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ANALYSIS OF THE KRŠKO NPP SPENT FUEL STORAGE CRITICALITY SAFETY UNDER HYPOTHETICAL DEGRADED CONDITIONS

ANALIZA ZAGOTOVITVE VARNOSTNE MEJE PRED KRITIČNOSTJO BAZENA ZA IZTROŠENO GORIVO NUKLEARNE ELEKTRARNE KRŠKO PRI HIPOTETIČNIH DEGRADIRANIH POGOJIH

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Keywords: Criticality safety, PWR fuel, pool boiling, optimum moderation, MCNP6, ENDF/B-VII.1

Abstract

An analysis of the Krško NPP's old racks under hypothetical degraded pool conditions has been performed. Pool boiling and the optimum neutron moderation scenario with the absence of soluble boron normally present in the cooling water have been analysed. MCNP neutron transport code version 6.1.0 and the neutron continuous energy cross section ACE library based on the ENDF/B-VII.1 nuclear data files have been used. Four out of four and three out of four cell positions loaded have been considered. Where appropriate, burnup curves were determined.

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Povzetek

V prispevku je predstavljena analiza starih rešetk bazena za iztrošeno gorivo Nuklearne elektrarne Krško ob hipotetičnih degradiranih pogojih bazena. Upoštevano je vretje hladilne vode in primer optimalne nevtronske moderacije ob predpostavki, da ni raztopljenega bora v hladilu. Za preračun transporta nevtronov je uporabljen program MCNP verzija 6.1.0 in ACE knjižnica nevtronskih presekov evaluirana iz ENDF/B-VII.1 podatkov. Analizirani so primeri štiri od štirih in tri od štirih zapolnjenih lokacij v rešetki bazena. Kjer je bilo potrebno, so bile določene omejitvene krivulje izgorelosti.

1 INTRODUCTION

After its use in the reactor, the Krško NPP's nuclear fuel is temporarily stored in the spent fuel storage pool. One of the basic safety functions of a nuclear facility, such as a Spent Fuel Pool (SFP), is to ensure sub-criticality, which is to be fulfilled during all design-basis events. Evaluation of the NEK's old storage racks based on the design basis accident scenarios and fulfilling all legislation requirements and safety standards was performed by Framatome ANP GmbH (FANP), *[1, 2].* The Krško NPP's pool has been licensed based on this evaluation. However, after the Fukushima accident, there was also an interest in the industry (EU stress tests) to explore beyond design basis accident scenarios under severe or hypothetical degraded storage conditions. Supplemental calculations, related to the hypothetical loss of all neutron poison (soluble boron) in the SFP coolant, as well as for the hypothetical optimum moderation conditions are examined in this paper to establish loading curves for the mitigation of the above hypothetical scenarios.

2 ASSUMPTIONS

2. 1 Calculation Methodology

In the criticality safety calculations, the adequacy of the safety margin, when criticality safety limits have been established through computer-based calculation methods, must be assured. Appropriate bias should be determined from the difference between calculated and experimental results that reflects the accuracy of the calculation methodology. The bias and the uncertainty associated with the bias are used in combination with an additional subcritical margin to establish an upper safety limit. The adequate subcritical margin is considered assured if the calculated results are below the upper safety limit and are within the area of applicability of the validation, *[3]*.

The MCNP code version MCNP 6.1.0, *[4]*, and ENDF/B-VII.1 nuclear data library, *[5],* were used in all calculations. Since the code and library are different than in FANP, *[1, 2]*, analysis, a validation procedure is needed to determine appropriate bias. In order to validate the MCNP code for criticality safety calculations, several suitable benchmark experiments from the Handbook of Evaluated Criticality Safety Benchmark Experiments, *[6]*, also known as the ICSBEP Handbook, have been calculated, *[7]*:

- LEU-COMP-THERM-020 (LCT020)
- LEU-COMP-THERM-021 (LCT021)
- LEU-COMP-THERM-071 (LCT071)
- LEU-COMP-THERM- 077 (LCT077)
- LEU-COMP-THERM-083 (LCT083)
- KRITZ-LWR-RESR-001
- KRITZ-LWR-RESR-002
- KRITZ-LWR-RESR-003

Benchmark results were evaluated based on the NRC guidance provided in *[3]*. A weighted single-sided lower tolerance limit (K_L) has been determined to be 0.98914.

2. 2 Geometrical and material data

A geometrical model from the original FANP analysis, *[1, 2]*, was adopted. The model takes into account the whole rack, consisting of an arrangement of 27 × 23 storage cells. The radial cross sections of all considered cases are presented in Figures 1–3. The rack is surrounded by a 30-cm layer of water (yellow) and 1 m of concrete (red).

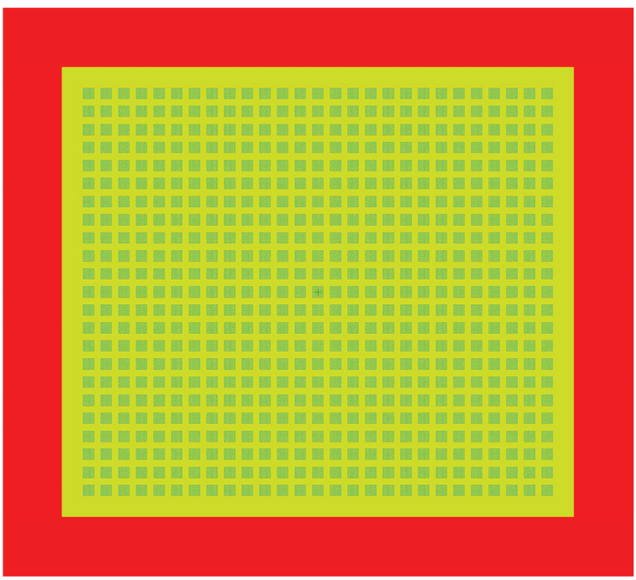

Figure 1: *NPP Krško old storage rack, radial view, 4 out of 4 positions loaded*

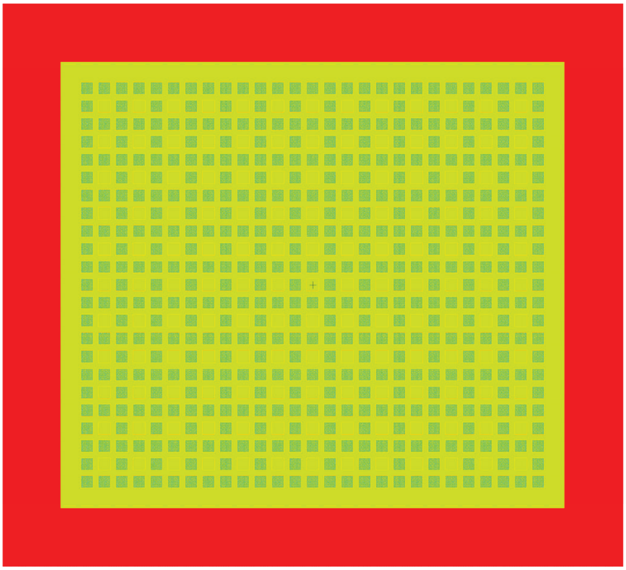

Figure 2: *NPP Krško old storage rack, radial view, 3 out of 4 positions loaded*

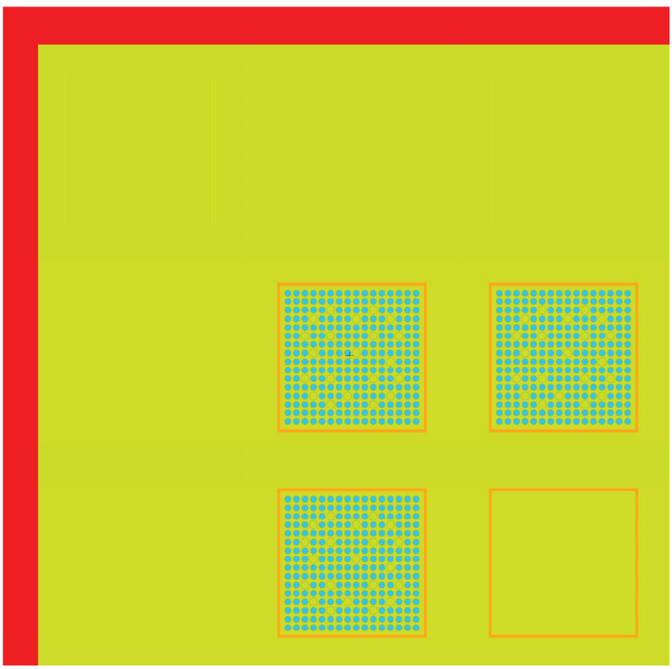

Figure 3: *NPP Krško old storage rack, upper left corner, 3 out of 4 positions loaded*

The entire rack is represented in the axial direction (Figure 4) with an additional reflector consisting of a 30-cm water layer (density 1 g/cm^3 in all cases) on the top (blue). The thickness of the water beneath the rack is 15 cm. The bottom concrete thickness is again 1 m.

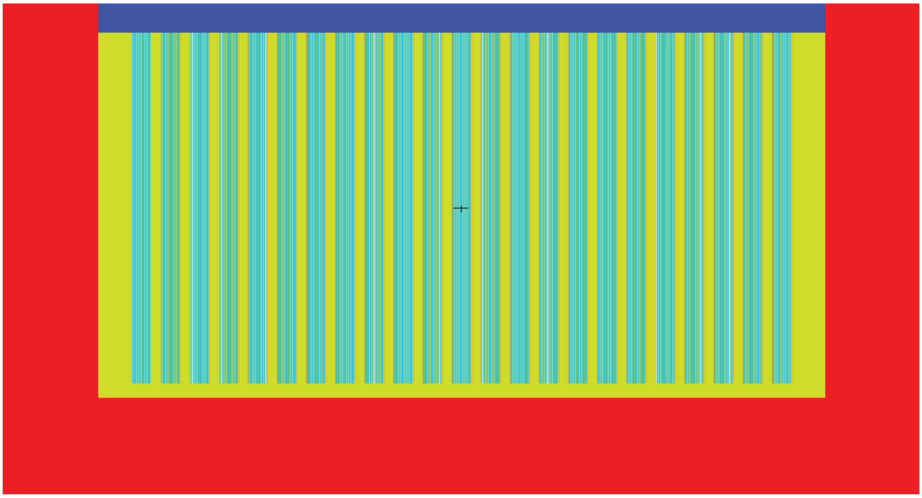

Figure 4: *NPP Krško old storage rack, axial view, 4 out of 4 positions loaded*

Nominal dimensions of the fuel assembly and rack are used, except for the cell wall thickness, which is taken at a minimal thickness of 0.475 cm. The isotopic composition of materials is taken from original input files used in the FANP analysis.

2. 3 Cross sections' temperature model

The neutron cross section library, *[5]*, is available only at some selected temperatures. The MAKXSF code, *[8]*, was used to take into account Doppler broadening at needed temperatures. Cross-section sets at 80 °C, 100 °C, and 120 °C were generated and used in appropriate pool boiling cases. Linear temperature interpolation of the multiplication factor was carried out to take into account thermal scattering kernel data $S(\alpha,\beta)$ at the proper temperature in a similar manner as in *[7]*. The following equation is used:

$$f_L = \frac{T_H - T}{T_H - T_L}. \qquad (2.1)$$

$S(\alpha,\beta)$ temperatures T_L and T_H are 20 °C and 127 °C, respectively. The multiplication factor at needed temperature T is determined as a weighted average of the multiplication factors, where weight f_L is used for lower temperature $S(\alpha,\beta)$ calculation and $1\text{-}f_L$ is used for higher temperature results. SFP temperatures and water densities are listed in Table 1 and are the same as those used in the original FANP analysis.

Table 1: *SFP temperatures and densities*

Temperature [°C]	Density [g/cm³]
20	1
80	0.971798
100	0.958364
120	0.943083

The results are presented in Figures 5-7. For all cases, the highest multiplication factor occurs at 120 °C. It is clear from the figures that the multiplication factors obtained at high S(α,β) temperature are higher than the results at lower temperatures. In addition, since 127 °C is conservative but very close to the desired 120 °C, it is judged to be acceptable to use results at this temperature without further lengthy temperature interpolation for all cases representing 120 °C.

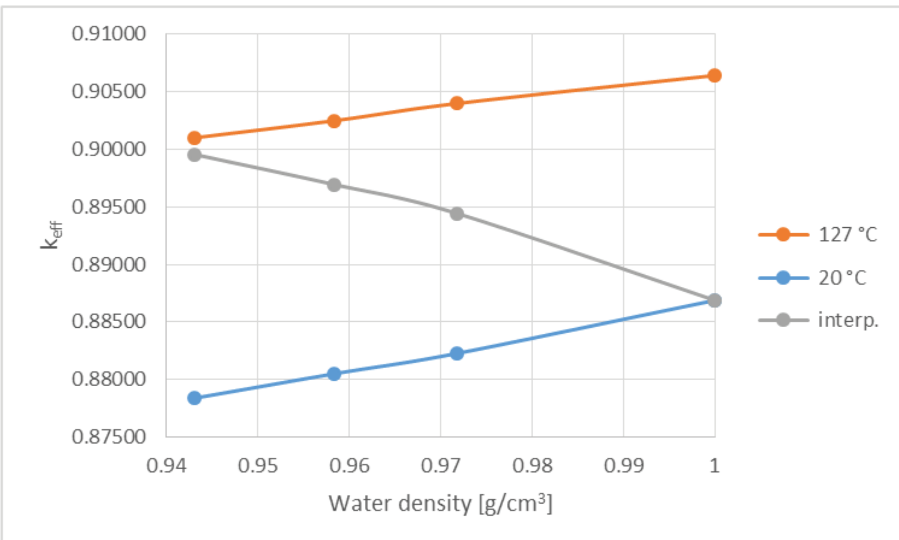

Figure 5: *Interpolation of thermal scattering kernel data, 4 out of 4 positions loaded, 3.5% enrichment*

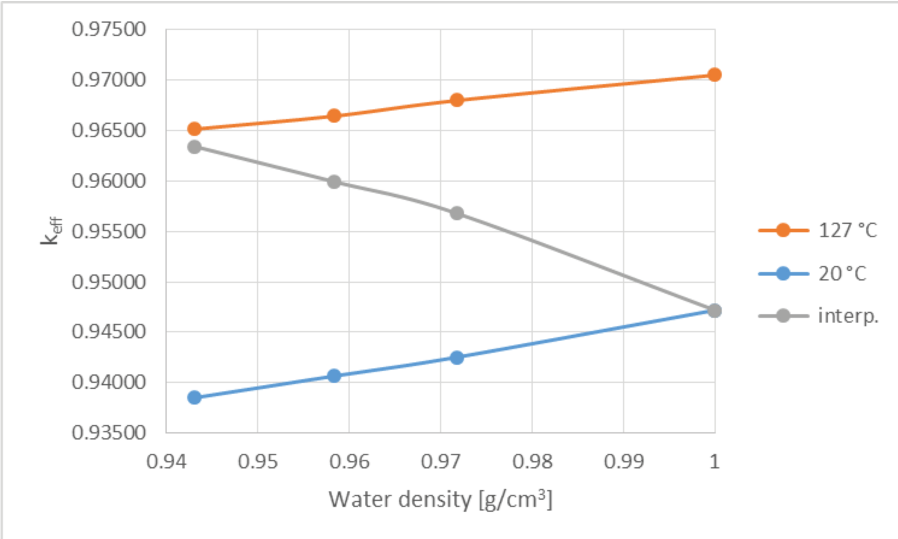

Figure 6: *Interpolation of thermal scattering kernel data, 4 out of 4 positions loaded, 5% enrichment*

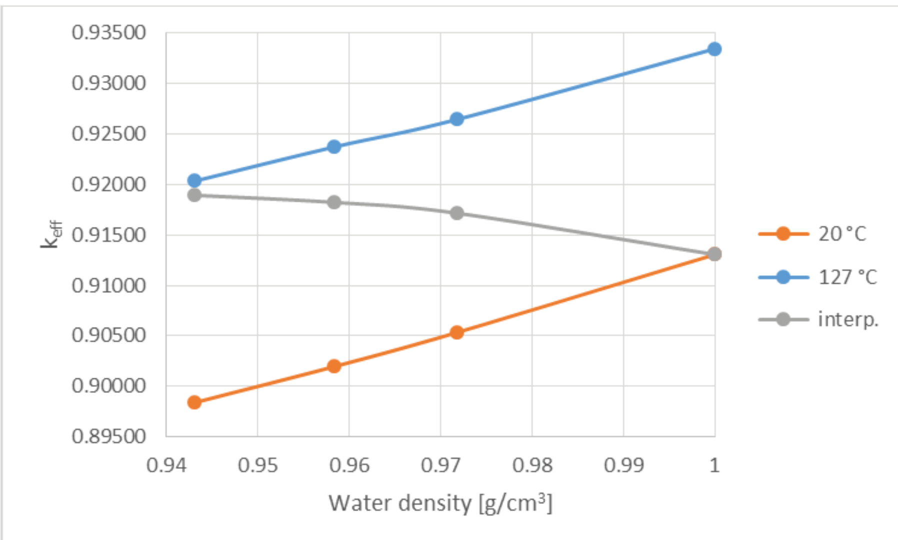

Figure 7: *Interpolation of thermal scattering kernel data, 3 out of 4 positions loaded, 5% enrichment*

3 CRITICALITY SAFETY EVALUATION

A limiting multiplication factor k_{limit} is determined by the following equation:

$$k_{limit} = K_L - \Delta k_m - \Delta k_{man} - \Delta k_{dep} \tag{3.1}$$

where:

K_L weighted single-sided lower tolerance limit of calculational methodology (0.98914),

Δk_m margin arising from legislation requirements (0.05),

Δk_{man} uncertainty arising from specific modeling features as well as manufacturing tolerances concerning dimensions, construction materials, etc.,

Δk_{dep} bias caused by the uncertainties in the depletion calculations.

3. 1 4 out of 4 positions loaded, pool boiling, theoretical coolant density

Taking into account uncertainties Δk_{man} and Δk_{dep} from the original FANP analysis, the limiting multiplication factor has been determined to be k_{limit}=0.91355.

As shown in Figures 5 and 6, a case of 120 °C with a theoretical density of 0.943083 g/cm³ is the limiting case. Calculation results are presented in Table 2. In the last column, the statistical uncertainty of calculations (1σ) is listed.

Table 2: *Effective multiplication factors, 4 out of 4 positions loaded, pool boiling*

Enrichment/Burnup	k_{eff}	
3.5%	0.90102	±0.00007
4.0%	0.92626	±0.00007
4.0% 23 MWd/kgU	0.80770	±0.00007
4.5%	0.94718	±0.00007
4.5% 29 MWd/kgU	0.80648	±0.00007
5.0%	0.96515	±0.00008
5.0% 34 MWd/kgU	0.80799	±0.00007

The results of the fresh fuel cases are shown in Figure 8. For better readability the limiting multiplication factor line is also drawn. The presented curve is fitted with a parabolic function. Enrichment is determined where the fitting curve +3σ intersects the limiting value. The obtained limiting enrichment is 3.727%. As shown in Table 2, three cases with supplied burnup isotopic composition were also calculated:

- 4.0% 23 MWd/kgU,
- 4.5% 29 MWd/kgU,
- 5.0% 34 MWd/kgU.

To determine the necessary limiting burnup, linear interpolation is used instead of the standard fitting procedure, since only two multiplication factors are available for each particular enrichment. The obtained loading curve is presented in Figure 9. The area above the curve represents the combination of enrichment and burnup suitable for storage in SFP.

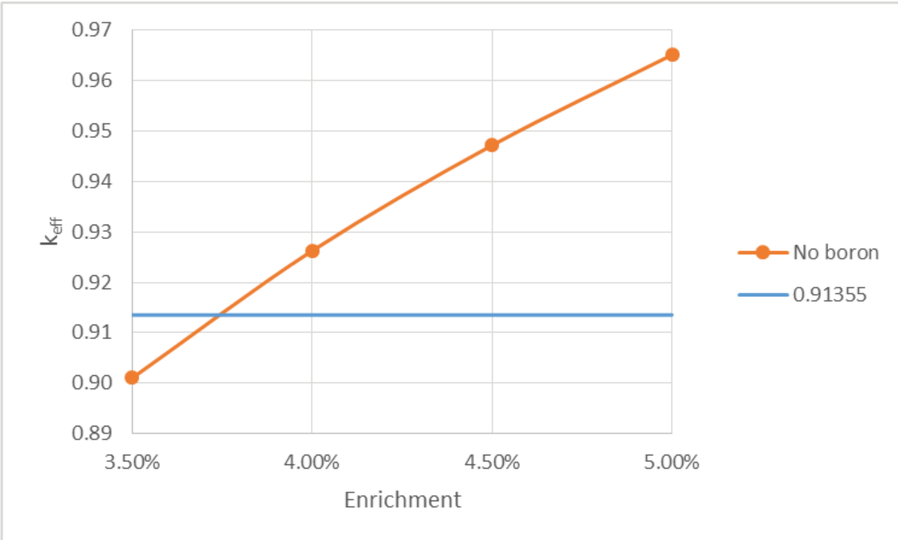

Figure 8: *Effective multiplication factor, 4 out of 4 positions loaded, pool boiling, fresh fuel*

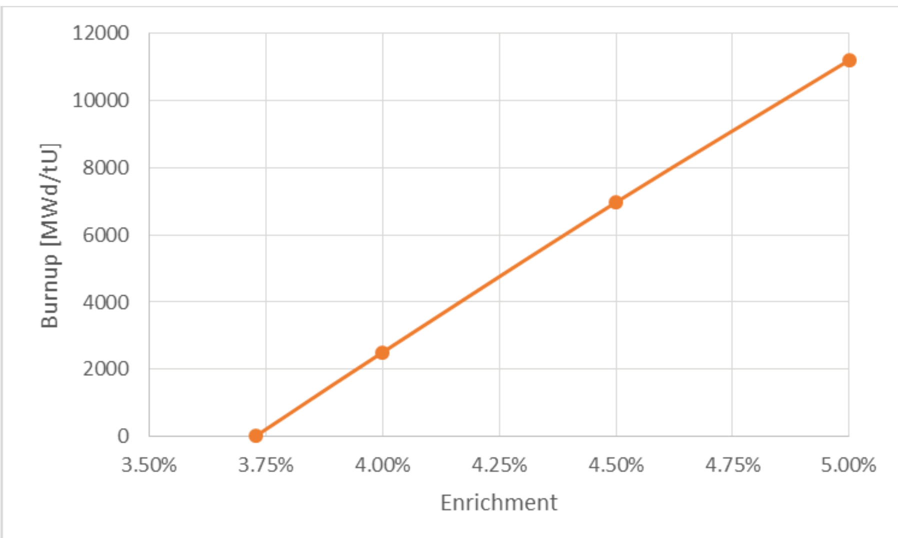

Figure 9: *Loading curve, 4 out of 4 positions loaded, pool boiling*

3.2 4 out of 4 positions loaded, optimum moderation

Taking into account uncertainties Δk_{man} and Δk_{dep} from the original FANP analysis, the limiting multiplication factor has been determined to be k_{limit}=0.92828.

Calculation results are presented in Table 3. For each enrichment, a parabolic fit is applied to determine optimum water density and maximal k_{eff}. The weighting function $1/\sigma^2$ is used. The pooled variance is taken as a final uncertainty.

The results of the fresh fuel cases are shown in Figure 10. For better readability the limiting multiplication factor line is also drawn. The presented curve is fitted with a cubic fit. Enrichment is determined where the fitting curve +3σ intersects the limiting value. The obtained limiting enrichment is 2.372%. As shown in Table 3, the following cases with supplied burnup isotopic composition were also calculated:

- 3.0% 7 MWd/kgU,
- 3.5% 17 MWd/kgU,
- 4.0% 23 MWd/kgU,
- 4.5% 29 MWd/kgU,
- 5.0% 34 MWd/kgU.

To determine the necessary limiting burnup linear interpolation is used instead of the standard fitting procedure, since only two multiplication factors are available for each particular enrichment. Burnup values higher than 20000 MWd/tU are additionally increased to take into account reactivity end effects of the axial burnup shapes. Increase is estimated from the FANP analysis [1] as a linear function having 0 MWd/tU at 20000 MWd/tU and 5000 MWd/tU at 45000 MWd/tU. The obtained loading curve (denoted as “No boron”) is presented in Figure 11. For comparison purposes, the licensed loading curve (denoted as “boron”) from FANP analysis obtained assuming 2000 ppm of boron in the SFP is also shown.

Table 3: *Effective multiplication factors, 4 out of 4 positions loaded, pool boiling*

Enrichment/Burnup	Density	k_{eff}	
2.0%			
	0.19	**0.88220**	**±0.00006**
	0.20	**0.88259**	**±0.00006**
	0.21	**0.88235**	**±0.00006**
	0.22	**0.88162**	**±0.00006**
Max	**0.20146**	**0.88258**	**±0.00006**
2.5%			
	0.19	**0.94082**	**±0.00006**
	0.20	**0.94141**	**±0.00006**
	0.21	**0.94121**	**±0.00006**
	0.22	**0.94066**	**±0.00006**
Max	**0.20381**	**0.94141**	**±0.00009**

2.5% 4 MWd/kgU			
	0.19	**0.91320**	**±0.00006**
	0.20	**0.91388**	**±0.00006**
	0.21	**0.91409**	**±0.00006**
	0.22	**0.91359**	**±0.00006**
Max	**0.20734**	**0.91407**	**±0.00007**
3.0%			
	0.19	**0.98661**	**±0.00006**
	0.20	**0.98711**	**±0.00006**
	0.21	**0.98704**	**±0.00006**
	0.22	**0.98632**	**±0.00006**
Max	**0.20346**	**0.98716**	**±0.00006**
3.0% 7 MWd/kgU			
	0.19	**0.93414**	**±0.00006**
	0.20	**0.93504**	**±0.00006**
	0.21	**0.93530**	**±0.00006**
	0.22	**0.93496**	**±0.00006**
Max	**0.20939**	**0.93531**	**±0.00006**
3.5%			
	0.19	**1.02362**	**±0.00006**
	0.20	**1.02403**	**±0.00007**
	0.21	**1.02380**	**±0.00006**
	0.22	**1.02315**	**±0.00006**
Max	**0.20189**	**1.02400**	**±0.00007**
3.5% 17 MWd/kgU			
	0.20	**0.91200**	**±0.00006**
	0.21	**0.91277**	**±0.00006**
	0.22	**0.91275**	**±0.00006**
	0.23	**0.91223**	**±0.00006**
Max	**0.21604**	**0.91284**	**±0.00008**
4.0%			
	0.19	**1.05424**	**±0.00006**
	0.20	**1.05495**	**±0.00006**
	0.21	**1.05464**	**±0.00006**
	0.22	**1.05384**	**±0.00006**
Max	**0.20300**	**1.0549**	**±0.00010**
4.0% 23 MWd/kgU			
	0.20	**0.91148**	**±0.00006**
	0.21	**0.91227**	**±0.00006**
	0.22	**0.91235**	**±0.00006**
	0.23	**0.91213**	**±0.00006**
Max	**0.21902**	**0.91241**	**±0.00009**

4.5%			
	0.18	**1.07931**	**±0.00006**
	0.19	**1.08067**	**±0.00006**
	0.20	**1.08077**	**±0.00006**
	0.21	**1.08053**	**±0.00006**
Max	**0.19970**	**1.08091**	**±0.00016**
4.5% 29 MWd/kgU			
	0.20	**0.90992**	**±0.00006**
	0.21	**0.91081**	**±0.00006**
	0.22	**0.91107**	**±0.00006**
	0.23	**0.91075**	**±0.00006**
Max	**0.21955**	**0.91108**	**±0.00006**
5.0%			
	0.19	**1.10321**	**±0.00006**
	0.20	**1.10345**	**±0.00006**
	0.21	**1.10335**	**±0.00007**
	0.22	**1.10232**	**±0.00006**
Max	**0.20050**	**1.10353**	**±0.00011**
5.0% 34 MWd/kgU			
	0.20	**0.91234**	**±0.00006**
	0.21	**0.91311**	**±0.00006**
	0.22	**0.91353**	**±0.00006**
	0.23	**0.91320**	**±0.00006**
Max	**0.22045**	**0.91347**	**±0.00009**

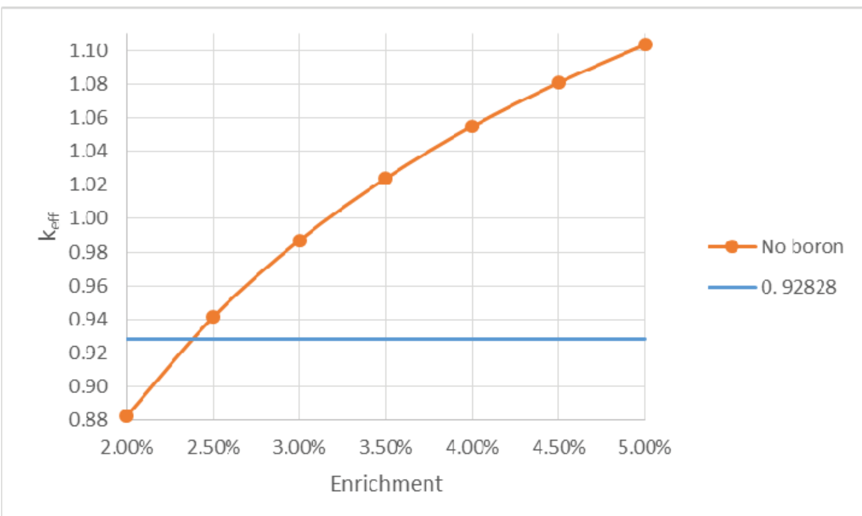

Figure 10: *Effective multiplication factor, 4 out of 4 positions loaded, optimum moderation, fresh fuel*

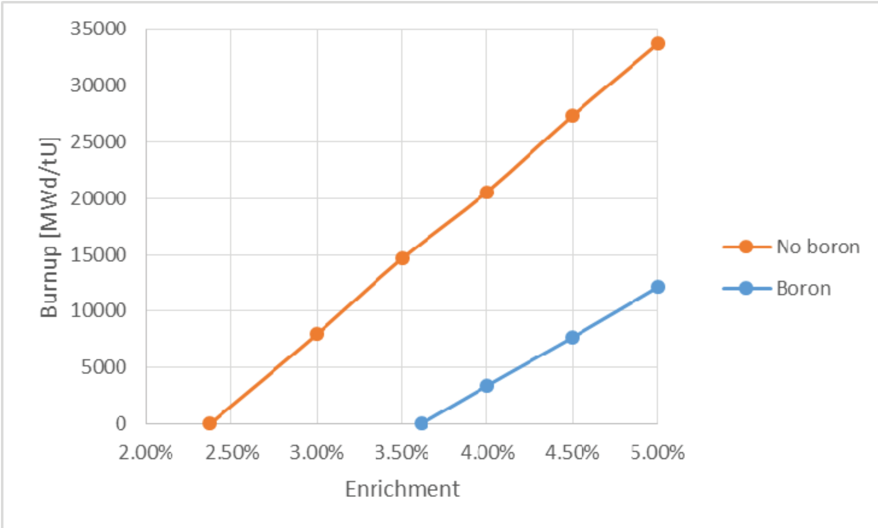

***Figure 11:** Loading curve, 4 out of 4 positions loaded, optimum moderation*

3. 3 3 out of 4 positions loaded, pool boiling, theoretical coolant density

Taking into account uncertainties Δk_{man} and Δk_{dep} from the original FANP analysis, the limiting multiplication factor has been determined to be k_{limit}=0. 92742.

The results are presented in Figure 7. The maximal k_{eff}=0.92035±0.00008 occurs at 120 °C and coolant density of 0.943083 g/cm³. It is well below the limiting value. Therefore, the pool remains subcritical under those conditions for the fuel assemblies with the enrichment below 5%.

3. 4 3 out of 4 positions loaded, optimum moderation

Taking into account uncertainties Δk_{man} and Δk_{dep} from the original FANP analysis, the limiting multiplication factor has been determined to be k_{limit}=0.92634.

The results of calculations are presented in Table 4. For each enrichment, parabolic fit is applied to determine optimum water density and maximal k_{eff}. The weighting function $1/\sigma^2$ is used. The pooled variance is taken as the final uncertainty.

The results of the fresh fuel cases are shown in Figure 12. For better readability, the limiting multiplication factor line is also drawn. The presented curve is fitted with a parabolic fit. Enrichment is determined where the fitting curve +3σ intersects the limiting value. The obtained limiting enrichment is 4.247%. As shown in Table 4, two cases with supplied burnup isotopic composition were also calculated:

- 4.5% 29 MWd/kgU,
- 5.0% 34 MWd/kgU.

Since only two multiplication factors are available for each particular enrichment, linear interpolation is used instead of the standard fitting procedure to determine the necessary limiting burnup. The obtained loading curve is presented in Figure 13. Based on the FANP analysis, there are no burnup limitations if at least 2000 ppm of boron is present in the SFP.

Table 4: *Effective multiplication factors, 3 out of 4 positions loaded, optimum moderation*

Enrichment/Burnup	Density	k_{eff}	
3.5%			
	0.10	0.88055	±0.00006
	0.11	0.88291	±0.00006
	0.12	0.88382	±0.00006
	0.13	0.88319	±0.00006
Max	0.12091	0.88381	±0.00006
4.0%			
	0.10	0.91019	±0.00006
	0.11	0.91233	±0.00006
	0.12	0.91298	±0.00006
	0.13	0.91212	±0.00006
Max	0.11037	0.91298	±0.00006
4.5%			
	0.10	0.93604	±0.00006
	0.11	0.93801	±0.00006
	0.12	0.93827	±0.00007
	0.13	0.93705	±0.00006
Max	0.10953	0.93838	±0.00007
4.5% 29 MWd/kgU			
	0.11	0.78828	±0.00006
	0.12	0.78982	±0.00007
	0.13	0.79020	±0.00006
	0.14	0.78942	±0.00006
Max	0.12828	0.79022	±0.00006
5.0%			
	0.10	0.95862	±0.00007
	0.11	0.96041	±0.00007
	0.12	0.96041	±0.00006
	0.13	0.95913	±0.00007
Max	0.11599	0.9606	±0.00011
5.0% 34 MWd/kgU			
	0.11	0.79185	±0.00006
	0.12	0.79328	±0.00006
	0.13	0.79341	±0.00006
	0.14	0.79284	±0.00006
Max	0.12810	0.79352	±0.00011

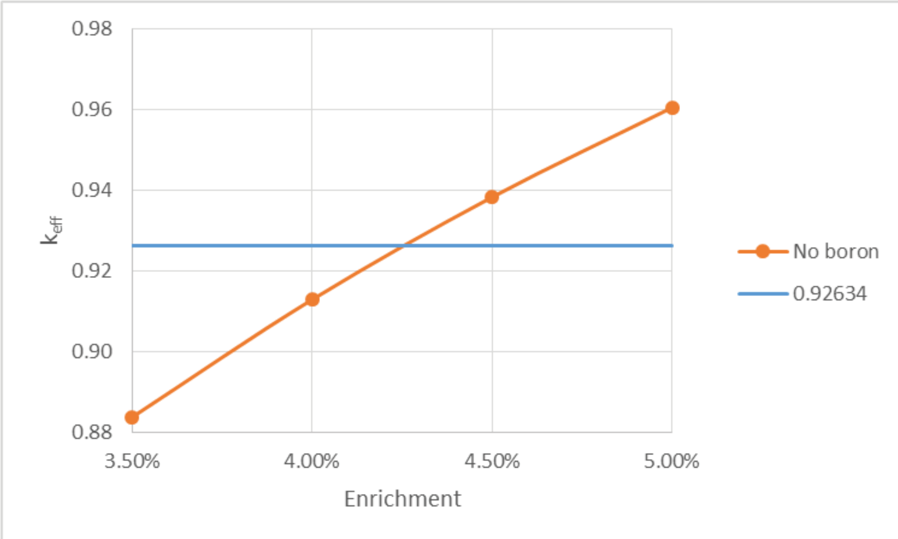

Figure 12: *Effective multiplication factor, 3 out of 4 positions loaded, optimum moderation, fresh fuel*

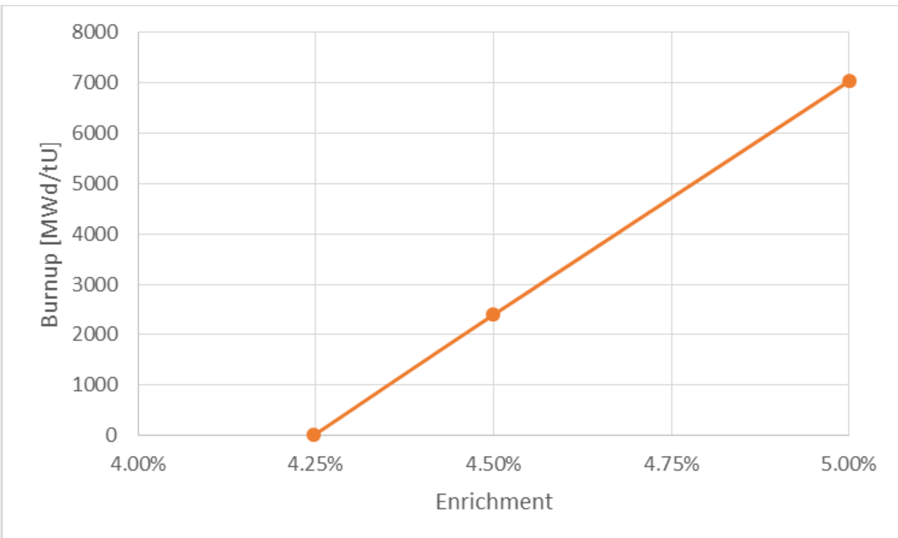

Figure 13: *Loading curve, 3 out of 4 positions loaded, optimum moderation*

4 SUMMARY

NPP Krško old racks have been re-analysed under hypothetical degraded SFP conditions, exploring some hypothetical scenarios beyond the design basis. In addition to the optimum moderation scenario, it was assumed that no soluble boron was present in the SFP coolant. The MCNP stochastic code with a continuous energy neutron library based on the ENDF/B-VII.1 nuclear data files has been used. Cases 3 out of 4 and 4 out of 4 positions loaded with fuel assemblies were considered. Pool boiling and cases with optimum moderation were analysed.

For the abovementioned hypothetical scenarios, this analysis showed that in the 3 out of 4 positions loaded case, fresh fuel assemblies with the enrichment up to 5% were subcritical if the pool was boiling provided that the SFP was covered with water. In the hypothetical optimum moderation scenario, the maximum fresh fuel enrichment was calculated at 4.25%. For higher enrichments, a burnup credit curve was determined. In 4 out of 4 cases, the limiting enrichments were 3.73% for the pool boiling conditions and 2.37% for the optimum moderation scenario. For higher enrichments, burnup credit curves were determined.

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Nomenclature

FANP	Framatome ANP GmbH
NPP	Nuclear Power Plant
PWR	Pressurized Water Reactor
SFP	Spent Fuel Pool
US NRC	United States Nuclear Regulatory Commission