	0.3967 (+1%)	0.4026 (+2.5%)
		0.3888 (-1%)	0.3830 (-2.5%)
Core Temperature (K)	1300K	1310.27 (+1%)	1402.7 (+10%)
		1289.7 (-1%)	1197.3 (-10%)
Sodium Density (gm/cm3)	0.836985	0.845327 (+1%)	0.920653 (+10%)
		0.828588 (-1%)	0.753262 (-10%)
Subassembly Pitch (cm)	16.2471	16.4095 (+1%)	16.6532775 (+10%)
		16.084629 (-1%)	15.8409225 (-10%)

The sensitivity analysis involves identifying geometric and physical input parameters for evaluation.

Two types of sensitivity analyses, namely Small and Large Sensitivity, are defined for each parameter. These analyses require perturbations of 1% and 2.5% or 10%, respectively, to the physical and geometrical parameters, ensuring that such perturbations do not cause interferences [6]. In cases where interferences occur, particularly with the 10% perturbation, upper and lower limits are determined. For each parameter, two rows are presented and the first indicates the value for a positive perturbation, while the second displays the value for a negative perturbation. It has been summarized in Table III.

3.2 Simulation and Results

The MOX-1000 is modeled for sensitivity analysis by using MCS. A total of 20 different cases for input parameters such as Subassembly duct outer flat-to-flat, cladding outer radius, core temperature, sodium density, and subassembly pitch have been modified to perform sensitivity analysis. Also, we have utilized four different group cross-section data like ENDF/B-VII.1, and ENDF/B-VII.0, ENDF/B-VIII, and JENDL-4.0 library for evaluating how the system's response changes when specific input parameters are altered, helping identify key processes and assess the impact of parameter variations. The sensitivity coefficients obtained from this analysis are valuable for estimating uncertainties in k_{eff} due to cross-section data and sensitivity coefficients associated with reactivity responses. Each criticality simulation runs with 20 numbers of in-active cycles and 80 active cycles with a batch size of 100 for 50,000 histories.

Table IV: MCS results for MOX-1000 core for different libraries

Library	k_{eff}	Standard Deviation (pcm)	β_{eff}	Standard Deviation (pcm)
ENDF/B-VII.0	1.03107	3.8	333	3.2
ENDF/B-VII.1	1.02974	2.3	333	2.3
ENDF/B-VIII	1.02735	3.4	334	3.1
JENDL-4.0	1.03280	4.7	330	4.0

The different calculations for neutronic parameters k_{eff} and β_{eff} (delayed neutron fraction) have been obtained at the beginning of the cycle (BOC) and are well summarized in Table IV with standard deviations.

It is acknowledged that the parameters utilized in design calculations may deviate from the actual core parameters, such as the cladding outer radius. In this section, a set of key input parameters was selected, and variations were introduced for four scenarios: small negative change, small positive change, large negative change, and large positive change. This comprehensive analysis was instrumental in enhancing our understanding of the influence exerted by each input parameter and the detailed variation can be found in Table V. In the table, the Δk_{eff} was calculated by using the following equation:

$$\Delta k_{eff} = \frac{k_{eff}^{nominal} - k_{eff}^{Perturbation}}{k_{eff}^{nominal} * k_{eff}^{Perturbation}} * 10^5 \quad (2)$$

Table V: Results of Sensitivity Analysis

Input Parameters	Nominal value	Small Sensitivity (pcm)	Large Sensitivity (pcm)
Subassembly duct outer flat-to-flat (cm)	15.8123	20.75	43.40
		-23.57	-44.30
Cladding outer radius (cm)	0.3928	172.88	455.74
		-181.67	-458.98
Core Temperature (K)	1300K	8.48	56.61
		-16.02	-98.79
Sodium Density (gm/cm3)	0.836985	29.24	81.17
		-19.80	-108.33
Subassembly Pitch (cm)	16.2471	471.93	1179.79
		-466.45	-1159.17

3.3 Results Discussion

In this section, the sensitivity analysis results have been discussed. The recent studies performed with MCS have shown satisfactory agreement for different cross-section libraries for nuclear data calculation with very small standard deviations for endf 7.0 with other research institutions like ANL (Argonne National Laboratory) etc [2]. But all other libraries like endf 8.0 or 7.0 and jendl 4.0 have attributed the discrepancy to variations in the algorithms employed for interpolating neutron cross-sections across distinct core and structural temperatures. The effective delayed neutron fractions for all different nuclear data libraries are in relatively good agreement with each other. We have observed that as the positive small or large perturbation is implemented, the multiplication factor has decreased as compared to the negative small or large perturbation. The Perturbation in cladding outer radius and subassembly lattice pitch has shown a very high effect on the multiplication factor (more than 450 pcm and 1100 pcm respectively) as illustrated in Fig.4.

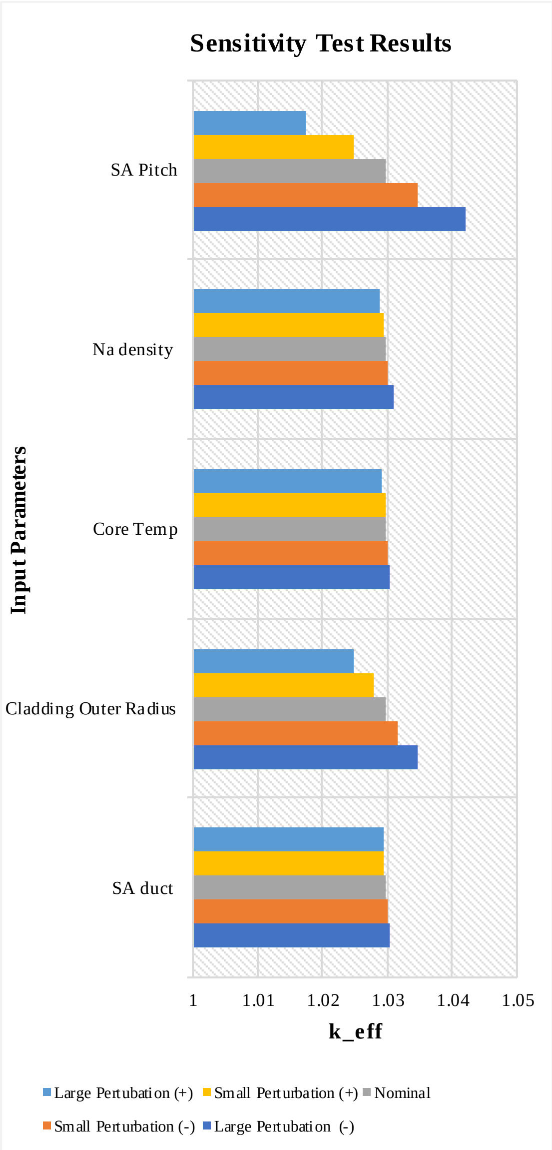

Fig. 4. Sensitivity Results for Subassembly duct outer flat-to-flat, Cladding Outer, Core Temperature, Subassembly Pitch, and Sodium Density

3. Conclusion

The parameters used in design calculation are different from the actual core parameters such as cladding outer radius or subassembly pitch. Hence, the sensitivity of the k_{eff} to the input parameters was analyzed. We only considered a single effect of the perturbed input parameters on the multiplication factor and it shows a constant decrement when the perturbation is varied from positive to negative. The sensitivity analysis of this study will act as a reference in future uncertainty quantifications for design calculations and the evaluation of the safety parameters. This study mainly focuses on the sensitivity analysis of the large discrepancies that occur in the criticality calculation of MOX-1000 MW_{th} among the other SFRs. This indicates that the processing accuracy of assemblies within a core has a great impact on the estimation of criticality. The parameters that affect k_{eff} the most are duct outer flat-to-flat, sodium density, and Cladding outer radius. Overall this work demonstrates the relative importance of the various model parameters. The detailed in-depth uncertainty and sensitivity analysis and their combined effect shall be carried out in future work.

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