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Original Research Article

Neutronic and Safety Analysis of CAREM-25 Small Modular Reactor Using Supermc Advanced Code

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Abstract

Computer simulation is crucial due to the importance of estimating various parameters of a reactor in different functions. Hence, simulation codes and programs must have high credibility to perform complex calculations. SuperMC is a powerful, accurate graphic user interface Monte Carlo method-based code to simulate and model nuclear systems due to the unique features of CAREM-25 reactor, including high efficiency, complex geometry is chosen to be modeled by SuperMC and MCNPX codes to calculate neutronic and control parameters such as multiplication factor, flux and power distribution, and control rod worth. Comparing the results of the two simulations mechanism indicates the proximity of the computed values with less than a %2 difference in neutronic parameters. Also, SuperMC results show an appropriate consistency with benchmarks and references. Consequently, SuperMC can be considered an accurate, simple, and GUI Advanced program to simulate nuclear reactors.

Keyword: SuperMC; CAREM-25; MCNPX; Neutronic; Small Modular Reactors.

Nomenclature and Units

Symbol	Parameters	Units
K	Effective multiplication factor	-
r	Enrichment	*%*
Dimension	Length, width, and height	*mm*
V	Volume	*Mm*^{3}
φ	Flux	*#/cm*^{2}*.sec*
Power	Power	*MW*
Reactivity	Reactivity	*mK*

1. Introduction

Designing, developing, and constructing Small Modular Reactors (SMRs) have become a topic of interest in many countries for their advantages, such as higher efficiency, higher power plant economy, higher safety, and others in recent years [1]. This type of reactor would generate less than 700 MW of electric output in medium sizes and less than 300 MW of electric output in small sizes. This type of reactor is produced in separate modules in the factory, and then the modules are assembled at the power plant site. According to IAEA reports, SMRs are divided into four technological categories [1-2].

1. Advanced SMRs, including an integrated pressurized water reactor.
2. SMRs with an innovative design, including generation IV Small Reactors with non-water coolant and moderator.
3. Modified SMRs, including the offshore floating power plants.
4. Conventional small modular Reactors, including generation II nuclear power plants, are currently in operation.

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CAREM-25 (Central Argentina de Elementos Modulares) reactor is one the first integral pressurized reactors with light water in the world that is designed by Argentina National Atomic Energy Commission (CNEA) and other nuclear manufacturers, which is deployed in Argentina [1]. CAREM-25 reactor generates an electric output of 32 MW and a thermal power of 100 MW [3-4]. This reactor has been developed to deliver power, economic, and safety efficiency for Argentina. Most of the technologies and equipment utilized in CAREM-25 are produced in Argentina (at least %70) to reduce expenses [5-6]. It should be noted that CAREM-25 is a prototype for evaluating and examining different parts of the reactor. If the trial results were a triumph, reactors with an electric output of 150-300 MW would be manufactured [1-7].

The physical behavior of a nuclear reactor is characterized by the distribution of neutron density inside its core. It is usually obtained from the neutronic analysis of the reactor core with the specified material compositions and geometrical data. The estimated neutron flux distribution forms the basic input to derive all other core parameters such as criticality, power, absorber rod worth, fuel burnup, reactivity coefficients, and fission product poisoning. Generally, detailed neutronic calculations for a reactor core are difficult to perform because of the complex dependence of neutron flux on variables such as position, energy, angle, and time. Neutron behavior is one essential parameter to be determined in nuclear reactors. Developing advanced nuclear codes requires research on even more complex neutron behaviors [8].

Super Monte Carlo Program for Nuclear and Radiation Simulation (SuperMC) is a general-purpose, intelligent, precise, and accurate advanced simulation software to simulate and calculate various parameters for nuclear systems [9-10]. SuperMC is developed by the FDS Team in China [9]. SuperMC computes the Monte Carlo simulation of neutron, photon, and coupled neutron-photon transport and depletion and activation calculations. This advanced code can be equipped with automatic modeling and visualization functions. This code has several calculation modes, such as Transport Calculation, Transport-Burnup Coupled Calculation, Point Activation Calculation, Transport-Activation Coupled Calculation, and Shutdown Dose Calculation to perform various parameters [9].

SuperMC has many capabilities to simulate the geometry, such as self-sufficiency in creating CAD models without acquiring any support from other commercial CAD software, striking traits including parameterized-based hierarchical structure modeling, automatic modeling, and processing of complex 3D geometries. **Figure 1** displays the Functional architecture of SuperMC [9]. Researchers worldwide have already performed many studies of SuperMC advanced code using benchmark models in nuclear fission and fusion [10-13].

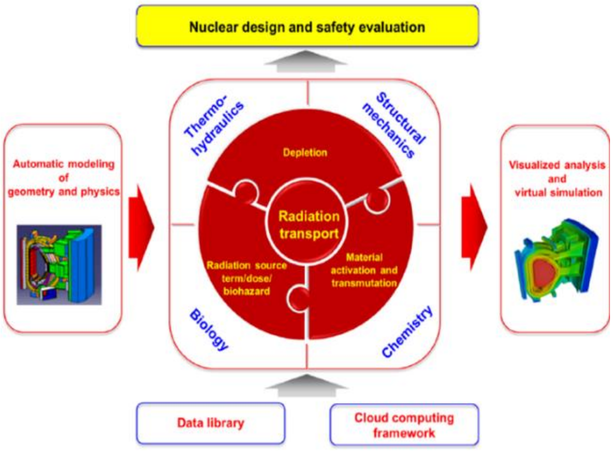

Figure 1. Functional architecture of SuperMC

MCNPX is a general Monte Carlo code designed to track many particle types over broad ranges of energies. MCNPX code can be used in several transport modes: neutron, photon, electron, and combined neutron/photon transport to solve the equation. The MCNPX does not solve an explicit transport equation. MCNPX code uses the Monte Carlo method to simulate the geometry and solve transport equations by tracing individual particles and recording some aspects (tallies) of their normal behavior [14-15].

Although several reports and papers on various technical aspects of SuperMC code have been published recently, the neutronic analysis of SMRs using this advanced code is not discussed in detail. Louhanrong Yu et al., in 2020, developed and tested coupled SuperMC and SUBCHANFLOW codes for Light Water Reactor (LWR) simulations. The coupling code is tested with a PWR single-pin case, a BWR 3 × 3 cluster case, and a PWR full-assembly case. Results presented a good agreement with the reference results calculated by other similar coupling codes. Moreover, this study demonstrates the ability of SuperMC to perform large-scale steady-state coupled neutronics and thermal-hydraulics simulations of LWRs [16]. In 2021, a gas-cooled fast reactor integral shielding experiment was analyzed by Isaac Kwasi_Baidoo et al. using SuperMC code. Results show that most of the calculated threshold reaction rates agreed with experimental values within total uncertainty at the 2σ level. Also, an appropriate consistency of the SuperMC for modeling and calculation for reactor analysis was resented [17]. 2019 Liqin_Hu et al. used SuperMC's advanced code for nuclear design and safety evaluation. In this paper, the

SuperMC Cloud has been developed and designed to offer secure, efficient, and convenient cloud service for nuclear simulation. It consists of two parts: the High-Performance Calculation (HPC) and the HPG [18]. In 2018, Zeeshan_Jamil et al. validated the SuperMC code by simulating a metal-cooled fast reactor – BFS-62-3A. According to the results, deviations of less than 0.4% and 0.8% appeared in the calculated values of the multiplication factor and spectral indices, respectively.

In comparison, average discrepancies for radial fission rate distributions in the fuel region and control rod worths were found to be 2.7% and less than 5%, respectively, which showed a good agreement of the simulation results with the benchmark's measured data [19]. In 2015, Yican Wu et al. worked on a CAD-based Monte Carlo program for integrated simulation of nuclear system SuperMC. The design objective, architecture, and main methodology of SuperMC are presented in this paper. Also, the SuperMC code has been developed and verified using a series of benchmarking cases, such as the fusion reactor ITER model and the fast reactor BN-600 model [20].

According to the capabilities of SuperMC advanced code, detailed and accurate nuclear models can be created and used to perform accurate and high-efficiency nuclear analysis. This study assessed the SuperMC and MCNPX codes to simulate a complex small modular reactor. CAREM-25 is chosen as the case study for Neutronic simulation by the SuperMC and MCNPX codes in equal terms. Several Neutronic parameters were evaluated, including effective multiplication factor, neutron flux distribution, and control rod worth in the core. Finally, the results were compared with the benchmarks to show appropriate consistency.

2. Materials and Methods

2.1 CAREM-25 Small Modular Reactor

CAREM-25 is an integrated and self-pressurized reactor with a primary natural circulation cooling system. According to the integrated design, the pressurizer, the control rod driving mechanism, and twelve mini-helical once-through steam generators are inside the reactor pressure vessel. The reactor pressure vessel diameter is 3.2 (m), and the length is 11 (m) [20-22]. The CAREM-25 reactor pressure vessel is illustrated in **Figure 2**. The CAREM-25 core consists of 61 hexagonal fuel assemblies (FAs). Each FA has 108 fuel rods, 18 guide thimbles, and 1 instrumentation thimble (**Figure 3**). The fuel is Uranium Oxide with 1.8% and 3.1% enrichment [23-24]. CAREM-25 design parameters are given in **Table 1** [1].

Table 1. CAREM-25 design parameters

Parameter	Value
Country of origin	Argentina
Reactor type	Integral PWR
Electrical capacity (MW)	27
Thermal capacity (MW)	100
Design life (year)	60
Coolant/moderator	Light water
Primary circulation	Natural circulation
System pressure (MPa) (Primary Cycle)	12.25
The main reactivity control mechanism	control rods
RPV height (m)	11
RPV diameter (m)	3.2
Coolant temperature, core inlet (ºC)	284
Coolant temperature, core outlet (ºC)	326
Power conversion process	Indirect Rankine cycle
Passive safety features	Yes
Active safety features	Yes
Fuel type	UO2 pellets
Assembly Array	Hexagonal type
Fuel active length (m)	1.4
Number of FA	61
Fuel enrichment (%)	3.1 (prototype)
Fuel burn-up (GWd/ton)	24 (prototype)
Fuel cycle (month)	14 (prototype)
Modules per plant	1

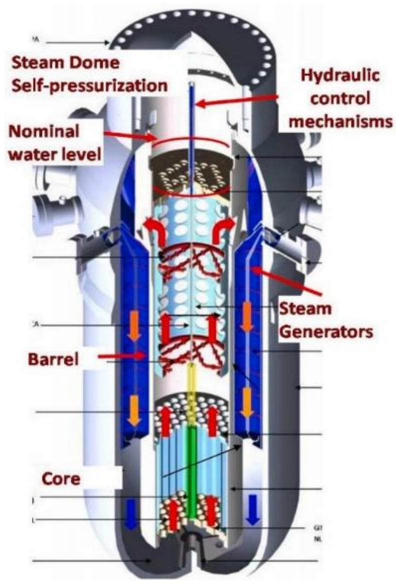

Figure 2. CAREM-25 reactor pressure vessel

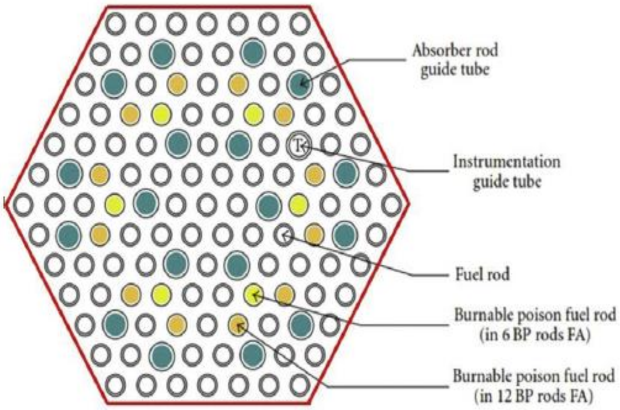

Figure 3. CAREM-25 FA

Core reactivity is controlled by the use of gadolinium oxide (Gd2O3) as burnable poison in specific fuel rods in 42 FAs and Adjust (19 FAs) and safety (6 FAs) Control rods. It especially omits the soluble burnable poisons from the Reactivity Control system during normal operating mode. Absorbing Materials used in the Control rods are Silver, Cadmium, and Indium [23-24]. CAREM-25 fuel rod and control rod design criteria are listed in **Table 2** and **Table 3** [1-4, 24-25].

Table 2. CAREM-25 fuel rod design criteria

Parameter	Value
Total Length (mm)	1600
Active Length (mm)	1400
Cladding Outside Diameter (mm)	9
Cladding Thickness (mm)	0.625
Pellet Diameter (mm)	7.6
Fuel Density	95%
Plenum Volume (mm^3)	6800
Cladding Material	Zry-4
Fuel Pellet	$UO_2Gd_2O_3$ -UO_2

Table 3. Control rod design criteria

Parameter	Value
Total Length	1708
Active Length (mm)	1400
Cladding Outside Diameter (mm)	8.5
Cladding Thickness (mm)	0.65
Pellet Diameter (mm)	7
Pellet Length (mm)	50
Cladding Material	AISI 316 L
Absorbent Pellet	Ag - In- Cd

2.2 SuperMC advanced code

The present paper uses SuperMC code to simulate the CAREM-25 small modular reactor core. On the other hand, the core has been simulated by MCNPX code in equal terms to compare and benchmark the results to show appropriate consistency. This code created an input for the core simulation to calculate the Neutronic parameters such as effective multiplication factor, neutron flux distribution, axial power distribution, and the worth of control rods.

In the first step, transport calculation is selected for calculation mode. All types of elements in their respective heterogeneous geometry, including fuel rods, control rods, burnable poisons, and empty tubes, were all modeled first. Next, all components were imported into the lattice to form the core in the same heterogeneous geometry. **Figure 4** illustrates the configuration of the FAs into the core. For high-precision calculations, the temperature of each cell is selected as the specified velocity in the property tab.

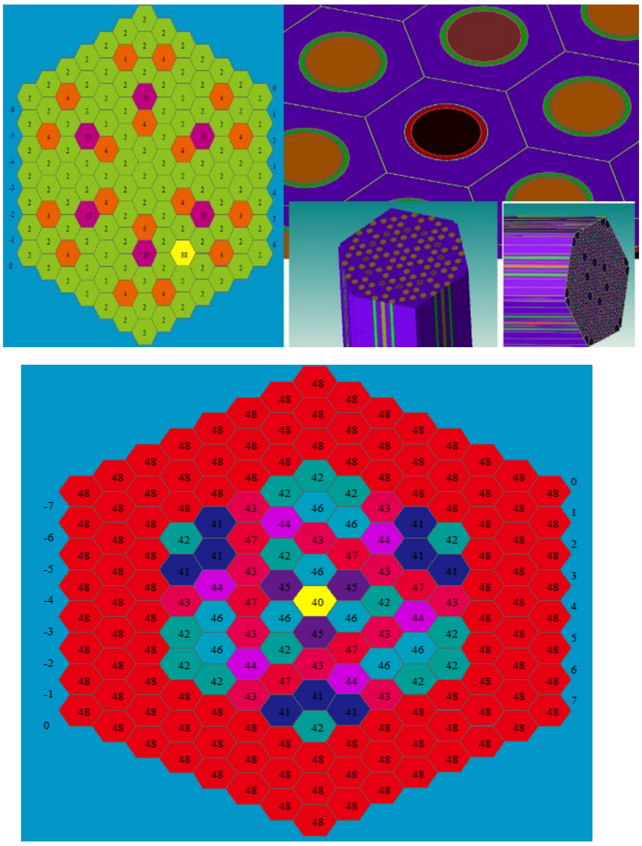

Figure 4. CAREM-25 simulation in SuperMC

Now, via the CAD-based hierarchical modeling feature of the code, the geometry of the core, comprising thousands of fuel and control rods, was accurately modeled. Each element, including fuel pellets, gap, clads, control rods, and burnable poison, was modeled in detail in the material modeling section. The ENDF-B-VII library and 42.C, 71.C, 72.C, and 30.y identification databases were employed in the SuperMC input file (**Figure 5**). This study selects a critical source to add KCODE and KSRC with 700000 particles and 200 cycles. Also, the neutron is chosen as the source of a particle in this section.

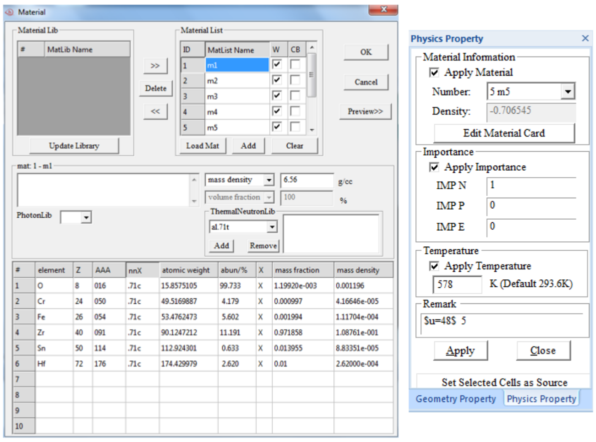

Figure 5. Material modeling in SuperMC

On the other hand, the MCNPX code is utilized to simulate the CAREM-25 core to calculate the Neutronic parameters in a steady state for fresh fuel in equal terms. This code uses the KCODE and KSRC cards for critical calculations mode. Also, 700000 particles with 200 cycles were selected. The importance of neutron particles in all cells has been defined as equal. The axial coolant temperature changes from 284 (ºC) in the core inlet to 326 (ºC) in the core outlet. Hence, the temperature of the moderator is considered 305 (C) as an average coolant temperature using the ENDF/B-VI library and 42.C, 51.C, 52.C, and 70.C identification database codes in the MCNPX input file.

3. Results and Discussion

In the present paper, the neutronic and safety modeling of the CAREM-25, an advanced small modular reactor, is performed using two nuclear Monte Carlo codes: the MCNPX and SuperMC. In order to verify the accuracy of results, the reactor core is modeled via two Monte Carlo codes code to calculate and analyze the neutronic and control parameters of the core, such as multiplication factor and excess reactivity, neutron flux and power distribution, and control rod worth.

3.1 Criticality calculations

The effective multiplication factor is calculated to be 1.04592 with a statistical uncertainty of 0.00029 in SuperMC and 1.04576 with a statistical uncertainty of 0.00036 in MCNPX code when 10% of the adjusted control rods are inserted into the core. A comparison of results shows that the values of effective multiplication factors are very close. The low-value difference also confers acceptable accordance between SuperMC results and references [26]. The reactor core's effective multiplication factor and excess reactivity are listed and compared in **Table 4**.

Table 4. Control rod design criteria

Control rods mode	K-Factor		Excess Reactivity (mK)	
	Super MC	**MCNPX**	**SuperMC**	**MCNPX**
10 % adjust group	k=1.04592 0.00029	k=1.04576 0.00036	43.90	43.75
10% (safety group) + 50% (adjust group)	k=1.00033 0.00033	k=1.00027 0.00039	0.32	0.26

3.2 Neutron Flux distribution

Figures 6 and **7** show the axial flux distribution in the core in ten height intervals by SuperMC and MCNPX codes. Due to the figures, a good compromise has been obtained between two different calculated results. Also, the SuperMC results show adequate consistency with the benchmarks.

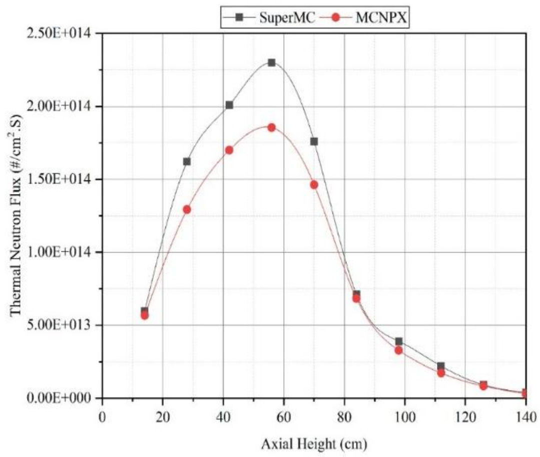

Figure 6. Axial thermal flux distribution.

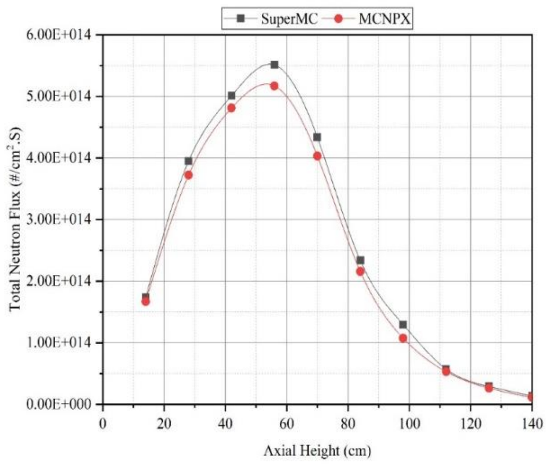

Figure 7. Axial total flux distribution

According to the figures, the maximum flux is about 57 (cm) from the height of the core in a critical situation. Inserting the control rods into the core can move the peak of flux distribution of about 40% to the end.

3.3 Power distribution

Given the physical correlation between flux and power, axial flux and power distribution will reach the maximum value at the same axial height. Hence, the peak of the axial power distribution diagram is about 57 (cm) from the height of the core (**Figure 8**)

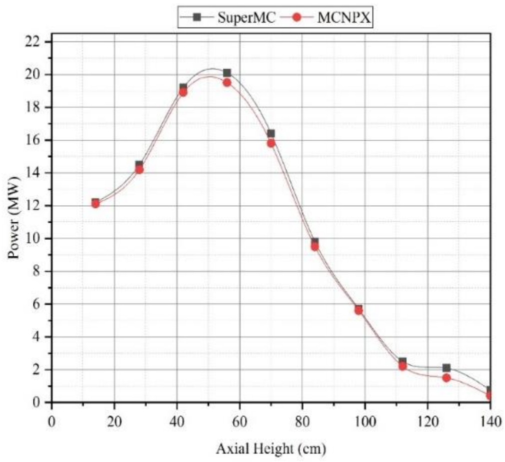

Figure 8. Axial power distribution

3.4 Control rod worths

Control rods are used as the main reactivity control mechanism in the CAREM-25 core into twenty-five FAs. Control rods are classified into two groups: adjusting and safety control rods. Adjusting control rods are applied in 19 FA. On the other hand, safety rods are applied to just six FAs. The integral worth of the control rod is the total reactivity produced along the control rod via insertion into the core. Integral worth diagrams are plotted for SuperMC and MCNPX calculation (**Figure 9**). Good agreement has been obtained according to the comparison of the two diagrams.

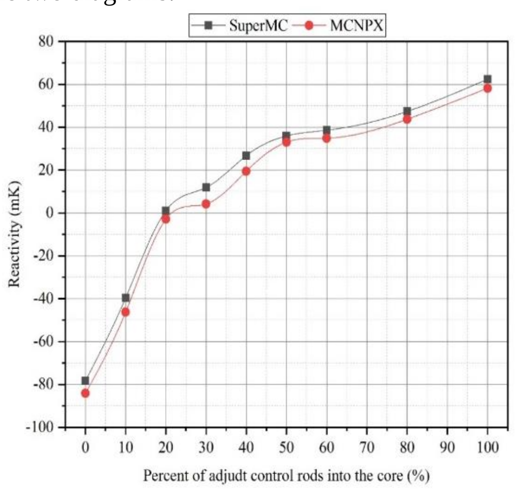

Figure 9. Integral worth of adjust control rods group

4. Conclusions

In this paper, the Neutronic evaluation of the CAREM-25 advanced small modular reactor is performed by comparing Monte Carlo codes modeling. According to some unique feathers and complex geometry, the CAREM-25 advanced small modular reactor was selected as the reference system in this study to simulate SuperMC and MCNPX Monte Carlo codes in equal terms. CAREM-25 is an SMR development project based on pressurized water reactor technology coordinated by the Argentina National Atomic Energy Commission. The results showed less than a 4% difference between the SuperMC and MCNPX codes, which resulted in criticality calculations. Also, appropriate consistency was obtained between the calculations via SuperMC code and the reactor reports for the neutronic parameters, including criticality, flux distribution, and control rod worths. Considering the capabilities of SuperMC code, including modeling the complex geometry, high accuracy and reliability, and easier correlation with other codes such as MCNP, Geant, fluka, etc., SuperMC is capable and advanced code to be utilized for reactor simulation and calculation.

5. Conflicts of interest

The authors declared that they have no conflicts of interest in this paper. Also, we declare the following financial interests that represent a conflict of interest concerning the research works submitted.

6. Ethical Consideration

The article's authors certify that all research ethical principles have been completely met.

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