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Criticality Safety Analysis of Spent Fuel Storage Pool for NPP Mochovce using MCNP5 Code

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ABSTRACT

The paper presents results of nuclear criticality safety analysis of spent fuel storage and handling for the 1st and 2nd unit of NPP Mochovce. Spent fuel storage pool (compact and reserve grid) and T-12 transport cask were modeled using the Monte Carlo code MCNP5. Conservative approach was applied and calculation of k_{eff}^{max} values was performed for normal and various postulated emergency conditions in order to evaluate the final maximal k_{eff}^{max} values. The requirement of current safety regulations to ensure 5% subcriticality was met except some especially conservative cases.

Keywords: sub criticality, spent fuel storage, safety regulation

1 INTRODUCTION

Criticality safety associated with the packaging of spent nuclear fuel is a challenging issue for the scientific and legislative communities involved in efforts to prevent criticality accidents [3]. Safety issues associated with criticality accidents are assessed through appropriate nuclear criticality calculations which are usually performed on the assumption that the spent nuclear fuel is represented by its fresh composition. This is a simple approach, doing unnecessary any knowledge of the fuel irradiation history. However, it overlooks any possible decrease in the fuel reactivity due to the changes in fuel nuclide composition. Some of these nuclides are responsible for the decrease in the reactivity of the spent fuel. Therefore, the inclusion of these nuclides may result in a considerable improvement regarding criticality safety [6]. In this work criticality safety analysis of the spent fuel storage pool (both compact and reserve grid) was performed. Two basic loading scenarios were considered for the analysis - full loading with fresh Gd-II fuel assemblies (enrichment of 4.87 %) and partial loading with fresh and highly burned (45 and 50 MWd/kg) fuel assemblies.

2 ANALYSIS CODE AND VALIDATION

The criticality safety analysis was based on the determination of the effective neutron multiplication factor (k_{eff}) which is a key parameter for criticality safety. The continuous-energy

Monte Carlo Code MCNP5, version 1.40 and continuous-energy neutron cross section data ENDF/B-VII.0 were used [7]. Additionally, S(α,β) thermal scattering data for hydrogen in light water was applied to water and concrete. Code validation was conducted analyzing the BaW XI (2) case of the Criticality Safety Validation Suite [4, 5]. Based on this validation, bias and its uncertainty to be taken into consideration for criticality safety analysis are 0.0001 and 0.00142 respectively. The MCNP5 validation calculation was run with 200 active cycles. This number of active cycles was sufficient to rend the computation uncertainty from the MCNP5 calculation essentially negligible relative to the given benchmark uncertainty.

Table 1: MCNP5 result for BaW XI (2) case of the Criticality Safety Validation Set.

Case	**Benchmark k_{eff}**	**Calculated k_{eff} ENDF/B-VII.0**
BaW XI (2)	1.0007 ± 0.0012	1.0006 ± 0.00076

The bias and its uncertainty were calculated according formulas:

$$\Delta_{bias} = k_{eff}^{bench} - k_{eff}^{calcul} \tag{1}$$

$$\sigma_{bias} = \sqrt{\sigma_{bench}^2 - \sigma_{calcul}^2} \tag{2}$$

where:

Δ_{bias}	is	the bias,
σ_{bias}	is	the bias uncertainty derived from the code validation,
k_{eff}^{bench}	-	the benchmark (experimental) k_{eff},
k_{eff}^{calcul}	-	the calculated k_{eff},
σ_{bench}	-	uncertainty of the benchmark k_{eff} value,
σ_{calcul}	-	uncertainty of the calculated k_{eff} value.

3 EVALUATION METHOD

Conservative approach was applied and calculation of k_{eff} values was performed for normal and various postulated emergency conditions in order to evaluate the final maximal k_{eff} values. All conditions improving neutron multiplication in the storage pool were taken into account. Selected conservative parameters are listed in Table 2.

Table 2: Selected conservative parameters

No	**Parameter**	**Nominal value**	**Tolerance**	**Conservative value**
1	Lattice pitch of fuel pins	12.3 mm	± 0.12 mm	12.42 mm
2	Lattice pitch of absorption tubes of the compact grid	162 mm	± 0.842 mm	161.158 mm
3	Lattice pitch of the reserve grid	225 mm	± 0.842 mm	224.158 mm
4	Lattice pitch of hermetic tubes of the compact grid	230 mm		230 mm
5	Average fuel enrichment of fresh Gd-II fuel assembly	4.87 w%	± 0.05 w%	4.92 w%
6	Gd_2O_3 ratio in the fuel	3.35 w%	± 0.15 w%	3.2 w%
7	Uranium mass in the FA	126.3 kg	± 1.9 kg	128.2 kg
8	Boron content of NEUTRONIT steel of	1.05 – 1.2 %		1.05 %

	the compact grid			
9	Coolant temperature in the compact grid of the storage pool	50 °C		4 °C
10	Coolant temperature in the reserve grid of the storage pool	50 °C		100 °C

The maximal effective multiplication factor $k_{eff}^{\max}$ was evaluated as a sum of the calculated conservative k_{eff}, the systematic error Δ_{bias}, and the combined uncertainty multiplied by 1.645 which is the one-sided tolerance limit factor for a normal distribution at 95% probability.

$$k_{eff}^{\max} = k_{eff}^{conser} + \Delta_{bias} + 1.645\sqrt{\sigma_{bench}^2 + \sigma_{calcul}^2 + \sigma_{conser}^2} \qquad (3)$$

where:

k_{eff}^{conser} is the calculated conservative k_{eff},

σ_{conser} - uncertainty of the calculated conservative k_{eff}.

4 CALCULATION MODEL

The following detailed models were developed in the MCNP5 for criticality safety analysis:

- model of compact grid of the spent nuclear fuel storage pool, Figure 1 – 5,
- model of reserve grid of the spent nuclear fuel storage pool, Figure 6.

MCNP model of the compact grid consists of 603 hexagonal absorption tubes filled with profiled Gd-II fuel assemblies with the enrichment of 4.87 %, 54 hermetic tubes, supporting plate, and concrete well. Nominal lattice pitch of the absorption tubes represents 162 mm and 230 mm for the hermetic tubes. The reserve grid model consists of 296 fuel assemblies, 54 hermetic tubes, supporting plate, and concrete well.

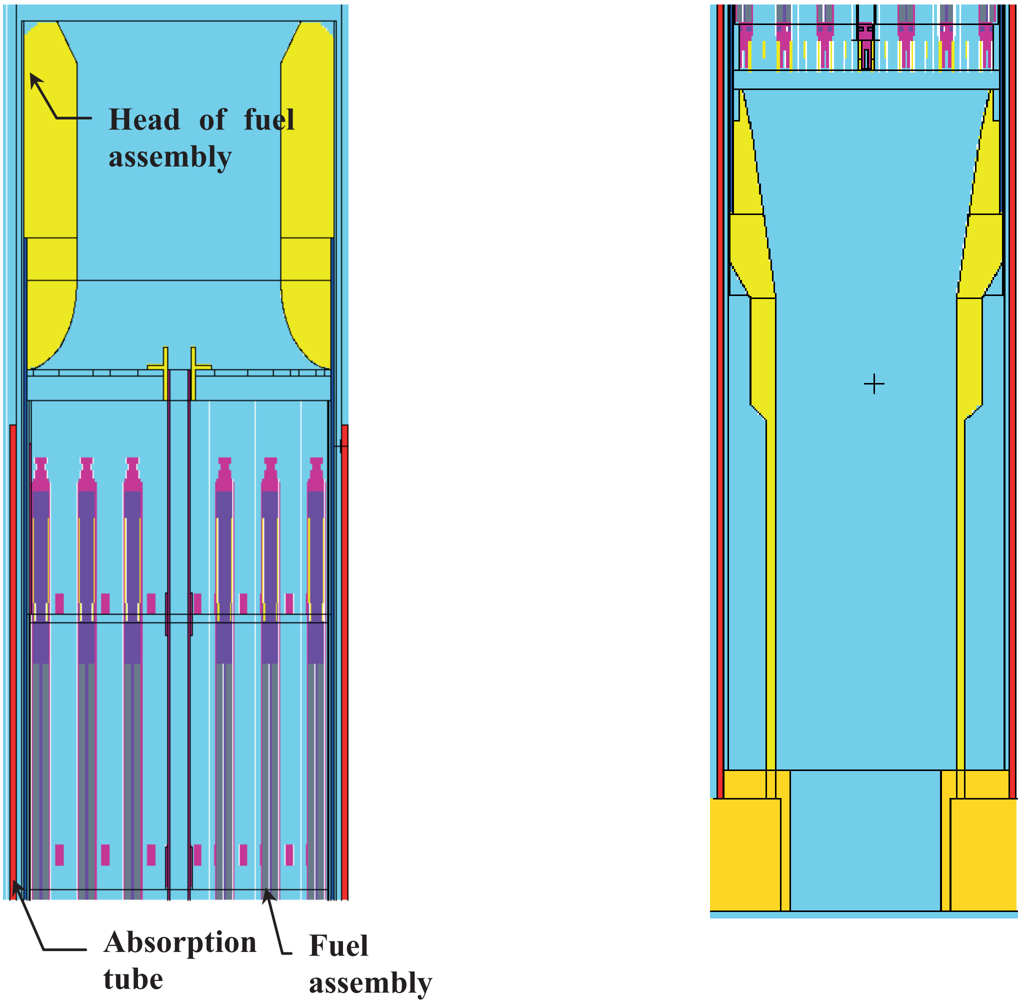

Figure 1: MCNP model of the hexagonal absorption tube filled with FA – vertical cross section.

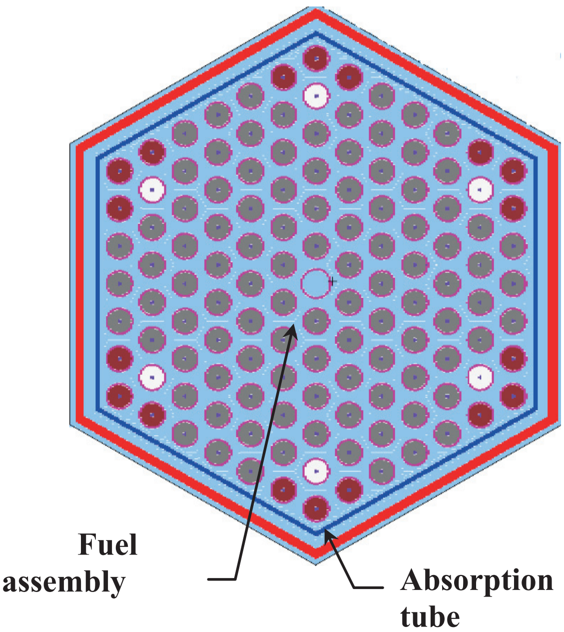

Figure 2: MCNP model of the hexagonal absorption tube filled with FA – horizontal cross section.

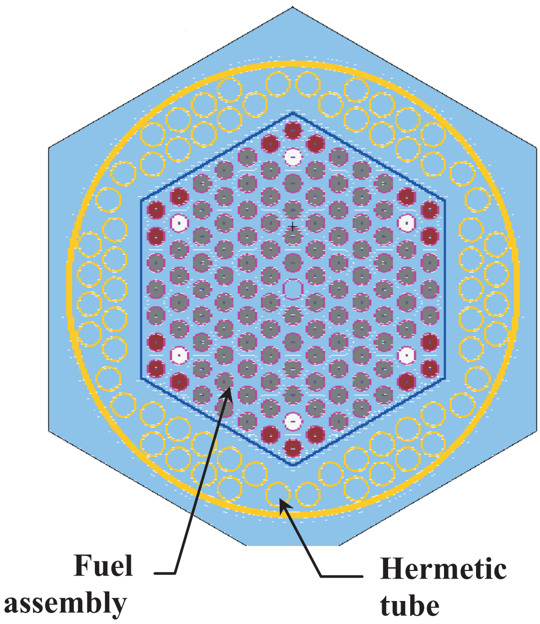

Figure 3: MCNP model of the hermetic tube filled with FA - horizontal cross section.

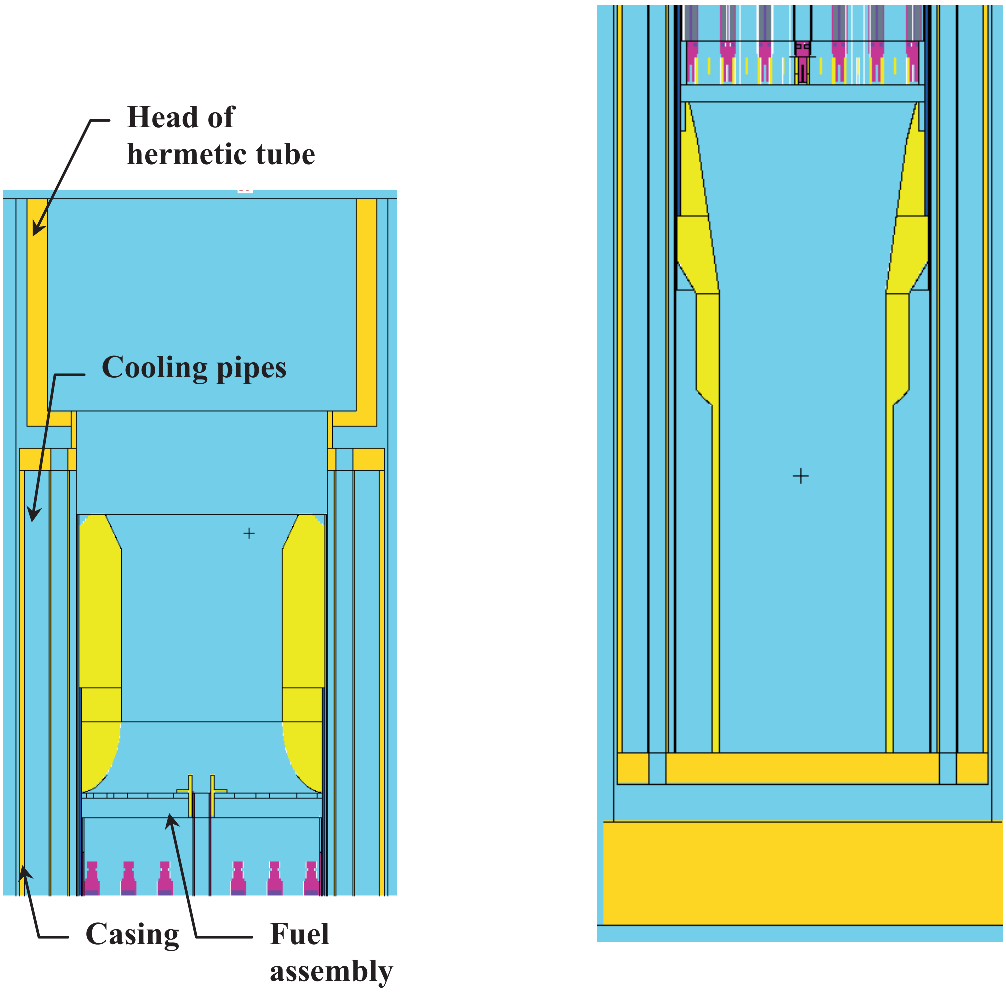

Figure 4: MCNP model of the hermetic tube with FA – vertical cross section.

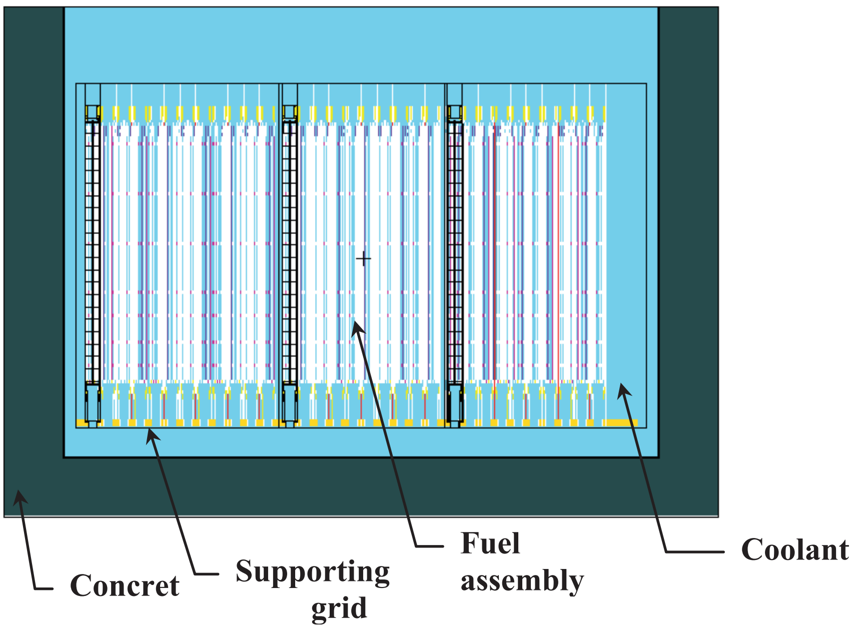

Figure 5: MCNP model of compact grid of the spent fuel storage pool – vertical cross section.

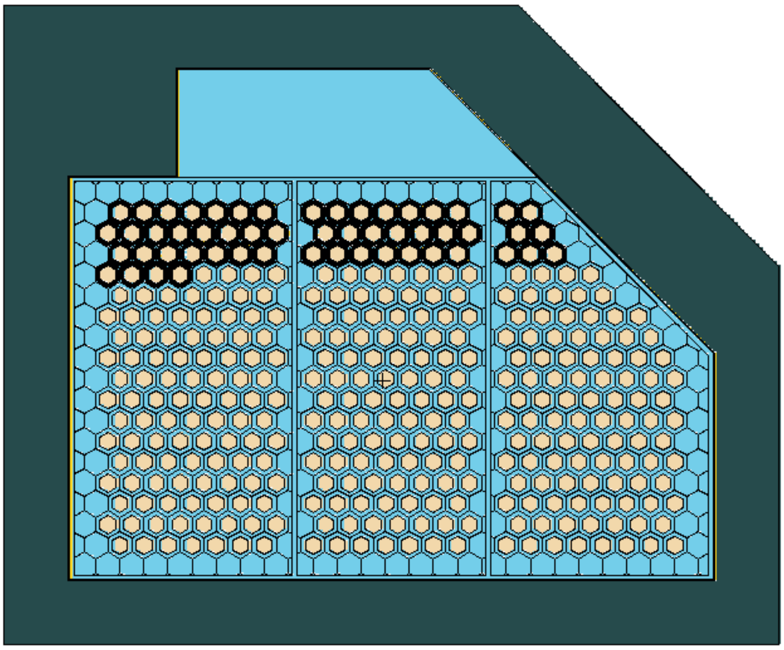

Figure 6: MCNP model of reserve grid of the spent fuel storage pool – horizontal cross section.

(Variant R1– full loading with 4.87 % enriched FAs, variant R2 – full loading with 45 MWd/kg burned FAs).

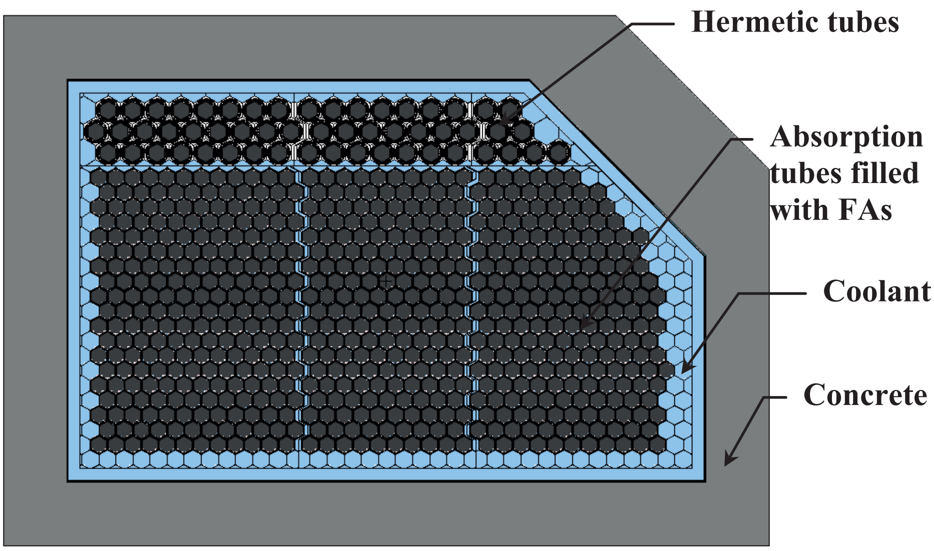

Figure 7: MCNP model of compact grid of the spent fuel storage pool – horizontal cross section.

(Variant A – all positions loaded with 4.87 % enriched fresh FAs.)

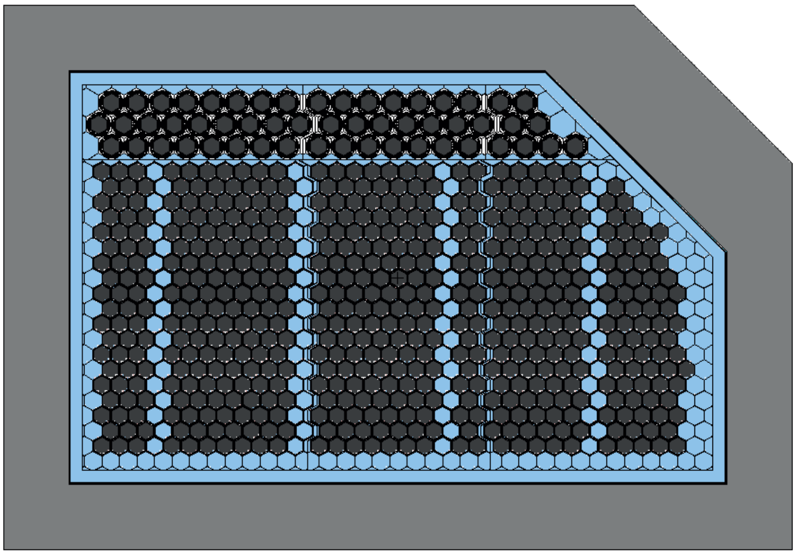

Figure 8: MCNP model of compact grid of the spent fuel storage pool – horizontal cross section.

(Variant B – loading with 4.87 % enriched fresh FAs and four empty rows.)

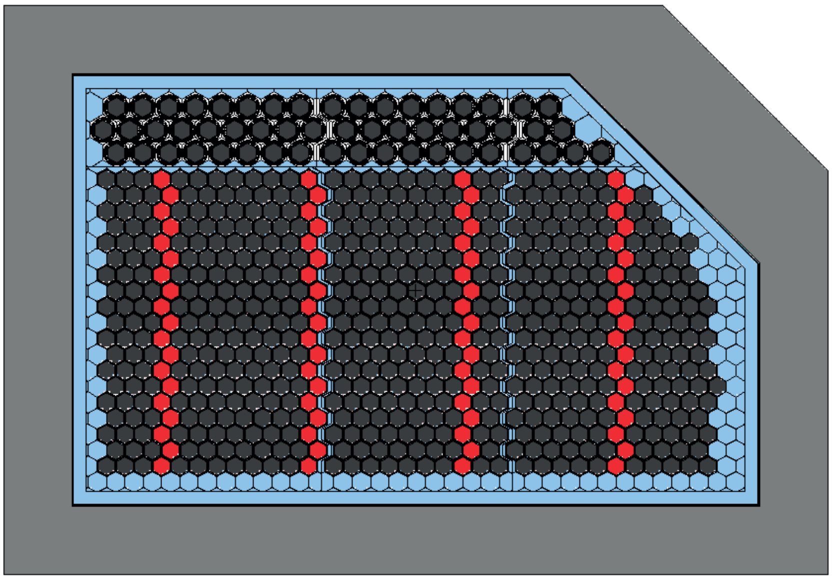

Figure 9: MCNP model of compact grid of the spent fuel storage pool – horizontal cross section.

(Variant C1 (D1) – loading with 4.87 % enriched FAs and four rows of 45 MWd/kg (50 MWd/kg) burned FAs.)

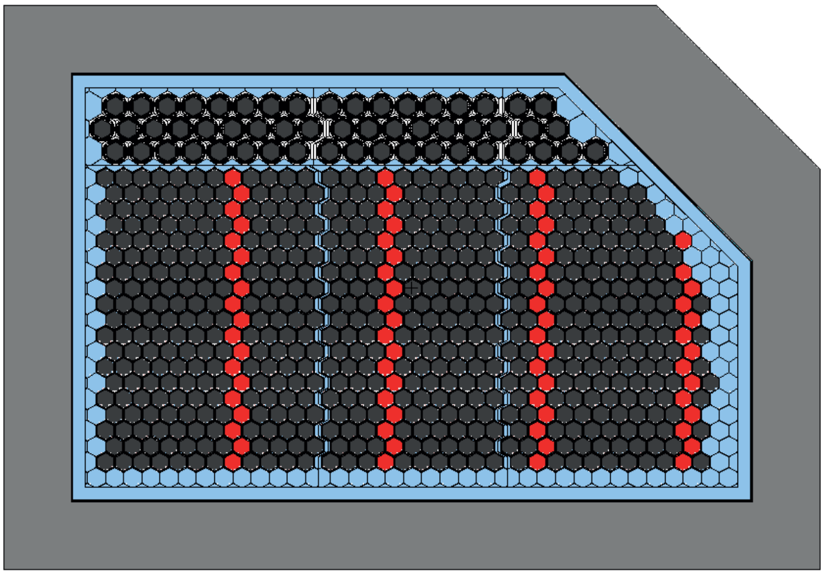

Figure 10: MCNP model of compact grid of the spent fuel storage pool – horizontal cross section. (Variant C2 (D2) – loading with 4.87 % enriched FAs and four rows of 45 MWd/kg (50 MWd/kg) burned FAs.)

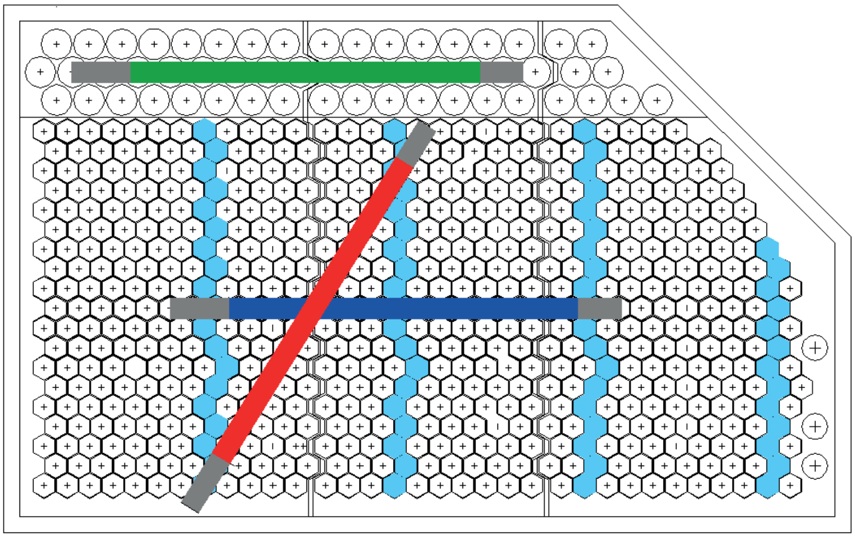

Figure 11: Compact grid with positions of fallen fuel assembly.

(red – diagonal downfall, blue – longitudinal downfall, grenn – downfall on the hermetic tubes)

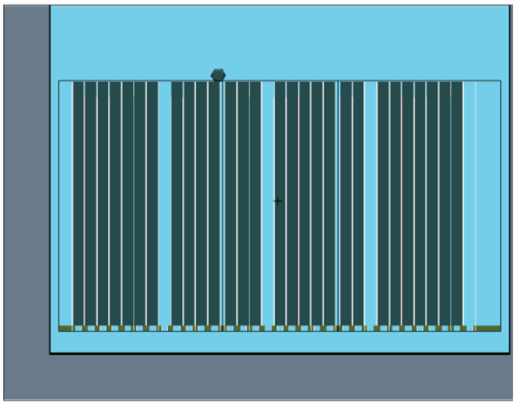

Figure 12: MCNP model of fully loaded compact grid with fresh FAs, four empty rows, and diagonally fallen fresh fuel assembly–variant E11.

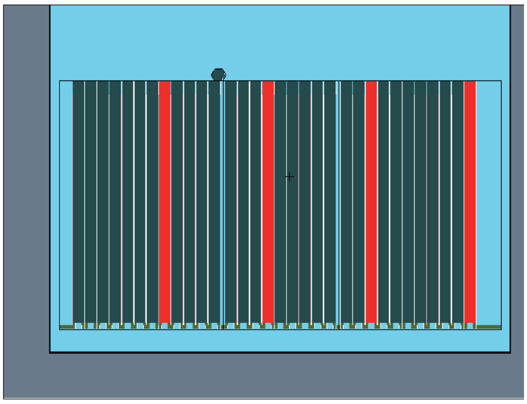

Figure 13: MCNP model of fully loaded compact grid with fresh FAs, four rows of 45 MWd/kg burned FAs, and diagonally fallen fresh fuel assembly – variant E12.

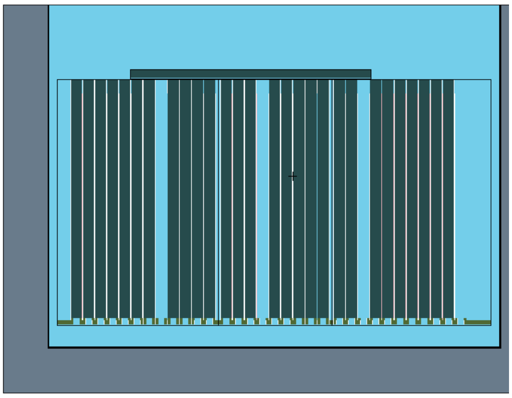

Figure 14: MCNP model of fully loaded compact grid with fresh FAs, four empty rows, and longitudinally fallen fresh fuel assembly

– variant E21.

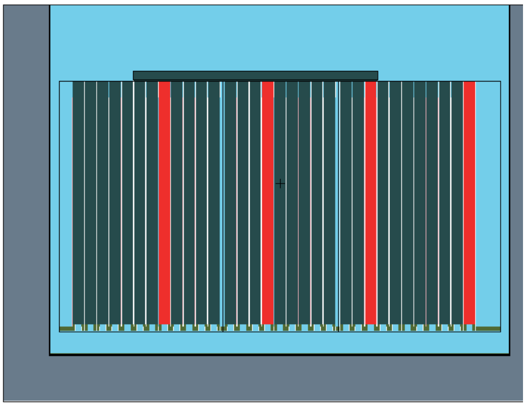

Figure 15: MCNP model of fully loaded compact grid with fresh FAs, four rows of 45 MWd/kg burned FAs, and longitudinally fallen fresh fuel assembly – variant E22.

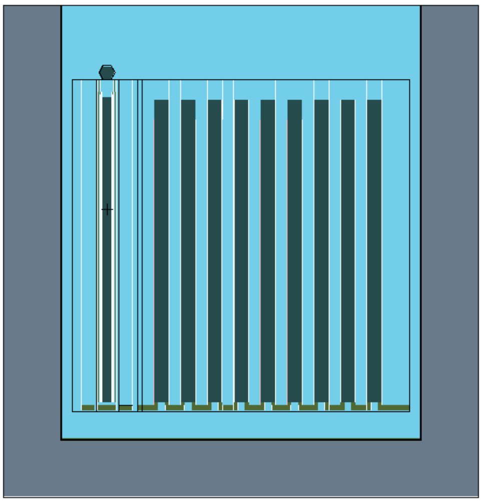

Figure 16: MCNP model of the compact grid, and longitudinally fallen fresh fuel assembly on the hermetic tubes –

variant E31 and E32.

5 RESULTS

Concerning criticality safety analysis of the compact grid, the following basic variants of storage pool loading were investigated:

variant A all positions loaded with 4.87 % enriched fresh FAs (Figure 7),
variant B loading with 4.87 % enriched fresh FAs and four empty rows (Figure 8),
variant C1 loading with 4.87 % enriched FAs and four rows of 45 MWd/kg burned FAs (Figure 9),
variant C2 loading with 4.87 % enriched FAs and four rows of 45 MWd/kg burned FAs (Figure 10),
variant D1 loading with 4.87 % enriched FAs and four rows of 50 MWd/kg burned FAs (Figure 9).
variant D2 loading with 4.87 % enriched FAs and four rows of 50 MWd/kg burned FAs (Figure 10).

Table 3: Results of the criticality safety analysis for compact grid (basic variants).

Variant	k_{eff}^{conser}	σ_{conser}	k_{eff}^{max}
A	0.95136	0.00004	**0.95520**
B	0.93672	0.00004	**0.94056**
C1	0.94152	0.00007	**0.94397**
C2	0.94064	0.00007	**0.94309**
D1	0.94042	0.00007	**0.94287**
D2	0.93949	0.00007	**0.94194**

variant R1 all positions loaded with 4.87 % enriched fresh FAs (Figure 6),
variant R2 all positions loaded with 45 MWd/kg burned FAs (Figure 6).

Table 4: Results of the criticality safety analysis for reserve grid.

Variant	k_{eff}^{conser}	σ_{conser}	k_{eff}^{max}
R1	0.90877	0.00003	**0.91261**
R2	0.73597	0.00005	**0.73842**

In order to evaluate the influence of fallen fresh FA into the compact grid on k_{eff}^{max} value, the following six emergency conditions were investigated:

variant E11 loading with 4.87 % enriched FAs, four empty rows, and diagonally fallen fresh FA (Figure 12),
variant E12 loading with 4.87 % enriched FAs, four rows of 45 MWd/kg burned FAs, and diagonally fallen fresh FA (Figure 13),
variant E21 loading with 4.87 % enriched FAs, four empty rows, and longitudinally fallen fresh FA (Figure 14),
variant E22 loading with 4.87 % enriched FAs, four rows of 45 MWd/kg burned FAs, and longitudinally fallen fresh FA (Figure 15),
variant E31 loading with 4.87 % enriched FAs, four empty rows, and longitudinally fallen fresh FA on the hermetic tubes (Figure 16),
variant E32 loading with 4.87 % enriched FAs, four rows of 45 MWd/kg burned FAs, and longitudinally fallen fresh FA on the hermetic tubes (Figure 16).

Table 5: Results of the criticality safety analysis for compact grid (emergency variants).

Variant	k_{eff}^{conser}	σ_{conser}	k_{eff}^{max}
E11	0.93640	0.00007	**0.93885**
E12	0.94069	0.00007	**0.94314**
E21	0.93631	0.00010	**0.93877**
E22	0.94057	0.00010	**0.94303**
E31	0.93645	0.00007	**0.93890**
E32	0.94046	0.00007	**0.94291**

6 CONCLUSION

Criticality issues associated with compact and reserve grid of the spent fuel storage pool, located in the NPP Mochovce 1 and 2, were investigated using MCNP5. The criticality safety analysis focused on the evaluation of maximal neutron multiplication factor values at normal and some emergency conditions applying conservative approach. The outcomes of the investigations showed that the requirement of current safety regulations to ensure 5 % subcriticality was met (including postulated emergency conditions), except one especially conservative case of the fully loaded compact grid with fresh 4.87 % enriched Gd-II FAs. Only in this case, the calculated k_{eff}^{max} value exceeded the required subcriticality limit of 0.95 by 0.55 %. Except this one scenario the analyses showed that nuclear criticality safety criteria in terms of the spent fuel storage pool are satisfied.

LIST OF NOMENCLATURE

ENDF	Evaluated Nuclear Data File
FA	Fuel Assembly
MCNP	Monte Carlo N-Particle Transport Code
NPP	Nuclear Power Plant

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