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Comparison of the SCALE, SERPENT and MCNP Criticality Safety Calculation of the NPP Krško Spent Fuel Pool

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ABSTRACT

Criticality safety reanalyzes of the NPP Krško spent fuel pool has been performed. Limiting criticality cases at optimal moderation conditions are calculated using different SCALE code versions (SCALE-4.4a, SCALE-5.1 and SCALE-6.1) with 44-group ENDF/B-V and 238-group ENDF/B-VII.0 derived cross section libraries. Relative small discrepancies are observed. Additional verification is provided with SERPENT and MCNP5 codes, which are capable to take into account neutron continuous energy cross section library based on ENDF/B-VII.0 files. Comparison has shown that the results of the pool design calculations are conservative, precluding racks criticality even at optimum moderation conditions.

1 INTRODUCTION

Development of the computer hardware and improvements in the neutron cross-section libraries enables more and more accurate calculations of the neutron transport determined with the Monte Carlo codes. With the increased reliance on computational tools comes the need and requirement for redundant validation of performed criticality safety analyses by alternate criticality codes. Design calculations of the NPP Krško spent fuel pool have been performed almost 10 years ago [1,2]. SCALE [3] versions 4.4a and 5.0 with the 44-group ENDF/B-V derived cross section library 44GROUPNDF5 have been applied. Since then, new codes and neutron libraries have been developed. The limiting criticality calculations of the NPP Krško spent fuel pool are repeated using the latest SCALE versions and the ENDF/B-VII.0 library. Additional verification is provided with SERPENT [4,5] and MCNP [6] codes, which are capable to take into account neutron continuous energy cross section library.

2 METHODS AND MODELS

Criticality safety investigation of the NPP Krško wet spent fuel storage has been performed. NPP Krško is a 2-loop Westinghouse plant with a gross electrical output of 730 MW. The core consists of 121 fuel assemblies. Each assembly has 235 fuel rods arranged in a 16×16 array. The remaining 21 positions are intended for control rods and the central instrumentation channel. Used

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fuel is stored in the storage pool, where two types of storage racks are implemented. Present analysis considers old racks configuration.

One storage cell with periodic boundary condition in the radial direction (representing infinite array of cells) has been applied in all cases. The radial and axial storage cell cross sections are presented in Figure 1. Water is represented in blue, UO_2 with red, cladding with light green. The stainless steel cell frame is in violet. Concrete structure of the pool is in light brown on the bottom of the right figure. It should be noted, that the aspect ratio of the axial slice is not preserved to allow reasonable geometrical presentation.

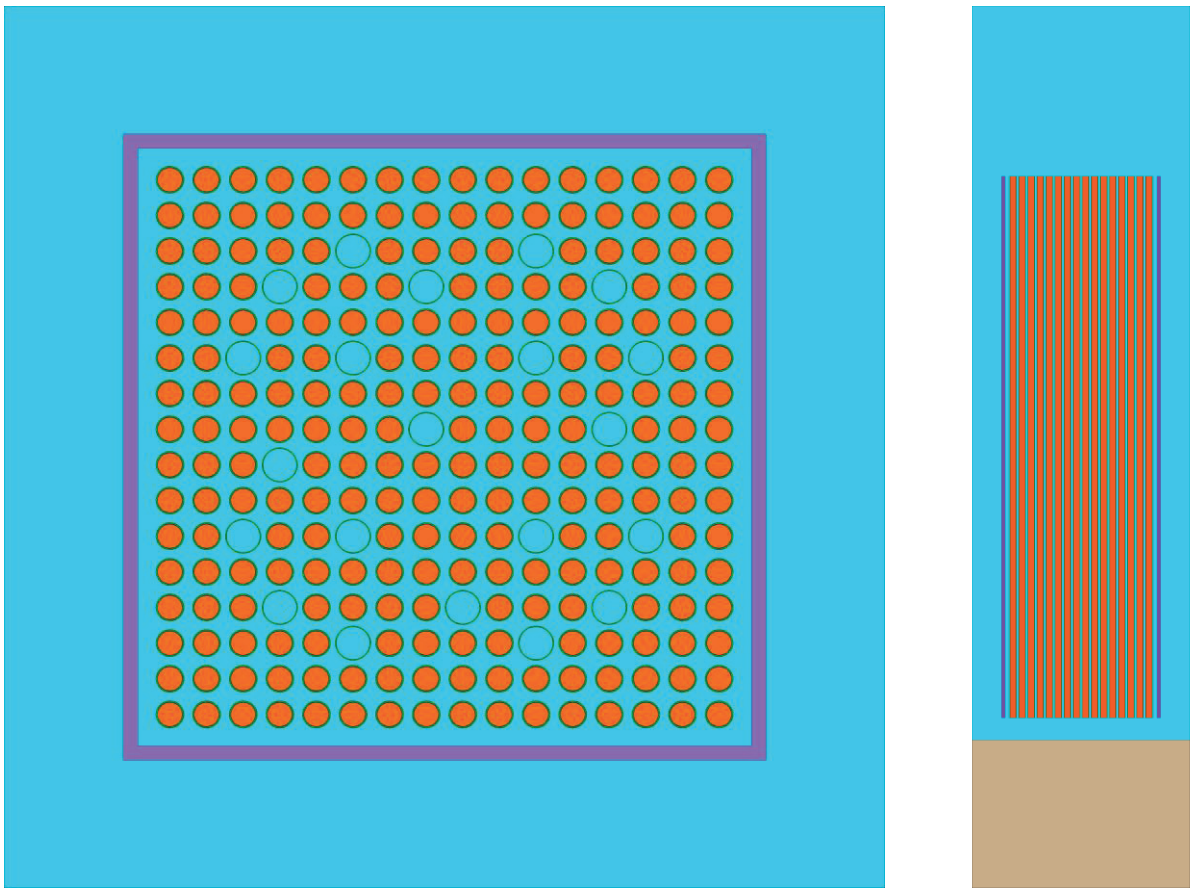

Figure 1: Geometrical layout of the NPP Krško storage cell, old racks

The design analysis [1,2] has shown that the limiting case (maximal k_{eff}) occurs at low water densities (optimal moderation). In such scenario with boiling pool water, fuel cooling is obstructed. Due to decay heat, temperature of the fuel could exceed temperature of the pool water. However, reactivity of the system would decrease with increasing fuel temperature due to the Doppler resonance broadening. At water temperature of 120 °C, water starts to boil at 2 bars. Such pressure corresponds to the depth of 10 m covering the storage of the fuel assemblies in the NPP Krško storage pool. Therefore, it is reasonably conservative to apply temperature level of 120 °C in the optimal moderation calculations. The highest possible fuel enrichment of 5 % has been considered in all cases.

The SCALE code package [3] is a comprehensive modeling and simulation suite for nuclear safety analysis and design that is developed and maintained by Oak Ridge National Laboratory (ORNL). It provides a verified and validated, user-friendly tool set for criticality safety, reactor physics, radiation shielding, radioactive source term characterization, and sensitivity and

uncertainty analysis. SCALE criticality calculations presented in the paper have been performed using the standard CSAS25 sequence. This control sequence activates the cross-section processing codes BONAMI, to provide resonance corrected cross sections in the unresolved resonance range, and WORKER, CENTRM and PMC, to provide resonance-corrected cross sections in the resolved resonance range. KENO V.a uses the processed cross sections and calculates the k_{eff} of three-dimensional (3-D) system models. The following code versions and neutron cross section libraries were used:

- SCALE-4.4a with 44-group ENDF/B-V derived cross section library 44GROUPNDF5 (updated 7/29/99).
- SCALE-5.1 with 44-group ENDF/B-V derived cross section library 44GROUPNDF5 (updated 3/25/2004).
- SCALE-6.1 with:
  - 44-group ENDF/B-V derived cross section library 44GROUPNDF5 (updated 3/25/2004) and
  - 238-group ENDF/B-VII.0 derived cross section library V7-238 (updated 12/17/09).

SERPENT [4] is a three-dimensional continuous-energy Monte Carlo reactor physics burnup calculation code, developed at the VTT Technical Research Centre of Finland. It uses a continuous energy neutron cross section library in an ACE format based on the ENDF/B-VII.0 evaluated nuclear data library [5]. The code is specialized for two-dimensional lattice physics calculations, but the universe-based geometry description allows the modeling of complicated three-dimensional geometries as well. SERPENT has the option to use a built-in Doppler broadening routine to adjust nuclide temperatures before the actual Monte Carlo calculation is performed.

MCNP [6] is a general-purpose Monte Carlo N–Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport, including the capability to calculate eigenvalues for critical systems. The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first- and second-degree surfaces and fourth-degree elliptical tori. Pointwise (continuous energy) cross-section data are used. The calculations reported in this paper were performed with version 5.1.40 of the code and ENDF/B-VII.0 evaluated nuclear data library. An auxiliary processing code MAKXSF was used to provide case specific neutron cross section library at 120 °C.

3 RESULTS AND DISCUSSION

Two cases are examined. Nominal boron concentration in the pool water is limited by the Technical Specifications [7] to 2000 ppm. In addition, k_{eff} is determined also for a hypothetical case where no soluble boron is present in the pool. It should be mentioned here, that the pool has been designed to preclude criticality when at least 2000 ppm of soluble boron is present in the pool water [1,2,7]. The loading curve has been determined, which relates fuel assembly enrichment and discharged burnup. Only assemblies with sufficiently high burnup are allowed to be stored in the pool. Therefore, assemblies with 5 % enrichment and no burnup are not allowed to be stored in this configuration, since they exhibit too high multiplication factor. However, since only relative comparison has been performed in presented analysis, fresh fuel with highest possible 5 % enrichment was considered.

3.1 Comparison of different SCALE versions

Results obtained with different SCALE code versions are presented in Tables 1-2 and Figures 2-3. Uncertainties listed in the k_{eff} columns represent statistical error of 1 σ. Although the exact versions of the code and library used in the pool design calculations are not available, sample calculations on the several design input files have shown that the SCALE-4.4a with 44-group ENDF/B-V derived cross section library 44GROUPNDF5 replicates pool design calculations almost inside statistical error. Differences to this basic setup are shown in the tables and can be seen as differences to the design calculations. SCALE 5.1 gives slightly higher multiplication factor at low densities and lower k_{eff} at higher densities. SCALE 6.1 with the same 44GROUPNDF5 library is lower at entire range. Differences when 238-group ENDF/B-VII.0 library is applied are even more negative in the 2000 ppm case. Almost the same trend is observed when no soluble boron is present. Since it is reasonable to assume that the newer code and library versions with highest number of energy groups are more accurate, we can safely deduce that the design calculations have been performed in conservative manner.

Table 1: Comparison of the multiplication factors obtained with different versions of SCALE, 2000 ppm of boron

	SCALE 4.4a 44-group ENDF/B-V	SCALE 5.1 44-group ENDF/B-V		SCALE 6.1 44-group ENDF/B-V		SCALE 6.1 238-group ENDF/B-VII.0	
Density [g/cm3]	k_{eff}	k_{eff}	Difference	k_{eff}	Difference	k_{eff}	Difference
0.05	0.96581 ± 0.00007	0.96793 ± 0.00007	0.00212	0.95765 ± 0.00007	-0.00816	0.94580 ± 0.00007	-0.02001
0.08	1.00995 ± 0.00008	1.01148 ± 0.00008	0.00153	1.00402 ± 0.00008	-0.00593	0.99519 ± 0.00008	-0.01476
0.10	1.01778 ± 0.00008	1.01927 ± 0.00007	0.00149	1.01285 ± 0.00007	-0.00493	1.00552 ± 0.00008	-0.01226
0.12	1.01491 ± 0.00007	1.01620 ± 0.00008	0.00129	1.01070 ± 0.00008	-0.00421	1.00504 ± 0.00008	-0.00987
0.15	0.99819 ± 0.00008	0.99903 ± 0.00008	0.00084	0.99478 ± 0.00008	-0.00341	0.99085 ± 0.00008	-0.00734
0.20	0.95477 ± 0.00008	0.95464 ± 0.00008	-0.00013	0.95189 ± 0.00008	-0.00288	0.94977 ± 0.00009	-0.00500
0.30	0.86147 ± 0.00009	0.86035 ± 0.00009	-0.00112	0.85874 ± 0.00008	-0.00273	0.85932 ± 0.00008	-0.00215
0.40	0.79065 ± 0.00009	0.78868 ± 0.00008	-0.00197	0.78798 ± 0.00008	-0.00267	0.78923 ± 0.00009	-0.00142
0.50	0.74596 ± 0.00009	0.74321 ± 0.00008	-0.00275	0.74291 ± 0.00008	-0.00305	0.74479 ± 0.00009	-0.00117
0.60	0.72116 ± 0.00009	0.71792 ± 0.00008	-0.00324	0.71834 ± 0.00009	-0.00282	0.72014 ± 0.00009	-0.00102
0.70	0.71099 ± 0.00009	0.70742 ± 0.00009	-0.00357	0.70796 ± 0.00009	-0.00303	0.70985 ± 0.00009	-0.00114
0.80	0.70968 ± 0.00009	0.70598 ± 0.00009	-0.0037	0.70696 ± 0.00009	-0.00272	0.70849 ± 0.00009	-0.00119
0.90	0.71402 ± 0.00009	0.71019 ± 0.00009	-0.00383	0.71141 ± 0.00009	-0.00261	0.71290 ± 0.00009	-0.00112
0.943	0.71685 ± 0.00009	0.71309 ± 0.00009	-0.00376	0.71440 ± 0.00009	-0.00245	0.71578 ± 0.00009	-0.00107

Table 2: Comparison of the multiplication factors obtained with different versions of SCALE, no boron in the water

	SCALE 4.4a 44-group ENDF/B-V	SCALE 5.1 44-group ENDF/B-V		SCALE 6.1 44-group ENDF/B-V		SCALE 6.1 238-group ENDF/B-VII.0	
Density [g/cm3]	k_{eff}	k_{eff}	Difference	k_{eff}	Difference	k_{eff}	Difference
0.10	1.10277 ± 0.00008	1.10496 ± 0.00008	0.00219	1.09802 ± 0.00008	-0.00475	1.09135 ± 0.00008	-0.01142
0.15	1.13646 ± 0.00008	1.13822 ± 0.00008	0.00176	1.13336 ± 0.00008	-0.00310	1.13050 ± 0.00008	-0.00596
0.20	1.13904 ± 0.00009	1.14063 ± 0.00008	0.00159	1.13703 ± 0.00008	-0.00201	1.13709 ± 0.00009	-0.00195
0.25	1.12696 ± 0.00008	1.12797 ± 0.00009	0.00101	1.12546 ± 0.00008	-0.00150	1.12748 ± 0.00008	0.00052
0.30	1.10790 ± 0.00009	1.10850 ± 0.00008	0.00060	1.10658 ± 0.00008	-0.00132	1.10993 ± 0.00008	0.00203
0.40	1.06380 ± 0.00009	1.06360 ± 0.00009	-0.00020	1.06244 ± 0.00008	-0.00136	1.06809 ± 0.00009	0.00429
0.50	1.02413 ± 0.00009	1.02300 ± 0.00008	-0.00113	1.02262 ± 0.00009	-0.00151	1.02911 ± 0.00009	0.00498
0.60	0.99419 ± 0.00009	0.99230 ± 0.00009	-0.00189	0.99245 ± 0.00009	-0.00174	0.99944 ± 0.00009	0.00525
0.70	0.97498 ± 0.00010	0.97251 ± 0.00009	-0.00247	0.97293 ± 0.00010	-0.00205	0.98000 ± 0.00010	0.00502
0.80	0.96586 ± 0.00010	0.96300 ± 0.00010	-0.00286	0.96379 ± 0.00009	-0.00207	0.97080 ± 0.00010	0.00494
0.90	0.96494 ± 0.00010	0.96182 ± 0.00010	-0.00312	0.96280 ± 0.00010	-0.00214	0.96968 ± 0.00010	0.00474
0.943	0.96664 ± 0.00011	0.96326 ± 0.00010	-0.00338	0.96456 ± 0.00010	-0.00208	0.97106 ± 0.00010	0.00442

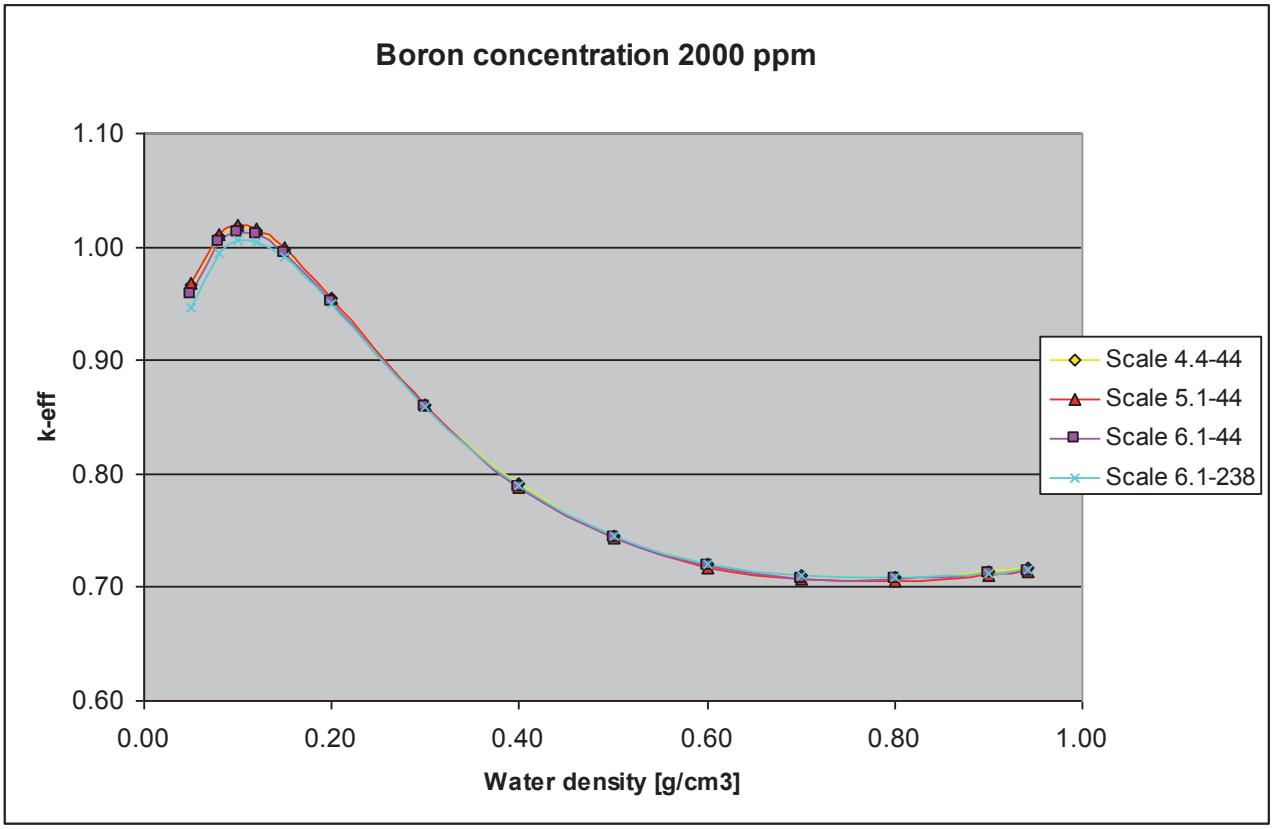

Figure 2: Comparison of the multiplication factors obtained with different versions of SCALE, 2000 ppm of boron

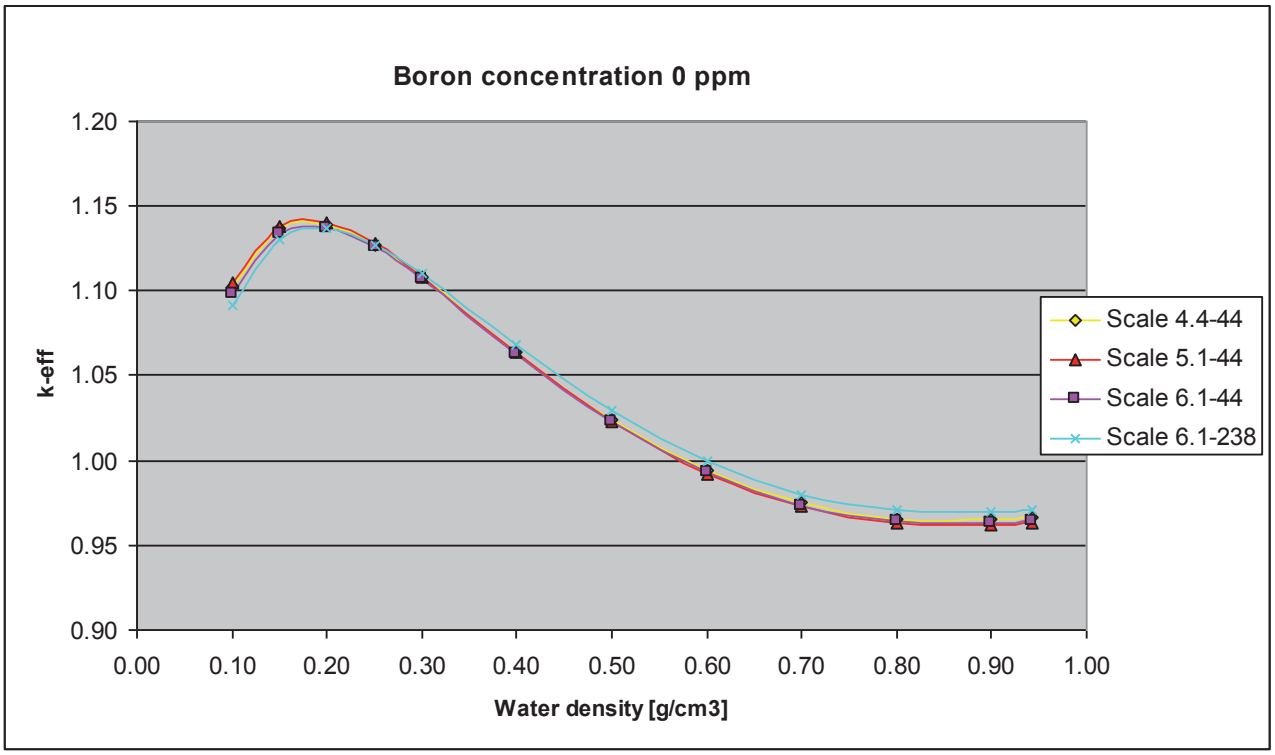

Figure 3: Comparison of the multiplication factors obtained with different versions of SCALE, no boron in the water

3.2 Comparison with the SERPENT and MCNP5

For additional verification calculations with the SERPENT and MCNP5 codes have been performed. Both codes are capable to take into account neutron continuous energy cross section library. Therefore, there is no need to perform additional spectral adjustments as in the multigroup case. Comparison is presented in Tables 3-4 and Figures 4-5. Discrepancies to the basic case are little larger than in previous SCALE comparison. However, both codes give significantly lower results again proving the conservative nature of the design calculations. SERPENT multiplication factors are slightly lower than MCNP5 results. That could be contributed to the internal temperature Doppler correction and lack of the temperature correction in the water energy dependent scattering kernel. Temperature corrections in the MCNP5 case have been done rigorously with the MAKXSF code.

4 CONCLUSION

Criticality safety reanalyzes of the NPP Krško spent fuel pool has been performed. Calculations of the pool racks with different water densities have been executed using the different SCALE code versions (SCALE-4.4a, SCALE-5.1 and SCALE-6.1) with the 44-group ENDF/B-V and the 238-group ENDF/B-VII.0 derived cross section libraries. Relative small discrepancies are observed. Multiplication factors are mainly under the basic setup consisting of SCALE-4.4a code with the 44-group ENDF/B-V library, which can be considered as a design setup. SCALE-6.1 with 238-group ENDF/B-VII.0 library gives lower values at low density range. Additional verification is provided with SERPENT and MCNP5 codes, which are capable to take into account neutron continuous energy cross section library. Cross sections based on the ENDF/B-VII.0 files have been used in both codes. Comparison has shown that the results of the pool design calculations are conservative, precluding racks criticality even at optimum moderation conditions.

Table 3: Comparison of the multiplication factors obtained with the SERPENT and MCNP5, 2000 ppm of boron

	SCALE 4.4a 44-group ENDF/B-V	SERPENT Continuous ENDF/B-VII.0		MCNP5 Continuous ENDF/B-VII.0	
Density [g/cm3]	k_{eff}	k_{eff}	Difference	k_{eff}	Difference
0.05	0.96581 ± 0.00007	0.91708 ± 0.00010	-0.04873	0.91825 ± 0.00008	-0.04756
0.08	1.00995 ± 0.00008	0.96456 ± 0.00010	-0.04539	0.96748 ± 0.00009	-0.04247
0.10	1.01778 ± 0.00008	0.97429 ± 0.00010	-0.04349	0.97824 ± 0.00009	-0.03954
0.12	1.01491 ± 0.00007	0.97348 ± 0.00010	-0.04143	0.97831 ± 0.00009	-0.03660
0.15	0.99819 ± 0.00008	0.95917 ± 0.00011	-0.03902	0.96495 ± 0.00009	-0.03324
0.20	0.95477 ± 0.00008	0.91920 ± 0.00011	-0.03557	0.92693 ± 0.00010	-0.02784
0.30	0.86147 ± 0.00009	0.83290 ± 0.00013	-0.02857	0.84195 ± 0.00010	-0.01952
0.40	0.79065 ± 0.00009	0.76850 ± 0.00015	-0.02215	0.77672 ± 0.00010	-0.01393
0.50	0.74596 ± 0.00009	0.72878 ± 0.00017	-0.01718	0.73611 ± 0.00010	-0.00985
0.60	0.72116 ± 0.00009	0.70843 ± 0.00017	-0.01273	0.71480 ± 0.00010	-0.00636
0.70	0.71099 ± 0.00009	0.70158 ± 0.00018	-0.00941	0.70667 ± 0.00011	-0.00432
0.80	0.70968 ± 0.00009	0.70311 ± 0.00018	-0.00657	0.70740 ± 0.00011	-0.00228
0.90	0.71402 ± 0.00009	0.70938 ± 0.00017	-0.00464	0.71273 ± 0.00011	-0.00129
0.943	0.71685 ± 0.00009	0.71283 ± 0.00017	-0.00402	0.71635 ± 0.00011	-0.00050

Table 4: Comparison of the multiplication factors obtained with the SERPENT and MCNP5, no boron in the water

	SCALE 4.4a 44-group ENDF/B-V	SERPENT Continuous ENDF/B-VII.0		MCNP5 Continuous ENDF/B-VII.0	
Density [g/cm3]	k_{eff}	k_{eff}	Difference	k_{eff}	Difference
0.10	1.10277 ± 0.00008	1.05388 ± 0.00010	-0.04889	1.05762 ± 0.00008	-0.04515
0.15	1.13646 ± 0.00008	1.08912 ± 0.00009	-0.04734	1.09500 ± 0.00009	-0.04146
0.20	1.13904 ± 0.00009	1.09305 ± 0.00009	-0.04599	1.10077 ± 0.00009	-0.03827
0.25	1.12696 ± 0.00008	1.08183 ± 0.00010	-0.04513	1.09162 ± 0.00009	-0.03534
0.30	1.10790 ± 0.00009	1.06384 ± 0.00010	-0.04406	1.07521 ± 0.00009	-0.03269
0.40	1.06380 ± 0.00009	1.02352 ± 0.00011	-0.04028	1.03639 ± 0.00009	-0.02741
0.50	1.02413 ± 0.00009	0.98831 ± 0.00012	-0.03582	1.00201 ± 0.00010	-0.02212
0.60	0.99419 ± 0.00009	0.96316 ± 0.00012	-0.03103	0.97695 ± 0.00010	-0.01724
0.70	0.97498 ± 0.00010	0.94892 ± 0.00013	-0.02606	0.96169 ± 0.00010	-0.01329
0.80	0.96586 ± 0.00010	0.94459 ± 0.00013	-0.02127	0.95579 ± 0.00011	-0.01007
0.90	0.96494 ± 0.00010	0.94743 ± 0.00014	-0.01751	0.95810 ± 0.00011	-0.00684
0.943	0.96664 ± 0.00011	0.95080 ± 0.00014	-0.01584	0.96054 ± 0.00011	-0.00610

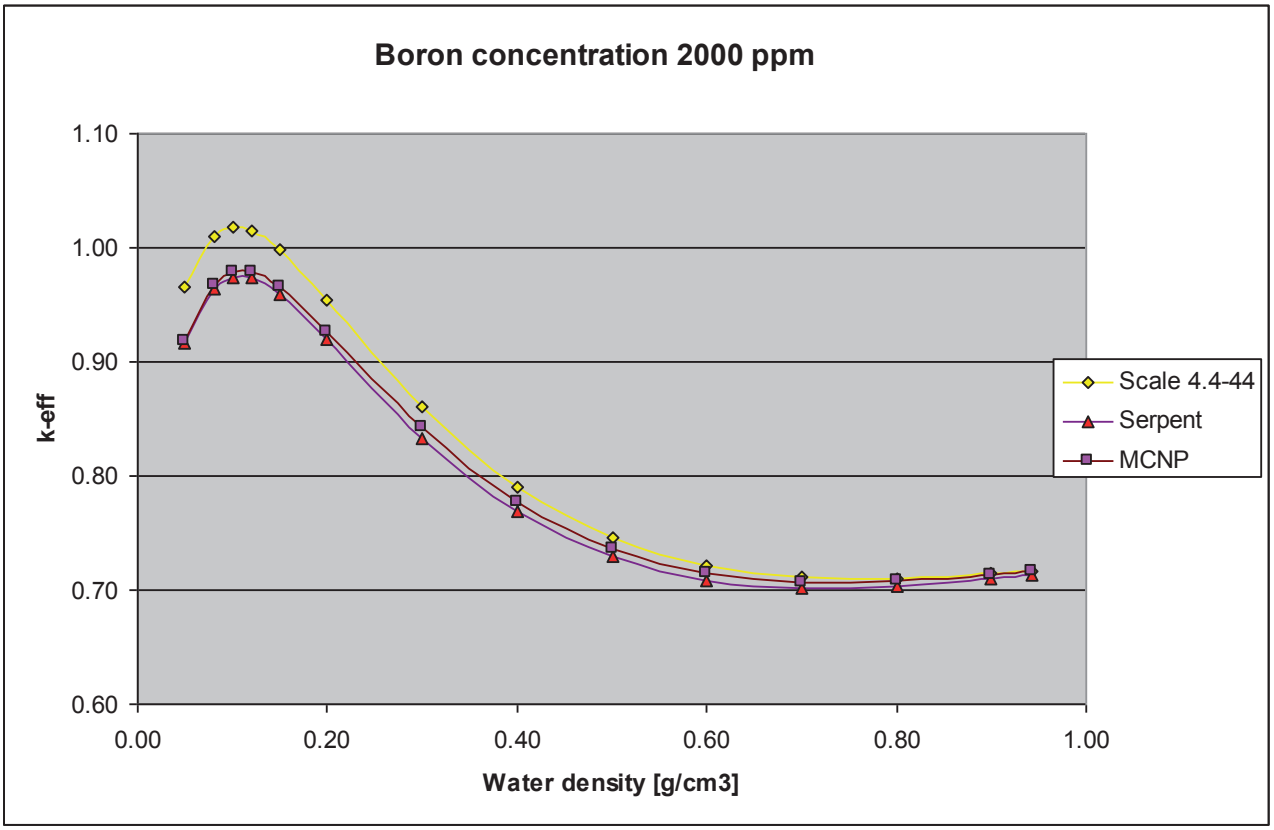

Figure 4: Comparison of the multiplication factors obtained with the SERPENT and MCNP5, 2000 ppm of boron

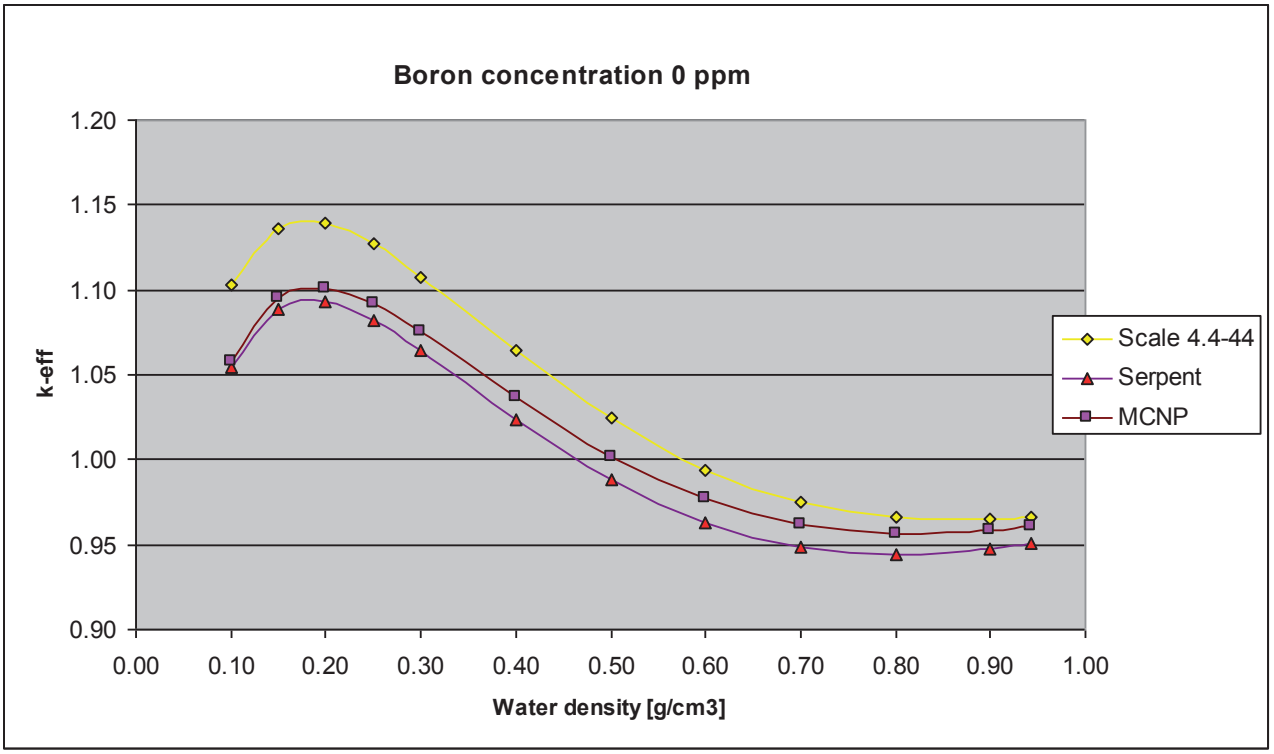

Figure 5: Comparison of the multiplication factors obtained with the SERPENT and MCNP5, no boron in the water

M. Kromar, B. Kurinčič, Comparison of the SCALE, SERPENT and MCNP Criticality Safety Calculation of the NPP Krško Spent Fuel Pool, Journal of Energy, vol. 62 Number 1–4 (2013) Special Issue, p. 200–208

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