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Evaluation of kinetic parameters of the Dalat nuclear research reactor with LEU fuel

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INTRODUCTION

- The Dalat Nuclear Research Reactor (DNRR) is a 500-kW pool-type nuclear research reactor. The core is loaded with low-enriched uranium (LEU) with the ^{235}U enrichment of 19.75 wt%.
- Kinetic parameters of the DNRR core loaded with 92 LEU fuel bundles were calculated, including the effective delayed neutron fraction (β_{eff}), the neutron generation lifetime (Λ), and the prompt neutron lifetime (l_p).
- The MCNP6.3 code and the latest versions of the ENDF/B and JENDL data libraries were used to calculate the kinetic parameters at the beginning of the cycle (BOC) with 46.88 days of operation and the end of the cycle (EOC) with 933.2 operational days of the DNRR. Two methods were used to calculate the β_{eff}: the adjoint weighted method and the prompt method. On the other hand, the adjoint weighted method and the *1/v* absorber insertion method were used to determine the l_p. A comparison between the methods and the data libraries was performed and presented.

DESCRIPTION OF THE DNRR AND CALCULATION MODEL

➢ The DNRR

- The DNRR consists of a cylindrical aluminum tank measuring 6.26 m in height and 1.98 m in diameter.
- The active core has a cylindrical shape with a height of 60 cm and a diameter of 44.2 cm. It includes 92 fuel assemblies, 12 beryllium block rods, 7 control rods, a neutron trap, and 3 irradiation channels.

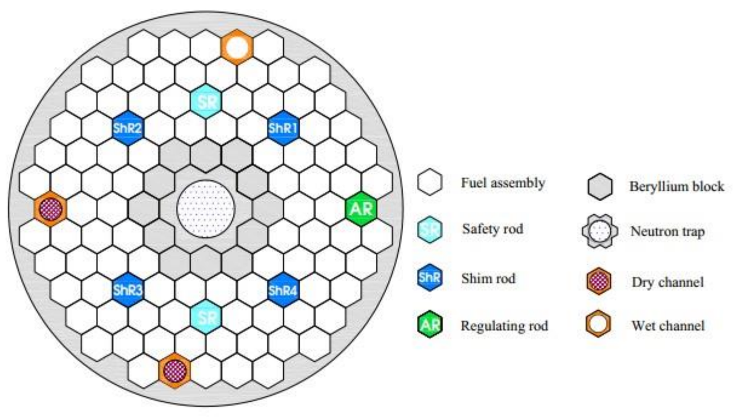

Fig. 1. Configuration of the DNRR core with 92 LEU fuel bundles.

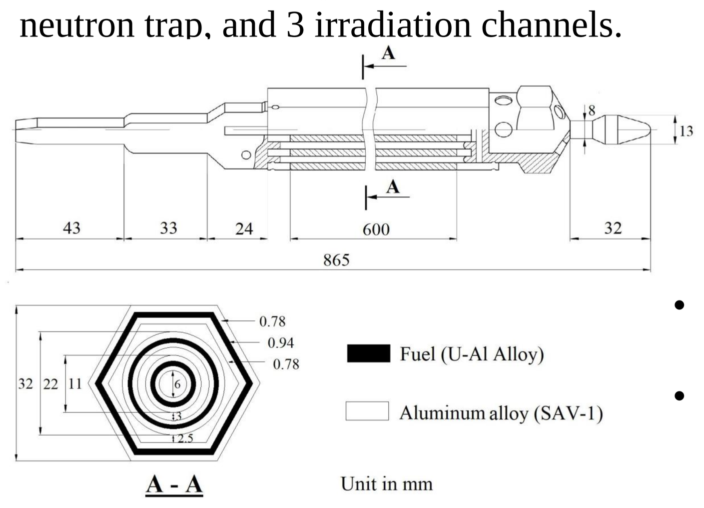

Fig. 2. Cross-sectional view of the Russian VVR-M2 type LEU fuel bundle.

- The LEU fuel bundle has three concentric annular tubes: the outermost hexagonal tube and two inner circular tubes.
- The fuel comprises a mixture of uranium dioxide (UO_2) and aluminum (Al).

➢ Calculation model

- The model is expanded from the active core to the reactor tank, with the dimensions of 198 cm in diameter and 184.5 cm in height.

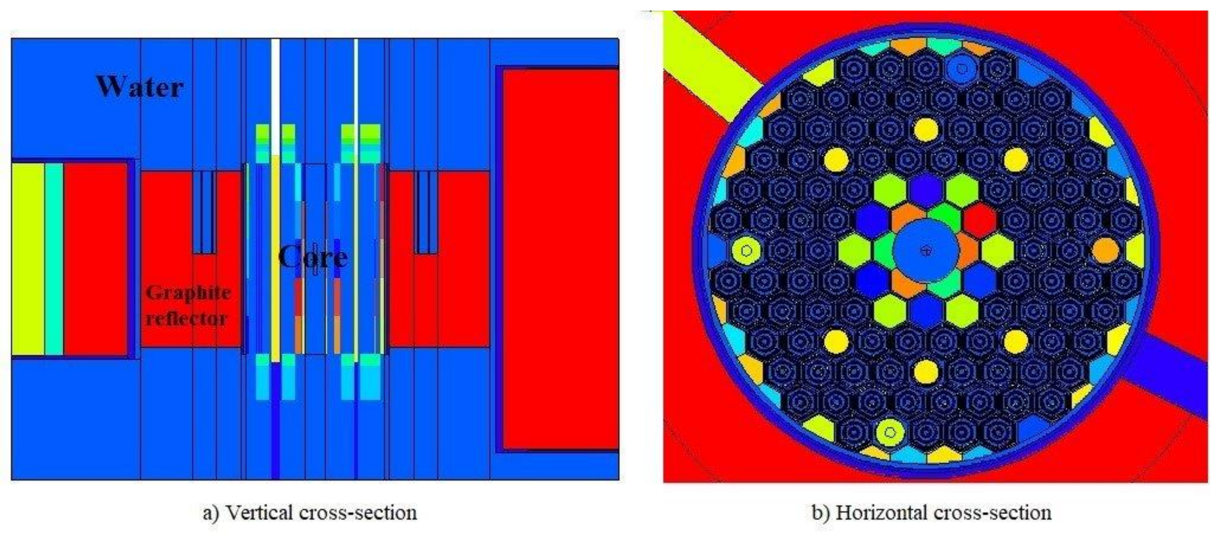

Fig. 3. Vertical (a) and horizontal (b) cross-sectional views of the DNRR core model in the MCNP6 code.

- The MCNP6.3 calculations were conducted with 200 cycles and 10^5 neutron histories per cycle for obtaining the statistical error of k_{eff} less than 20 pcm.

KINETIC PARAMETERS

➢ The delayed neutron fraction (β_{eff}):

- The delayed neutron fraction is defined as the ratio of the delayed neutron to the total neutron generated in a fission reaction. Two methods were employed to calculate the β_{eff} :

▪ The adjoint weighted method:

$$\beta_{eff} = \frac{\langle \phi^+, B\phi \rangle}{\langle \phi^+, F\phi \rangle} \quad [1]$$

where ϕ and ϕ^+ are the forward and adjoint neutron fluxes, respectively; *B* is the delayed neutron operator; *F* is the fission term operator; $\langle . \rangle$ is the integration over space and energy.

▪ The prompt method:

$$\beta_{eff} = \frac{k - k_p}{k} \quad [2]$$

where *k* is the eigenvalue for all neutrons and k_p is the eigenvalue for prompt neutrons only.

➢ Neutron generation time (Λ) and prompt neutron lifetime (l_p)

▪ The Λ and l_p are calculated based on the adjoint weighted method following equations:

$$\Lambda = \frac{\langle \phi^+ \frac{1}{\upsilon} \phi \rangle}{\langle \phi^+, F\phi \rangle} \quad and \quad l_p = \frac{\langle \phi^+ \frac{1}{\upsilon} \phi \rangle k_{eff}}{\langle \phi^+, F\phi \rangle} \quad [3 \text{ and } 4]$$

Where, k_{eff} is the effective multiplication factor; υ is the neutron speed.

▪ The 1/*v* absorber insertion method:

$$l_p = \lim_{N \to 0} \left(-\frac{\Delta k}{k} \frac{1}{N . \sigma_0 . \upsilon_0} \right) \quad [5]$$

where *N* is the atomic density of the B^{10}absorber (*#atoms/(b.cm)*); σ_0 is the thermal neutron absorption cross section of the absorber and υ_0 is the speed of thermal neutrons

➢ Sensitivity of the effective delayed neutron fraction

- Sensitivity and uncertainty analysis has been performed to investigate the contribution of major nuclides and nuclear reactions to the uncertainty sources of the kinetic parameters. The sensitivity of the β_{eff} is calculated as follows:

$$S_\sigma^{\beta_{eff}} = \frac{\sigma}{\beta_{eff}} \frac{\partial \beta_{eff}}{\partial \sigma} = \frac{(1-\beta_{eff})}{\beta_{eff}} \left(S_\sigma^k - S_\sigma^{k_p} \right) \quad [6]$$

where, S_σ^k and $S_\sigma^{k_p}$ are the sensitivities of *k* and k_p, respectively, obtained from the linear perturbation theory

- The formula to calculate the uncertainty of β_{eff} is given as:

$$U_\sigma^{\beta_{eff}} = \sqrt{\left[S_\sigma^{\beta_{eff}} \right]^T [C] \left[S_\sigma^{\beta_{eff}} \right]} \quad [7]$$

where, *[C]* is the data covariance matrix of the nuclear reactions for each isotope obtained by using the NJOY2021 code with 44 energy groups.

RESULTS AND DISCUSSION

➢ Effective delayed neutron fraction

- Tab. 1 shows the β_{eff} values at BOC and EOC in comparison between the methods and between the two data libraries.

Tab. 1. The effective delayed neutron fraction β_{eff} (pcm)

	ENDF/B-VIII.0		JENDL-5.0	
Method	BOC	EOC	BOC	EOC
Adjoint weighted	750 ± 6	704 ± 4	760 ± 22	708 ± 21
Prompt method	742 ± 6	712 ± 4	748 ± 22	700 ± 21

- Fig. 4 shows the β_{eff} decreases rapidly in the first 200 effective full power days (EFPDs), followed by a gradual decline.
- The β_{eff} decreases from BOC to EOC (800 EFPDs) by about 46–52 pcm.
- A good agreement was found with the discrepancy less than 1.6%.
- The discrepancy between the two data libraries is less than 1.7%

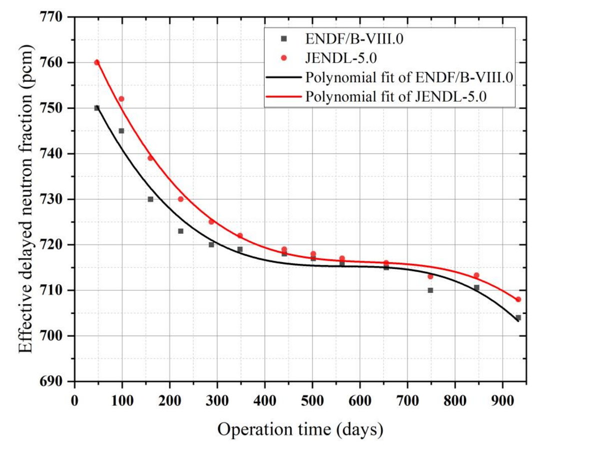

Fig. 4. The β_{eff} versus the burnup time

➢ Neutron generation time and prompt neutron lifetime

- The Λ and l_p are shown in Tab. 1

Tab. 2. comparison of the kinetic parameters calculated by the adjoint weighted method.

	ENDF/B-VIII.0		JENDL-5.0	
Parameter	BOC	EOC	BOC	EOC
β_{eff} (pcm)	750 ± 6	704 ± 22	760 ± 4	708 ± 21
Λ(μs)	86.80 ± 0.14	82.58 ± 0.45	86.99 ± 0.11	82.41 ± 0.45
l_p (μs)	78.68 ± 0.14	81.87 ± 0.15	79.01 ± 0.11	82.76 ± 0.15

- The values of Λ at BOC and EOC obtained from the adjoint weighted method and ENDF/B-VIII.0 library are 86.80 and 82.58 μs, and of that for l_p are 78.68 and 81.87 μs, respectively.
- The JENDL-5 library yielded values of 86.99 and 82.41 μs, and l_p values of 79.01 and 82.76 μs, respectively.
- Comparing between the two methods and between the two data libraries, the discrepancy of the l_p values is within 1%.

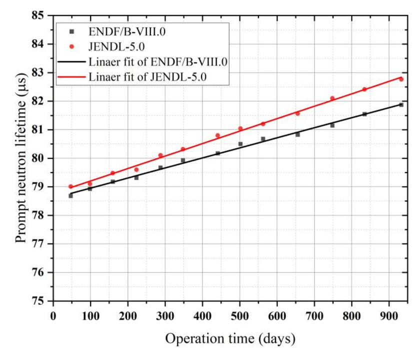

Fig. 5. The l_p versus burnup time using the adjoint weighted method.

➢ Sensitivity analysis

- Sensitivity and uncertainty analyses were conducted for the β_{eff}. Tab. 3 displays the β_{eff} sensitivities for isotopes and reactions contributing more than 0.1%. Tab. 4 outlines the main factor affecting the uncertainty of the β_{eff}.
- The most significant isotopes contributing to the DNRR core's β_{eff} sensitivities and uncertainties are AL-27, H-1, U-235, Be-9, and O-16.

Tab. 3. The β_{eff} sensitivities for the reactions of the main isotopes

		ENDF/B-VIII.0		JENDL-5.0	
Isotopes	Reaction	BOC	EOC	BOC	EOC
AL-27	Elastic	1.3852E+00	1.1819E-01	6.3456E-01	1.5800E+00
H-1	Elastic	7.2295E-01	-1.0563E+00	-6.9126E-01	1.6103E+00
U-235	Fission	6.3941E-01	-5.8594E-02	-2.2871E-01	-3.9581E-01
C-12	Elastic	1.5384E-01	1.4601E+00	-3.5330E-01	2.4960E-01
U-235	n,gamma	1.1602E-01	-2.8500E-02	-2.2858E-02	-7.0657E-02
H-1	n,gamma	7.4249E-02	-1.1660E-01	-1.0956E-01	-8.4802E-02
U-235	Total nu	-1.5140E-03	5.0846E-02	3.0140E-03	4.9472E-02
AL-27	n,gamma	-7.2922E-03	-2.0217E-02	-1.7805E-02	-2.8282E-02
U-238	n,gamma	-1.6830E-02	-4.6223E-02	-7.8695E-02	8.6402E-03
AL-27	Inelastic	-5.6704E-02	-1.2586E-01	-1.6582E-01	-1.2937E-01
Be-9	Elastic	-1.4541E-01	-1.0154E-01	9.4994E-02	1.3158E-01
O-16	Elastic	-5.0124E-01	-1.3802E-01	-1.0567E+00	1.9915E+00
Be-9	n,2n	-8.3409E-01	-1.0154E-01	9.4994E-02	1.3158E-01

Tab. 4. The β_{eff} uncertainty in the decreasing direction of BOC of ENDF-VIII.0 (%)

		ENDF/B-VIII.0		JENDL-5.0	
Isotopes	Reaction	BOC	EOC	BOC	EOC
AL-27	Elastic	4.93	3.16	-	-
Be-9	n,2n	3.43	0.22	-	-
Al-27	Inelastic	1.54	2.83	-	-
O-16	Elastic	0.77	0.55	0.44	0.69
U-235	Fission	0.34	0.11	0.29	0.23
Be-9	Elastic	0.21	0.22	-	-
H-1	Elastic	0.19	0.45	0.25	1.19
U-235	Total nu	0.17	0.07	0.17	0.11
H-1	n, gamma	0.15	0.24	0.23	0.18
U-238	n, gamma	0.12	0.08	0.10	0.06
C-12	Elastic	0.11	0.88	-	-

CONCLUSIONS

- The MCNP6.3 code, ENDF-VIII.0, and JENDL-5 nuclear data libraries were used to evaluate the kinetic parameters of the DNRR core with LEU fuel: the β_{eff}, the Λ and the l_p.
- The values of β_{eff}, Λ, and l_p at BOC obtained using the adjoint weighted method and ENDF/B-VIII.0 are 750 pcm, 86.80 μs and 78.86 μs.
- The differences of these values obtained with different method and data libraries are within 1%.
- Major isotopes contributing to the sensitivities and uncertainties of the β_{eff} include AL-27, H-1, U-235, Be-9, and O-16.