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Neutronic Analysis of the VVER-1200 Lattice cell fuel using WIMSD-5B Code

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A B S T R A C T

The calculation of safety parameters in nuclear reactors has an important influence on nuclear reactor control and safety. The infinite multiplication factor, reactivity coefficients, and power peaking factor parameters are the most important safety parameters for determining reactor status. The aim of the present study is to analyze the behavior of the nuclear safety parameters for the VVER-1200 core in a normal state of reactor operation. A lattice cell fuel model of the VVER-1200 reactor core was performed using WIMSD-5B. The cross-section library data based on the ENDF/B-VIII.0 was used. The investigated parameters were the value of infinite multiplication factor with different pitch, temperature, enrichment, and boron concentration. The calculation also investigated the reactivity coefficient parameters. The verification of WIMS model VVER-1200 was performed by comparing the results of the WIMSD-5B code with VVER-1200 data in the SAR document, and it was implied that they are in good agreement. The calculated values of reactivity coefficients illustrated a safe behavior.

1. INTRODUCTION

Many countries are constructing nuclear power plants for their energy needs. Seventy-seven VVER reactors have been built since the 1960s. The VVER is basically a pressurized water reactor (PWR). However, there are significant differences between VVER and other PWR types, both in terms of design and materials used. Distinguishing features of the VVER include the following: the use of horizontal steam generators, the use of hexagonal fuel assemblies; the avoidance of bottom penetrations into the VVER vessel, and the use of high-capacity pressurizers. The AES-2006 design (VVER-1200) is the latest development of the long line of VVER nuclear power plant, with increasing thermal power to around 3200 MWth and providing additional passive safety features [1]. The reactor includes international safety standards with evolutionary design improvement in the areas of fuel technology, modularized construction, safety systems, and standardized designs [2,3]. It meets all the international safety requirements for Gen III+ nuclear power plants [4,5].

There are two families of VVER-1200/AES-2006 plant designs, named VVER-1200/V491 and VVER-1200/V392M. The most important differences between the two designs are their safety systems. [6,7] Neutronic study of a nuclear reactor is

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carried out to ensure that the reactor can be operated safely with a sufficient safety margin. To accomplish this, a comprehensive study is carried out during the designing phase of a nuclear reactor. The core excess reactivity and the shutdown margin are important parameters for the safe and reliable operation of a nuclear reactor.

Due to the presence of excess reactivity in the reactor core, an appropriate safety margin is required. This means that a suitable absorbent material must be present to allow the reactor to be shut down in the event of an accident. The shutdown margin (SDM) is normally defined as negative reactivity by which the reactor is subcritical or would be subcritical from its operating condition if all control rods were fully inserted in the core except the more reactive one. The control system is responsible for keeping the stability and safe operation of the reactor. The control system will ensure the implementation of the reactor start-up process, adjust the power level, and normally shut down the reactor in case of an emergency situation. The control rod worth is a key parameter for safety assessments of a nuclear reactor since it affects the increase or decrease in reactivity. This value mainly depends on the characteristics and the sizes of the reactor core. Also, it depends nonlinearly on the rods' compositions and positions where the rods are inserted into the core. Therefore, the calculation of the control rods worth is of major importance.

Reactivity coefficients are also major parameters of reactor safety. It defines the change of reactivity per unit change in certain operating parameters of the reactor. The coefficients that are significant in the reactor are the fuel temperature (Doppler) coefficient, moderator temperature coefficient, and boron concentration coefficient. Moreover, reactor kinetic parameters are of high importance in nuclear power plant operations since they determine the time-dependent behavior of reactor power after reactivity insertion. Furthermore, the power peaking should be within the limits so that there is no hot spot in the core [8]. Therefore, a reliable neutronic analysis of the pin cell is required during the design phase of a reactor core.

The main purpose of this work is to estimate the neutronic parameters of the VVER-1200 reactor that are important for safety. The infinite multiplication factor (k_{inf}), temperature coefficients, and boron concentration coefficient are investigated under normal operating conditions. The investigation of the safety parameters was carried out for the VVER-1200/AES-2006 reactor [9] using the WIMSD-5B code [10]. The cross-section library data based on the ENDF/B-VIII.0 [11] was used.

2. VVER-1200 Reactor Core Description

The VVER-1200/AES-2006 reactor is a pressurized water-moderated reactor with a thermal capacity of 3200 MWth and a net electrical capacity of 1200 MWe. The reactor meets all the international safety requirements for Gen III+ nuclear power plants. The main design parameters of the VVER1200 core are presented in Table 1. The VVER-1200 reactor core is filled with 163 fuel assemblies (FAs). Each fuel assembly consists of a head and a bundle of 331 fuel rods. and a bottom nozzle. The bundle of 331 rods contains 312 fuel rods, one instrumentation channel, and 18 guide channels in which the control rods are inserted. There are six types of fuel assemblies, each has different enrichment, different numbers of fuel pins with different enrichment (radial profiling), as well as different pin numbers with burnable absorber and weight percentage of the burnable absorber Gd_2O_3. The enrichment levels of gadolinium oxide are 5.0% and 8.0%. Fig. 1 illustrates the fuel assemblies' arrangement in the VVER-1200 core. To control and maintain the safety of the reactor, the control and protection system (CPS) is employed. Control rods (CRs) are arranged into some groups called rod cluster control groups in each fuel assembly (RCCA), each one has twenty-four control rods. RCCAs are moved by the rod cluster control (RCC) system. There are 121 RCCAs divided into twelve banks that are used for adjusting reactivity and for reactor shutdown in normal and emergency operating conditions.

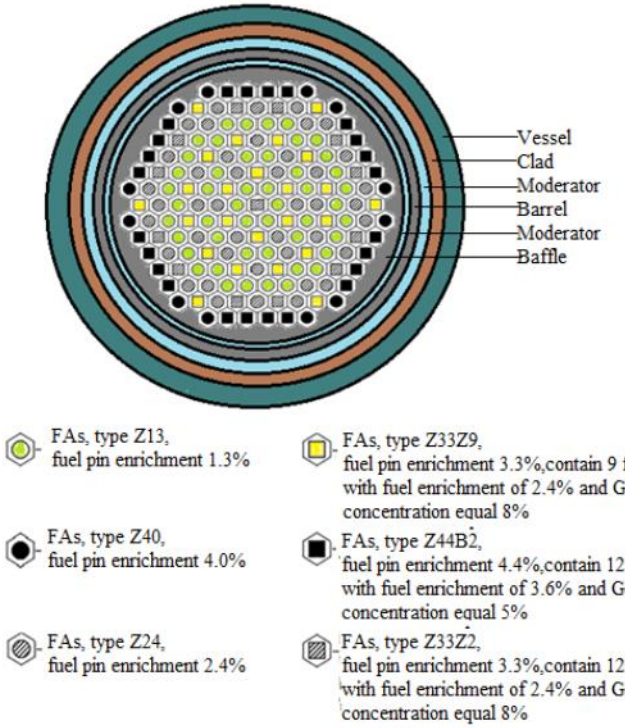

Fig. 1. Fuel assemblies' arrangement in the VVER1200 core [12]

Negative temperature and power reactivity coefficients are ensured. Fuel enrichment in fuel elements is limited to 4.95 %. Maximum FA burnup does not exceed 70 MWd/kgU. Maximum fuel element linear power does not exceed 420 W/cm. Maximum fuel element relative power (Kr) is not more than 1.57. Uranium-gadolinium fuel with natural isotopic composition is used as a burnable poison. The fraction of gadolinium dioxide in fuel is to be chosen from the interval 3-8 g/cm^3 that is accepted for use in VVER-1000 reactors. In VVER-1200, the CPS uses combined absorbers identical to those in operating VVER-1000s. The total number of control rods in CPS can reach 121 pcs. While arranging the VVER-1200 core the most irradiated fuel assemblies are placed at core periphery.

Table 1. Main design Parameters for VVER-1200/AES-2006 core [13]

Parameter	Value (unit)
Thermal power	3200 MWth
Unit electric power	1200 MWe
High reactor PV	11.185 m
The OD of the vessel	464.5 cm
The ID of the vessel	452 cm
The OD of the barrel	361 cm
The ID of the barrel	349 cm
The OD of the baffle	347 cm
The ID of the baffle	298 cm
Fuel assembly (FA)	Hexagonal
Number of FA in the core	163
Number of FA with CR	121
Number of the FR in each FA	312
Pitch of the FA	23.51cm
Type of fuel	UO2 and UO2+Gd2O3
Enrichment of fuel	Up to 4.5wt.%
U-235 Mass fraction of Gd2O3 in fuel	5.0 to 8.0wt.% Gd2O3
Fuel rod pitch	1.275 cm
The OD of FR cladding	0.91cm
The ID of fuel rod cladding	0.773cm
Height of cladding	393 cm
Diameter of fuel pellet	0.76 cm
Diameter of the central hole	0.12 cm
Height of fuel in the core	373 cm
The OD of guide channels in FA	1.29 cm

3. METHODOLOGY

The WIMS code calculates neutron flux as a function of energy and space in a one-dimensional cell using transport theory. The DSN (Discrete Sn = discrete ordinates) approach was used to solve the transport equation. Using the DSN method has more control over the accuracy of the flux solution by choices in the Sn order and mesh width. The fuel cell calculation step was then completed using this code. It converts the data from the input model into a macroscopic cross-sectional constant for the pin cell lattice material. The pin cell lattice element was modeled as a collection of annuli made up of meat, cladding, moderator, and additional region. The WIMS program package receives input in the form of reactor fuel with different elemental compositions and temperature values. The lattices were calculated at hot zero power condition temperature of the fuel (T_f) and moderator (T_m) = 600K, as well as hot full power condition T_f = 900K and T_m = 600K [14]. The new library in WIMS code used 69 groups and then collapsed into 4 groups with the following division, namely [15]: Fast neutrons, groups 1-5 with the energy of 0.821 MeV <E ~ 10 MeV; Retarding neutrons, with energy groups 6-15 with energies of 5,531 eV <E ~ 0.821 MeV; Resonant neutrons, group 16-45 with energy of 0.625 eV <E ~ 5,531 keV; Thermal neutrons with energies of <0.615 eV, groups 46-69.

The atomic density of the isotope given in the program input, as well as the microscopic cross-section of the program library, were used to calculate the macroscopic cross-section of the neutron spectrum, which is needed as a coefficient in the multi-group equation. Many groups were calculated in the second section. The cell was divided into four sections, with index 1 representing the fuel meat region, index 2 representing cladding, index 3 representing moderators, and index 4 representing the additional region. The dimension and

composition of each region are determined by program inputs. The multi-group constant was divided into four groups after obtaining the multi-group spectrum in each of the four regions.

For the VVER reactor with a hexagonal fuel assembly, the data of the UO_2 fuel cell pin can be seen in Table 2. Cell pin geometry configuration with $r_1 = 0.4$ cm, $r_2 = 0.45$ cm, and $r_3 = 0.677$ cm fuel radius, where the outer radius is the same as a square with 1/2 = 0.6 cm [16]. Fig. 2 shows the model of the fuel cell pin geometry.

Table 2. Initial material compositions

Parameter	Nuclide	Weight Percent (%)	Atomic Density (1/barn cm)
Fuel	^{232}Th	65.909	1.61215E-02
	^{234}U	0.034	8.24518E-04
	^{235}U	4.291	1.03615E-03
	^{238}U	17.740	4.22957E-03
	^{16}O	12.026	4.26835E-02
Cladding	Zr-4	100	4.31438E-02
Coolant	^{1}H	11.19	4.71053E-02
	^{16}O	88.81	2.35662E-02

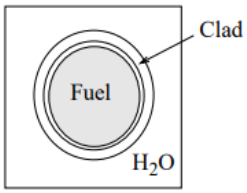

Figure 2. The unit cell of the VVER pin [17]

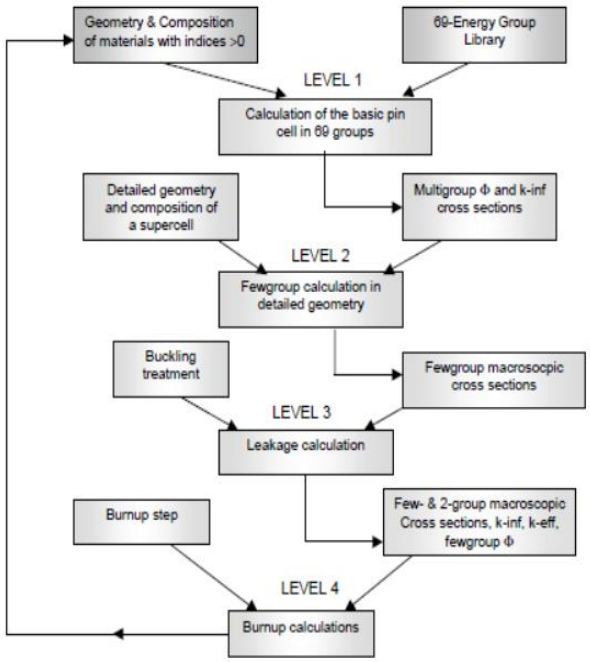

Figure 3. Flowchart of WIMS code [17]

Because the WIMS algorithm can only calculate one-dimensional neutron transport, modeling of the core cells is required. The formation of group constants in four energy groups was calculated using cell modeling. Calculation of cells using the WIMS software package and the flowchart of the WIMSD code as illustrated in Fig. 3 from the reactor cell unit type LWR consisting of fuel clusters with a square pitch arrangement. The cell unit dimensions were then determined, with each unit cell containing one fuel and a moderator. The fuel is surrounded by a moderator zone. The radius of the moderator surrounding the fuel element is then equal to the root of the aforementioned area divided by 3.14, yielding 0.53 cm. The cell dimension data was obtained from the comparable unit cell as input data for the WIMS software known as the annulus, shown in Fig. 2. Table 2 shows the atomic density that makes up the fuel pin. The goal of group constant generation is to get the average value of group constants in a cell by homogenizing it. The core buckling value (B_z^2) was acquired from the reference [18]. The group constants for the core constituent materials were calculated under the same conditions as previously. By enriching the fuel, the value of the k_{inf} and reaction rate were computed. Table 1 shows the pin cell variable and temperature parameters. The following steps were taken to calculate the neutronic parameter of pin cell calculation. Cells were calculated at hot full power (HFP) temperature conditions. On a heavy metal basis, the normal all-UO_2 fuel pellets were substituted with a U-238 combination at 94 percent of theoretical density, consisting of 75 w/o thorium and 25 w/o Uranium, with the latter enriched to 1.6 w/o U-235, for an overall enrichment of 4.4 w/o U-235 in total heavy metal load.

The pin cell model of a VVER fuel pin unit lattice cell is shown in Fig. 2. This model was used in the burn-up estimates mentioned in this paper. Because all actinides and the uranium chains will be created during burnup, this calculation is a test of all the actinide neutron libraries used by the WIMSD code. Table 3 provides the variable of the pin-cell model for a VVER pin lattice. In the calculations, parameters at full power were employed. Lattices were identified by a code, Pi/Wj/Bk/Tl, where,

P: lattice pitch (cm)
W: atomic enrichment (%)
B: boron concentration (H3BO3 g/l)
T: temperature (K) and the model of calculation indices correspond to the following values,

Table 3. Variable of the lattice fuel VVER reactor [18]

index	1	2	3	4	5	6	7	8
P		1.10	1.27	1.50	1.905			
W		1.6	3.6	4.4				
B	0.0	0.64	1.0	1.41	1.85	4.0	5.8	7.2
T		294	353	403				

The reactivity coefficient is the total sum of the reactivity coefficients due to moderator temperature (α_M), fuel (α_F), and boron concentration (α_{CB}). The reactivity coefficients are calculated as follows:

a. Fuel Temperature Coefficient (α_F)

The fuel temperature coefficient is given by the following mathematical expression.

$$\alpha_F = 1/k_{inf} \times \delta k_{inf}/\delta T_F \quad (1)$$

where,
k_{inf} is the infinite multiplication factor.
($\delta k_{inf}/\delta T_F$) is the change of infinite multiplication factor as a result of the change of fuel temperature or the slope of the curve that represents the relation between k_{inf} and T_F.

In the present calculations, the fuel coefficient was evaluated by varying the fuel temperatures from 600K - 1200K with 14 temperature steps, with each step a jump of 50K. Meanwhile, the clad and moderator temperatures were kept constant at 580K.

b. Moderator Temperature Coefficient (α_M)

The moderator temperature coefficient is given by Eq. 2

$$\alpha_M = 1/k_{inf} \times \delta k_{inf}/\delta T_M \quad (2)$$

Where:
k_{inf} is the infinite multiplication factor.
$\delta k_{inf}/\delta T_M$ is the change of the infinite multiplication factor as a result of the change of moderator/coolant temperature, or the slope of the curve that represents the relation between $k$inf and TM.

The moderator temperature coefficient was evaluated by varying the moderator temperature from 580 -760K,10 temperature steps, and each step is 20K. The fuel temperature was fixed at 600K.

c. Total Temperature Coefficient (α_T)

The total temperature coefficient of reactivity, α_T, is the combination of both the fuel temperature coefficient α_F and the coolant/moderator temperature coefficient α_M as implied in Eq. 3.

$$\alpha_T = \alpha_F + \alpha_M \quad (3)$$

c. Boron Coefficient (α_{CB})

The Boron coefficient is given by Eq. 4:

$$\alpha_{CB} = 1/k_{inf} \times \delta k_{inf}/\delta_{CB} \quad (4)$$

Where k_{inf} is the infinite multiplication factor and $\delta k_{inf}/\delta_{CB}$ is the change of infinite multiplication factor as a result of the change of boron concentration or the slope of the curve that represents the relation between k_{inf} and C_B. The boron concentration coefficient was evaluated by varying the concentration of boron gradually from 0-7.2 g/l with the temperature of both fuel and moderator fixed at 580K.

2. RESULTS AND DISCUSSION

The calculation results of the WIMSD-5B using existing and newest library programs are presented in Table 4. It was obtained that the k_{inf} values of VVER pin cell using WIMSD-5B code are different with different pitch, enrichment boron concentration, and temperatures. The higher the temperature, the smaller the value of k_{inf}. From these results, it can be said that the value of the coefficient of reactivity of the fuel is negative and the reactor core is under-moderated. Likewise with boron concentration, the larger the boron concentration in the coolant, the smaller the value of k_{inf} obtained, so that the boron fulfills its function to reduce the reactivity of the reactor core and also shut down the reactor core. Similarly, with increasing fuel enrichment and other variables (C_B, Pitch, and T) at a constant value, the calculation results show that the value of k_{inf} increases. Therefore, to insert more reactivity or increase the length of the cycle in the reactor core, it is necessary to increase fuel enrichment. The fuel pitch also shows the same result, namely the greater the pitch the larger the value of k_{inf}.

Table 4. Eigenvalues WIMSD-5B as a function of pitch, enrichment, boron concentration, and temperature.

Cases	Pitch (cm)	E (%)	CB(g/l)	T(K)	k_{inf}
1	1.27	3.6	0	294	1.411902
2	1.27	3.6	0	353	1.404712
3	1.27	3.6	0	403	1.396136
4	1.27	3.6	4.0	294	1.302995
5	1.27	3.6	4.0	353	1.299554
6	1.27	3.6	4.0	403	1.295858
7	1.27	3.6	5.8	294	1.260010
8	1.27	3.6	5.8	353	1.257886
9	1.27	3.6	5.8	403	1.255925
10	1.27	3.6	7.2	294	1.228776
11	1.27	1.6	0	294	1.200359
12	1.27	1.6	1.85	294	1.123876
13	1.27	4.4	0	294	1.449215
14	1.27	4.4	0.64	294	1.432569
15	1.27	4.4	7.2	294	1.284468
16	1.10	3.6	0	294	1.301347
17	1.10	3.6	0	353	1.290474
18	1.10	3.6	0	403	1.277428
19	1.10	3.6	1.0	294	1.287521
20	1.10	3.6	1.41	294	1.281971
21	1.50	3.6	0	294	1.443249
22	1.50	3.6	4.0	294	1.260018
24	1.50	4.4	0	294	1.491352
25	1.905	3.6	0	294	1.372342

When the moderator temperature rises, the k_{inf} value is lower. The moderator reactivity coefficient tends to lower from -1.935E02 pcm/K to -1.785E02 pcm/K. The average value is -1.876E02 pcm/K. This value conforms to standards in the VVER-1200 FS-SAR which range from -197.8pcm/K to -176.7pcm/K [18].

Table 5. The result of the calculation for moderator temperature coefficient.

Case	Pitch (cm)	E (%)	T(K)	k_{inf}	α_m (pcm/K)
26	1.27	3.6	580	1.390257	-
27	1.27	3.6	600	1.389870	$-1.935x10^2$
28	1.27	3.6	620	1.389486	$-1.920x10^2$
29	1.27	3.6	640	1.389103	$-1.915x10^2$
30	1.27	3.6	660	1.388723	$-1.900x10^2$
31	1.27	3.6	680	1.388341	$-1.910x10^2$
32	1.27	3.6	700	1.387964	$-1.885x10^2$
33	1.27	3.6	720	1.387594	$-1.850x10^2$
34	1.27	3.6	740	1.387237	$-1.785x10^2$
35	1.27	3.6	760	1.386880	$-1.785x10^2$

The fuel reactivity coefficient values are negative. Values range between -4.050 pcm/K and -2.994 pcm/K. The average value is -3.443 pcm/K. These values conform to the results taken from reference [12] which range from -4.44 pcm/K to -2.73pcm/K. Reactivity coefficients are the total temperature coefficient of reactivity, fuel temperature coefficient, moderator temperature coefficient, and boron concentration coefficient.

Table 6. The result of the calculation for fuel temperature coefficient

Case	Pitch (cm)	E (%)	T(K)	k_{inf}	α_f (pcm/K)
36	1.27	3.6	600	1.389449	-
37	1.27	3.6	650	1.387424	-4.050
38	1.27	3.6	700	1.385478	-3.892
39	1.27	3.6	750	1.383604	-3.748
40	1.27	3.6	800	1.381791	-3.626
41	1.27	3.6	850	1.380035	-3.512
42	1.27	3.6	900	1.378329	-3.412
43	1.27	3.6	950	1.376638	-3.382
44	1.27	3.6	1000	1.374990	-3.296
45	1.27	3.6	1050	1.373384	-3.212
46	1.27	3.6	1100	1.371818	-3.132
47	1.27	3.6	1150	1.370288	-3.060
48	1.27	3.6	1200	1.368791	-2.994

From Table 6, the k_{inf} will decrease as the fuel temperature increases for the UO_2 fuel core. The results of this calculation are in good agreement with the other calculation, showing that the presence of UO_2 in the core will lower the k_{inf} [14]. The effect of increasing fuel temperature will cause a decrease in the value of k_{inf}. It is caused by the increase of resonance absorption and fission capture. By referring to the k_{inf} values in Table 6, the Doppler reactivity coefficient (α_f) can be determined using equation (1) as shown in Table 6.

Table 7. Coefficient reactivity of boron ($\boldsymbol{\alpha_{CB}}$)

CB (g/l)	k_{inf}	$\boldsymbol{\alpha_{CB}}$ (pcm/(g/l))
0	1.411902	-
4.0	1.302995	-0.027227
5.8	1.260010	-0.026190
7.2	1.228776	-0.025434

The calculation of the effect of boron concentration on the value of k_{inf} can be seen in Table 7, the value of k_{inf} decreases with increasing boron concentration in the core. The value of the reactivity coefficient is negative and this value is in accordance with the results of the VVER1200 core design [18]. The average of these values is -0.026283667 pcm/(g/l).

3. CONCLUSION

Despite the different roles that WIMSD-5B code plays in neutronic calculations, it appears from the latest findings that they can concur on UO_2 calculations. To assure the safe functioning of the nuclear reactor with sufficient safety margins, a neutronic examination of the reactor was conducted. This report presents a thorough neutronic examination of the VVER-1200 reactor. The values of k_{inf}, moderator and fuel temperature reactivity coefficients were the variables examined. The ENDF/B-VIII.0 nuclear data library and the WIMSD-5B code were used to do the computations. The results of the calculation are suitable when compared to those provided in the safety analysis report for VVER-1200.

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AUTHOR CONTRIBUTION

Juniastel Rajagukguk carried out a model of pin cell input, and Santo Paulus Rajagukguk carried out cell calculation using WIMSD-5B. Both authors performed data analysis. Santo Paulus Rajagukguk and Juniastel Rajagukguk as the main contributions to this paper. All authors read and approved the final version of the manuscript.

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